ENERGY STORAGE SYSTEMS

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Energy Storage Systems: The Future of Clean Energy

"The future isn't just about generating clean energy, but storing it wisely."

The global transition toward clean and sustainable energy has become one of the most critical priorities of the 21st century. As nations strive to reduce carbon emissions and combat climate change, renewable energy sources such as solar and wind power are being rapidly deployed. However, these sources are inherently intermittent; solar power is only available during daylight hours, and wind energy depends on weather conditions. This variability creates significant challenges in maintaining a stable and reliable power supply. Energy Storage Systems (ESS) emerge as a transformative solution to bridge this gap.

Energy Storage Systems play a vital role in capturing excess energy generated during periods of low demand and storing it for use when demand is high or generation is low. By doing so, they enhance grid stability, improve energy efficiency, and enable a higher penetration of renewable energy into the power system. Technologies such as battery energy storage, pumped hydro storage, compressed air energy storage, and emerging innovations like hydrogen storage are shaping the future of modern power systems.

Beyond supporting renewable integration, ESS contributes to peak load management, frequency regulation, and energy security. It also reduces dependency on fossil fuel-based backup generation, thereby lowering greenhouse gas emissions and operational costs in the long term. With advancements in technology, declining costs, and supportive policy frameworks, energy storage is rapidly becoming a cornerstone of the global energy transition.

This flyer explores the significance, technologies, applications, and future prospects of Energy Storage Systems, highlighting their pivotal role in building a resilient, efficient, and sustainable energy infrastructure for generations to come.

CONTENTS

- xxi. Silver Zinc Battery (AgZn)
- xxii. Nickel Iron Battery (NiFe)
- xxiii. Zinc Bromine Battery (ZnBr2)
- xxiv. Vanadium Redox Battery (VRB)
- xxv. Sodium Nickel Chloride Battery (NaNiCl2 / ZEBRA)
- xxvi. Lithium Polymer Battery (LiPo)
- xxvii. Lithium Air Battery (Li-Air)
- xxviii. Zinc Manganese Dioxide Battery (Zn-MnO2)
- xxix. Nickel Hydrogen Battery (NiH2)

II. Advanced Chemical Energy Storage

- i. CO_2 Battery.
- ii. Highview Power Cryo Battery.
- iii. Ammonia Energy Storage

III. Flow batteries

- i. Vanadium Redox flow Battery.
- ii. Zinc Bromine flow Battery.
- iii. Iron flow Battery

IV. Gravitational Storage

- i. Pumped Hydro Storage.

VIII. Magnetic Energy Storage

i. Superconducting Magnetic Energy Storage.

IX. Hydrogen Based energy storage

CHEMICAL BATTERIES

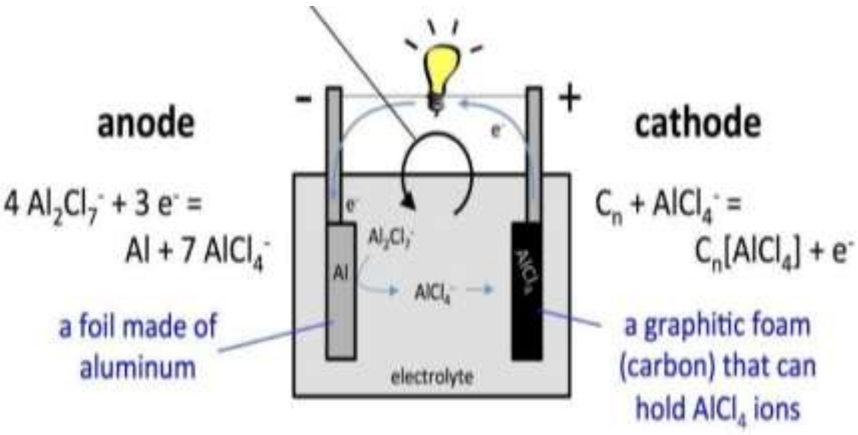
Chemical batteries store chemical energy and convert it to electrical energy using electrochemical reactions. They are made up of two electrodes and an electrolyte. When connected to a circuit, electrons flow from the anode to the cathode, providing an electric current.

Chemical batteries are used in a wide variety of applications, including consumer electronics, automotive, industrial, military, and aerospace. They offer a number of advantages, including being relatively inexpensive, portable, and having a high energy density. However, they also have some disadvantages, such as a limited lifespan and the potential to be harmful to the environment or flammable.

Chemical batteries are essential to modern life and are constantly being improved to make them more efficient, durable, and environmentally friendly.

i. ALUMINIUM-ION BATTERY

Overview



Aluminium–Ion batteries are an emerging type of rechargeable battery that use aluminium as the anode material and a suitable cathode material such as graphite or metal oxides. Aluminium is one of the most abundant metals in the Earth's crust, making this battery technology attractive for low-cost and sustainable energy storage applications. Aluminium-Ion batteries have gained significant attention in recent years due to their potential advantages such as high theoretical capacity, fast charging capability, improved safety, and long cycle life. Unlike lithium-ion batteries, aluminium-ion batteries use multivalent aluminium ions (Al^{3+}) for charge storage, which allows higher charge transfer during electrochemical reactions. Although still in the research and development stage, Aluminium-Ion batteries are considered promising for future energy storage systems, electric vehicles, and portable electronics.

Working Principle:

The operation of an Aluminium-Ion battery is based on the movement of aluminium ions between the anode and cathode through an electrolyte during charging and discharging. During discharge, aluminium at the anode releases ions, and these ions move to the cathode where they are stored, producing electrical energy. During the charging process, aluminium ions are deposited on the aluminium anode while electrons move through the external circuit.

The electrochemical reactions generally involve aluminium metal oxidation and reduction reactions combined with intercalation reactions in the cathode material. A typical system uses an aluminium metal anode, graphite cathode, and ionic liquid electrolyte, which enables reversible electrochemical reactions and stable battery operation.

Chemical Reaction:

$3C_n + 4Al_2Cl_7^- \rightleftharpoons 3C_n[AlCl_4] + Al + 7AlCl_4^-$

Research Universities/Institutions/Companies:

India: Indian Institute of Technology Madras, Indian Institute of Science, Indian Institute of Technology Bombay, and battery materials researchers working on low-cost energy storage.

Asia: Tsinghua University, Chinese Academy of Sciences, and other Asian research groups working on graphene-based electrodes and advanced electrolytes.

North America: Stanford University, MIT, and companies exploring advanced aluminum-ion concepts for stationary and lightweight applications.

Europe: University groups and materials labs focused on sustainable batteries, recycling, and next-generation electrochemistry.

Largest Acquired Capacity

Aluminium-ion batteries are still mostly at prototype and early commercialization stage, so there are not many large public deployments like lithium-ion or flow batteries. Current work is centered on improving cell performance and moving from lab-scale systems to pilot-scale demonstrations. In 2024, Graphene Manufacturing Group (GMG) successfully integrated graphene into their AIB prototypes, achieving significant performance boosts.

Specific Capacity

Aluminium-ion batteries have a high theoretical specific capacity approximately 2,980mAh/g (theoretical) and a high volumetric capacity of 8,046mAh/cm³ because aluminium can transfer three electrons per ion. However, practical specific energy in current prototypes is still limited by cathode instability and electrolyte constraints, so real-world performance remains below theoretical expectations, ranging between 100 – 400mAh/g.

Cost of Making

Aluminium-ion batteries are often presented as potentially low-cost, with potential at-scale manufacturing costs between $70 and $120 per kWh (projected future cost), because aluminium is inexpensive and abundant.

Space to Implement

Aluminium-ion batteries could be suitable for stationary storage, consumer electronics, and possibly transport applications if performance improves enough. At present, they are still being developed, so space requirements depend heavily on the final cell design and application.

Positives and Challenges

The positives of aluminium-ion batteries include abundance of raw materials, environmentally friendly and recyclable materials, lower potential cost, high theoretical capacity, and improved safety compared with some lithium-based systems. They also support fast-charge concepts because aluminium can move charge efficiently in the electrochemical process.

The challenges of aluminium-ion batteries include limited cycle life in current prototypes, difficulty finding stable cathode materials, and issues with electrolyte compatibility. The technology is also not yet widely commercialized, so large-scale manufacturing and long-term field data are still limited.

Applications

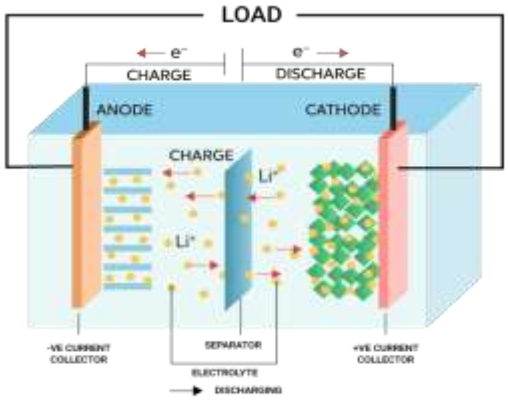
Aluminium-ion batteries are still in the research and early development stage, but their expected applications include stationary energy storage, fast-charging systems, consumer electronics, electric vehicles, and decentralized power systems. They are attractive where fast charging, safety, and low-cost materials are important.

Latest Developments

The latest development is the increase in research and pilot-level commercialization efforts focused on performance, stability, extending cycle life and improving electrode materials. Scientists are developing advanced cathode materials such as graphene-based and nanostructured carbon materials, which improve ion intercalation and increase energy storage capacity. New solid-state and ionic liquid electrolytes are also being investigated to enhance battery stability and safety. Another important update is the growing market interest driven by sustainability and reduced dependence on critical materials like lithium and cobalt. Reports from 2025-2026 indicate that the technology is being positioned for consumer electronics, EVs, and grid storage in the long term, although it still needs major technical progress before wide adoption.

ii. LITHIUM-ION BATTERY

Overview



A lithium-ion (Li-ion) battery is a rechargeable battery that uses lithium ions to generate electrical current. It consists of an anode (typically graphite), a cathode (usually a metal oxide), an electrolyte (a conductive substance facilitating ion flow), and a separator. Li-ion batteries are prevalent in electronics and electric vehicles due to their high energy density, light weight, and rechargeable nature. They operate by the movement of lithium ions between the anode and cathode during discharge and recharge cycles. Despite advantages like high energy density and long cycle life, they also have limitations, including sensitivity to high temperatures and a gradual capacity decline over time.

Working Principle

Lithium-ion (Li-ion) batteries operate through electrochemical reactions. During discharging, lithium ions move from the anode to the cathode, creating an electric current that powers a device. In charging, an external voltage reverses this process, moving lithium ions from the cathode back to the anode. Key components include the electrolyte, separator, and anode/cathode materials. This reversible movement of ions and electrons allows Li-ion batteries to store 10 and release electrical energy, making them widely used in electronics and electric vehicles.

Chemical Reaction

$LiC_6 + CoO_2 \rightarrow C_6 + LiCoO_2$

Research Universities/Institutions/Companies

America: University of California, Berkeley, Stanford University, Massachusetts Institute of Technology, University of Michigan, University of Texas at Austin, Argonne National Laboratory, National Renewable Energy Laboratory, Lawrence Berkeley

National Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, Clean Energy Institute, UL Electrochemical Safety Research Institute, Tesla, Panasonic, Solid Power, QuantumScape.

Europe: Fraunhofer Institute for Chemical Technology, Helmholtz-Zentrum Berlin für Materialien und Energie, Faraday Institution, CELEST Center for Electrochemical Energy Storage.

Asia: Tokyo Institute of Technology, Panasonic, LG Chem, Samsung SDI, CATL, BYD, SK Innovation, Envision AESC, Northvolt, Syrah Resources, Vulcan Energy, Central Electrochemical Research Institute, Council of Scientific and Industrial Research, Defence Research and Development Organisation, Indian Institute of Science, Indian Institute of Technology Bombay, Indian Institute of Technology Delhi, Indian Institute of Technology Kharagpur, Indian Institute of Technology Madras, International Advanced Research Centre for Powder Metallurgy and New Materials, National Chemical Laboratory, Centre for Materials for Electronics Technology, IIT Madras Research Park, IIT Bombay Centre for Energy and Environment, MIT World Peace University Battery Center, IIT BHU Battery Research Facility, Amara Raja Batteries, Ather Energy, Exide Industries, Hero Electric, Log9 Materials, Ola Electric, Reliance Industries, SES, Tata Chemicals, International Battery Seminar.

Largest Acquired Capacity

As of 2026, lithium-ion battery technology has advanced significantly in terms of large-scale deployment, energy density, and cost. Grid-scale lithium-ion energy storage systems have expanded rapidly, with several installations worldwide now reaching 4–6 GWh per site, particularly in the United States, China, and Australia, supporting renewable energy integration and grid stability. In terms of performance, modern lithium-ion batteries typically achieve 200–300 Wh/kg, while advanced high-nickel chemistries and optimized cell designs can reach 300–350 Wh/kg under commercial conditions.

Specific Capacity

150 and 260Wh/kg.

Cost of Making

The cost of lithium-ion battery packs has continued to decline due to economies of scale, improvements in manufacturing, and the widespread adoption of lithium iron phosphate (LFP) chemistry, with prices in 2025–2026 estimated at approximately $90–110 per kWh (₹7,500–₹9,000 per kWh). These developments confirm lithium-ion batteries as the leading technology for electric vehicles and large-scale energy storage applications.

Space to Implement

- **Electric vehicle (EV) battery pack:** As of 2026, lithium-ion EV battery packs are designed using advanced cell-to-pack and structural battery technologies, improving space utilization. Typical EV battery packs (≈40–120 kWh) require about 0.8–1.8 cubic meters, depending on vehicle size and design, with more compact packaging achieved in newer models.

- **Residential energy storage system:** Modern lithium-ion home battery systems (≈5–20 kWh), such as modular wall-mounted units, typically require about 0.3–0.8 cubic meters, reflecting improved energy density and compact enclosure designs suitable for residential use.

- **Commercial / grid-scale energy storage system:** Large lithium-ion battery energy storage systems (BESS) are deployed in containerized formats (e.g., 20-ft or 40-ft containers), with total space requirements ranging from hundreds to thousands of cubic meters, especially for multi-MWh to GWh-scale installations used for grid stability and renewable energy integration

- **Portable electronics (Consumer devices):** Lithium-ion batteries used in smartphones, laptops, and tablets require very small volumes, typically 0.00001–0.002 cubic meters, owing to high energy density and miniaturized cell design.

- **Electric two-wheelers and three-wheelers:** Common in countries like India, these lithium-ion battery packs (≈2–5 kWh) occupy around 0.05–0.15 cubic meters, optimized for lightweight and compact vehicle frames.

- **Aerospace and drones:** Lithium-ion batteries used in drones and electric aviation prototypes require about 0.01–0.1 cubic meters, depending on flight capacity and endurance requirements.

- **Industrial equipment and forklifts:** Lithium-ion battery packs for forklifts and warehouse equipment (≈10–80 kWh) typically occupy about 0.2–1.5 cubic meters, replacing traditional lead-acid systems with more compact designs.
- **Marine and energy backup systems:** Lithium-ion batteries used in boats, ships, and telecom backup systems usually require 0.5–5 cubic meters, depending on energy needs and modular configuration.

Positives and Challenges

Positives:

- **High energy density:** Lithium-ion batteries offer high energy density, typically 200–300 Wh/kg, with advanced chemistries reaching 300–350 Wh/kg, making them ideal for electric vehicles, portable electronics, and aerospace applications where weight and compactness are critical.
- **Long life span:** Modern lithium-ion batteries provide 1,000–3,000 charge cycles, while LFP (lithium iron phosphate) batteries can achieve 3,000–7,000+ cycles, supporting long operational lifetimes of 8–15 years in EVs and energy storage systems.
- **Low self-discharge rate:** Lithium-ion batteries have a low self-discharge rate of about 1–3% per month, allowing them to retain charge for extended periods with minimal energy loss.
- **Fast charging:** Advances in charging infrastructure and battery design enable fast charging (20–80% in 15–30 minutes) in many modern applications, particularly in electric vehicles.
- **Wide operating temperature range:** Lithium-ion batteries typically operate within −20°C to 60°C, with optimal performance between 15°C and 35°C, supported by advanced thermal management systems for stability and safety.

Challenges:

- **Cost:** Lithium-ion battery costs have declined significantly to about $90–110 per kWh (₹7,500–₹9,000 per kWh) by 2026; however, they still account for a major share of electric vehicle and energy storage system costs, and prices remain sensitive to fluctuations in raw material markets.
- **Safety:** Lithium-ion batteries can pose safety risks such as thermal runaway, fire, or explosion if damaged, improperly charged, or exposed to high temperatures. Advanced battery management systems (BMS), improved cell designs, and better thermal management have reduced risks, but safety remains a critical concern, especially in large-scale applications.
- **Resource constraints:** Lithium-ion batteries depend on key materials such as lithium, nickel, and cobalt. While efforts are underway to reduce cobalt use and improve material efficiency, supply chain limitations and geopolitical factors can still lead to price volatility and resource security concerns.
- **Recycling and disposal:** Lithium-ion batteries require proper recycling due to the presence of hazardous and valuable materials. Although recycling technologies and infrastructure are improving globally, large-scale, cost-effective recycling systems are still developing, particularly for high volumes of end-of-life EV batteries.
- **Performance degradation:** Over time, lithium-ion batteries experience capacity fade and efficiency loss, especially under high temperatures, fast charging, and deep discharge cycles, which affects long-term reliability.

Present Scenario

- Lithium-ion batteries are currently the leading energy storage technology for electric vehicles, portable electronics, and large-scale grid applications worldwide.
- Global manufacturing capacity has expanded rapidly, driven by major industry players such as CATL, BYD, and Tesla.
- Battery costs have significantly decreased to around $90–110 per kWh, improving affordability and accelerating EV adoption.

- Deployment of large-scale lithium-ion battery energy storage systems (BESS) has increased, with multi-GWh installations supporting renewable energy integration and grid stability.
- Continuous advancements in battery chemistry, manufacturing processes, and recycling technologies are further strengthening the role of lithium-ion batteries in the global energy transition.

Latest Developments

- **Advanced chemistries:** Development of low-cobalt and cobalt-free batteries (e.g., LFP) to improve sustainability.
- **Solid-state batteries:** Expected to offer higher energy density (350–500 Wh/kg) and improved safety in the future.
- **Recycling technologies:** Growing focus on recovering lithium, nickel, and cobalt efficiently to create a circular battery economy.
- **Fast charging advancements:** Progress toward ultra-fast charging (under 15 minutes) with improved battery durability.
- **Second-life applications:** Used EV batteries are increasingly repurposed for stationary energy storage, extending their lifecycle.

Environmental Impact

- **Positive impact:** Lithium-ion batteries play a crucial role in reducing greenhouse gas emissions by enabling electric vehicles and supporting renewable energy storage, thereby decreasing dependence on fossil fuels.
- **Resource extraction concerns:** Mining of key materials such as lithium, cobalt, and nickel can lead to land degradation, water depletion, and ecological damage if not managed sustainably.
- **Energy-intensive production:** The manufacturing process of lithium-ion batteries requires significant energy, which can result in a high initial carbon footprint, although this is decreasing with the use of renewable energy in production.

- **Recycling and waste management:** Improper disposal of lithium-ion batteries can cause soil and water contamination due to hazardous materials; however, advancements in recycling technologies are improving material recovery and reducing environmental risks.
- **Lifecycle benefits:** Despite environmental challenges, lithium-ion batteries generally provide a net positive environmental impact over their lifecycle, especially when paired with clean energy sources and efficient recycling systems.

iii. SODIUM-ION BATTERY

Overview

A sodium-ion (Na-ion or SIB) battery is a rechargeable electrochemical energy storage device that uses sodium ions (Na^+) as the charge carriers instead of lithium ions. Structurally analogous to lithium-ion (Li-ion) batteries, Na-ion cells consist of a sodium-containing cathode (typically layered transition-metal oxides, Prussian blue analogues, or polyanionic compounds), an anode (commonly hard carbon, soft carbon, or metal alloys), and a sodium-salt-based electrolyte. Unlike lithium-ion batteries, sodium-ion technology requires no cobalt, no lithium, and no nickel in many leading chemistries, relying instead on abundant elements such as sodium, iron, manganese, and carbon. First seriously researched in the 1980s alongside lithium-ion batteries, Na-ion technology was largely set aside as lithium-ion became dominant commercially. However, a sharp resurgence in research and investment from 2015 onward — driven by lithium and cobalt supply chain concerns and falling energy density gap — has transformed Na-ion into one of the fastest-growing battery technologies of the 2020s. China's CATL (Contemporary Amperex Technology Co. Limited) announced its first-generation Na-ion battery in 2021, followed by mass production commencement in 2023. By 2024–2025, Na-ion batteries have entered commercial deployment in electric vehicles, two-wheelers, stationary energy storage, and grid applications — primarily in China — with global expansion underway.

Working Principle

Sodium-ion batteries operate on the same fundamental electrochemical principles as lithium-ion batteries, with sodium ions (Na^+) shuttling between the cathode and anode through the electrolyte during charge and discharge. During discharge, Na^+ ions are extracted from the anode (de-intercalation or de-alloying) and migrate through the electrolyte to intercalate into the cathode, while electrons flow through the external circuit to power the load. During charging, an external voltage reverses the process — Na^+ ions are extracted from the cathode and inserted back into the anode. The key distinction from Li-ion batteries is that sodium ions are larger (ionic radius 1.02 Å vs. 0.76 Å for Li^+) and heavier (atomic mass 23 vs. 7 for Li), requiring cathode and anode host materials with larger interstitial sites and higher lattice tolerance. Hard carbon — a disordered, non-graphitizable carbon material — has emerged as the dominant anode material for Na-ion batteries, as sodium cannot intercalate into the layered graphite structure used in Li-ion anodes due to thermodynamic and size constraints. At the cathode, three primary material families dominate: layered transition-metal oxides (O3/P2-type Na_xMO$_2$, where M = Fe, Mn, Ni, Cu, Ti), Prussian blue analogues (PBAs, general formula $Na_2M[Fe(CN)_6]$), and polyanionic compounds (e.g., $Na_3V_2(PO_4)_3$, NASICON-type materials). Each family offers different trade-offs in energy density, cycle life, rate capability, and manufacturing cost.

Chemical Reaction

$Na_xC_6 + MO_2 \leftrightarrow C_6 + Na_xMO_2$

Researching Universities/Institutions/Companies

America: Argonne National Laboratory (cathode and electrolyte materials), Pacific Northwest National Laboratory, Lawrence Berkeley National Laboratory, Stanford University, Massachusetts Institute of Technology, University of Texas at Austin (Goodenough group legacy — polyanionic cathodes), University of California San Diego, University of Maryland (Professor Chunsheng Wang — high-performance hard carbon anodes), Natron Energy (Prussian blue-based Na-ion for fast-charging industrial applications, Santa Clara, CA), Altris AB (North America expansion), Faradion (acquired by Reliance Industries, with US partnerships).

Europe: Faradion Ltd. (UK — pioneer in layered oxide Na-ion, now owned by Reliance Industries), HiNa Battery Technology (European operations), Tiamat Energy (France — NASICON-type cylindrical Na-ion cells), Northvolt (Sweden — Na-ion R&D for stationary storage), Fraunhofer Institute for Chemical Technology (Germany), Fraunhofer IFAM, Helmholtz Institute Ulm, Technical University of Munich, CNRS (France), CEA (France — Na-ion pouch cells), Imperial College London, University of St Andrews (Scotland — Professor John Irvine group), Uppsala University (Sweden — Altris spinout origin), KTH Royal Institute of Technology (Sweden).

Asia: CATL (China — world's largest battery manufacturer, commercialized first-generation Na-ion 2021, mass production 2023), BYD (China — Na-ion development for e-bikes and EVs), HiNa Battery Technology (China — layered oxide Na-ion, partnership with SINOPEC), SVOLT Energy (China), EVE Energy (China), Hina Battery (China), REPT BATTERO (China), Great Power (China), Tsinghua University (China — Professor Yong-Sheng Hu group), Peking University, Fudan University, Chinese Academy of Sciences (Institute of Physics — Professor Hu Yong-Sheng), Samsung SDI (South Korea — Na-ion research division), LG Energy Solution (South Korea), Panasonic (Japan), Tokyo Institute of Technology, Kyoto University, Indian Institute of Technology Madras, IIT Bombay, Indian Institute of Science, Central Electrochemical Research Institute (CECRI, India), Amara Raja Batteries (India — Na-ion development partnership announced 2024).

Largest Capacity Acquired

- CATL commenced mass production of its first-generation Na-ion battery in 2023, with an energy density of 160 Wh/kg. By 2024, CATL had integrated Na-ion cells into hybrid Na-ion/Li-ion battery packs for electric vehicles, with the Chery iCAR 03 EV featuring a CATL Na-ion battery pack being among the first commercially launched Na-ion EVs globally.
- HiNa Battery Technology deployed a 10 MWh Na-ion stationary energy storage system in China in 2023 — one of the largest grid-scale Na-ion installations at the time — in collaboration with China Three Gorges Corporation for renewable energy storage.
- Natron Energy (USA) began commercial supply of Prussian blue Na-ion batteries for data center UPS applications in 2023–2024, targeting ultra-fast charging (over 20C rate) and extreme cycle life (50,000+ cycles).
- Multiple Chinese manufacturers — including EVE Energy, REPT BATTERO, and Great Power — have announced or commenced Na-ion battery production lines with planned annual capacities ranging from 1 GWh to over 10 GWh by 2025–2026.
- India's Amara Raja Batteries announced a partnership in 2024 to develop and manufacture Na-ion batteries domestically, targeting the two-wheeler and three-wheeler EV segment.
- Global cumulative Na-ion battery production capacity (announced + operational) is estimated to exceed 50–100 GWh/year by 2026, with actual deployment still ramping from single-digit GWh levels in 2024.

Specific Capacity

Practical gravimetric energy density (cell level, 2023–2025): 100–160 Wh/kg for first-generation commercial cells (CATL first-gen: 160 Wh/kg; HiNa: 140–150 Wh/kg). Advanced second-generation Na-ion cells under development (2024–2026) target 180–200 Wh/kg. Theoretical energy density varies by cathode chemistry: layered oxides up to ~550 Wh/kg theoretical; PBAs ~340–400 Wh/kg; polyanionic ~370–500 Wh/kg. Nominal cell voltage: 3.0–3.5 V. Hard carbon anode specific capacity: 250–350 mAh/g (practical); theoretical ~300–370 mAh/g depending on morphology and processing. Volumetric energy density: approximately 250–350 Wh/L for current commercial pouch and prismatic formats — lower than equivalent Li-ion cells at the same energy but improving with cell design optimization.

Cost of Making

Na-ion batteries are projected to be the lowest-cost rechargeable battery chemistry at scale, benefiting from the elimination of lithium, cobalt, and nickel. As of 2024–2025, cell-level manufacturing costs for Na-ion batteries are estimated at approximately $60–90 per kWh (₹5,000–₹7,500 per kWh) for Chinese mass-production lines, with pack-level costs of approximately $80–110 per kWh. For comparison, LFP (lithium iron phosphate) battery packs are currently at $80–100/kWh. CATL and other manufacturers project Na-ion pack costs to fall below $50–70 per kWh (₹4,200–₹5,800 per kWh) by 2026–2028 as manufacturing scales, potentially making Na-ion the cheapest rechargeable battery technology per kWh. The primary raw material cost advantage comes from the elimination of lithium carbonate (~$13,000–20,000/tonne, 2024) and cobalt (~$30,000/tonne), replaced by inexpensive sodium carbonate (~$150/tonne) and iron- or manganese-based cathodes.

Space to Implement

- **Electric vehicles (EVs and e-mobility):** Na-ion battery packs for EVs (20–80 kWh) are comparable in volume to LFP packs for similar energy content, requiring approximately 0.15–0.5 cubic meters. The CATL Na-ion/LFP hybrid pack (as used in Chery iCAR 03) provides a compact form factor for small EVs targeting ranges of 250–400 km. Two-wheelers and e-rickshaws (1–5 kWh Na-ion packs) require approximately 0.01–0.05 cubic meters — a key target market for Na-ion's cost advantage.

- **Stationary energy storage:** Na-ion battery systems for grid or commercial applications (100 kWh–10 MWh+) are deployed in rack-mounted or containerized formats. Space requirements are approximately 20–40% larger per MWh compared to high-energy-density NMC Li-ion, but comparable to LFP systems, with typical container configurations of 1–3 MWh per 20-foot container.

- **Data center UPS (Natron Energy Prussian blue Na-ion):** Modular rack-mounted units offering 5–50 kWh in standard server rack footprints (0.1–0.5 cubic meters per rack unit), optimized for ultra-high power density and fast response rather than energy density.
- **Telecommunications backup power:** Na-ion batteries for telecom towers (10–100 kWh) occupy compact outdoor enclosures of approximately 0.05–0.5 cubic meters, with the operational temperature range advantage (−40°C to 60°C) reducing the need for thermal management systems in extreme climates.
- **Consumer electronics and portable devices (research/future):** Na-ion cells for smartphones and laptops (10–100 Wh) would require minimal additional volume compared to current Li-ion, but commercialization in this segment awaits further energy density improvement.

Positives and Challenges

Positives:

- **No critical mineral dependencies:** Na-ion batteries require no lithium, cobalt, or nickel in leading chemistries (particularly iron/manganese-based layered oxides and PBAs), eliminating supply chain risks, ethical mining concerns, and geopolitical dependencies that constrain Li-ion battery scaling.
- **Abundant and ultra-low-cost raw materials:** Sodium is the sixth most abundant element in the Earth's crust, primarily sourced from virtually inexhaustible seawater or trona mineral deposits. Sodium carbonate costs approximately $150/tonne, vs. $13,000–20,000/tonne for lithium carbonate. Iron and manganese cathode materials are similarly abundant and cheap.
- **Wide operating temperature range:** Na-ion batteries maintain excellent performance at low temperatures (down to −40°C) with capacity retention significantly better than Li-ion batteries — a critical advantage for cold-climate applications, Arctic deployment, and electric vehicles in northern markets. This is due to the faster desolvation kinetics of Na^+ ions at low temperatures.
- **Compatibility with existing Li-ion manufacturing infrastructure:** Na-ion cells can be manufactured using existing Li-ion production equipment (electrode

coating, cell assembly, formation cycling), lowering the capital investment required to transition or add Na-ion production lines — a major factor enabling CATL and other manufacturers to scale rapidly.

- **No thermal runaway from zero-volt storage:** Na-ion batteries can be safely discharged to 0 V without permanent damage — unlike Li-ion cells — enabling safer shipping (no need for 30% state of charge shipping restriction), simplified logistics, and longer storage without active battery management.
- **High rate capability:** Na-ion batteries — particularly Prussian blue analogue and NASICON-type chemistries — can support very high charge and discharge rates (10C–20C+), enabling ultra-fast charging applications in industrial, data center, and grid frequency regulation use cases.
- **Sustainability potential:** The elimination of lithium mining (brine extraction with high water use in South America's Lithium Triangle) and cobalt mining (DRC) gives Na-ion batteries a substantially lower environmental and ethical footprint for raw material extraction.

Challenges:

- **Lower energy density than Li-ion:** Current commercial Na-ion cells achieve 100–160 Wh/kg, compared to 200–300 Wh/kg for Li-ion NMC and 150–200 Wh/kg for LFP. This limits Na-ion's direct competitiveness in applications where energy density is paramount, such as long-range EVs and portable electronics, without significant pack-design optimization.
- **Hard carbon anode limitations:** Hard carbon — the dominant Na-ion anode — suffers from lower initial Coulombic efficiency (ICE, typically 75–90%) than graphite anodes in Li-ion (93–95%), requiring pre-sodiation strategies or excess cathode material to compensate for first-cycle sodium loss. Hard carbon's specific capacity (250–350 mAh/g practical) is also lower than silicon-graphite composites in advanced Li-ion.
- **Electrolyte and SEI challenges:** Sodium-ion electrolytes form a less stable solid electrolyte interphase (SEI) on hard carbon anodes compared to Li-ion SEI on graphite. Developing stable, high-conductivity sodium-salt electrolytes —

particularly for low-temperature and high-voltage operation — remains an active research area.

- **Less mature global supply chain:** While raw materials are abundant, the supply chain for Na-ion specific components — particularly high-quality hard carbon anode material and optimized cathode precursors — is still developing outside China, creating near-term geographic concentration risks.
- **Voltage incompatibility with Li-ion BMS:** The slightly lower operating voltage of Na-ion cells (3.0–3.5 V) compared to Li-ion (3.6–3.7 V) requires minor recalibration of battery management systems designed for Li-ion, though this is a manageable engineering challenge rather than a fundamental barrier.
- **Limited long-term performance data:** As a newly commercialized technology (2023–), real-world long-term cycle life and calendar life data at scale are still being accumulated. Projected cycle life of 3,000–5,000+ cycles has been demonstrated in laboratory conditions but requires validation across diverse commercial deployment environments.

Present Scenario

- CATL began mass production of Na-ion batteries in 2023, integrating them into hybrid Na-ion/LFP battery packs for EVs. The Chery iCAR 03, launched in 2024, became one of the first mass-market EVs globally to use Na-ion battery technology in a commercial production vehicle.
- China dominates Na-ion commercialization, with over 20 manufacturers active in Na-ion cell production or development as of 2025, and planned aggregate production capacity exceeding tens of GWh per year across the industry.
- Natron Energy (USA) became the first company to commence commercial Na-ion battery sales in North America in 2023, targeting the data center UPS and industrial fast-charging markets with Prussian blue-based cells offering over 50,000 cycle life. • HiNa Battery Technology (China) deployed a 10 MWh grid-scale Na-ion energy storage project with China Three Gorges Corporation in 2023 — a landmark demonstration of Na-ion viability for utility-scale stationary storage.

- India's government and private sector have identified Na-ion as a strategic priority for domestic battery manufacturing, with CECRI, IIT institutions, and companies such as Amara Raja exploring Na-ion development to reduce dependence on imported lithium.

- Multiple startups and established players in Europe — including Altris (Sweden, PBA-based), Tiamat (France, NASICON cylindrical cells), and Faradion (UK, now Reliance Industries subsidiary) — have announced or commenced pilot production, targeting 2025–2027 for European commercial scale-up.

- CATL's second-generation Na-ion battery (announced 2024) targets an energy density of 175–200 Wh/kg with improved cycle life, intended for broader EV application including larger battery packs for passenger cars in the 300–500 km range class.

Latest Developments

- **Advanced cathode materials (2023–2026 breakthroughs):** Mn-rich layered oxides (P2/O3-type) achieving over 160 Wh/kg at the cell level while eliminating nickel; Cu-substituted layered oxides improving air stability and reducing moisture sensitivity during manufacturing; fluoride-doped PBAs reaching cycle lives exceeding 5,000 cycles at 80% capacity retention; and NASICON-type polyanionic cathodes ($Na_3V_2(PO_4)_3$, NVPF) demonstrating ultra-stable long-term cycling with excellent rate performance.

- **Hard carbon anode engineering:** Research at institutions including University of Maryland, Chinese Academy of Sciences, and Tsinghua has demonstrated hard carbon anodes with ICE above 90% through pre-sodiation, surface engineering, and closed-pore optimization — addressing the primary anode limitation. Soft carbon and carbon/oxide composite anodes are also under active development.

- **Solid-state Na-ion batteries:** Early-stage research into solid-state Na-ion electrolytes — including beta-alumina ceramics, sulfide-based (Na_3PS_4, NASICON glass-ceramics), and polymer electrolytes — aims to combine the safety and energy density advantages of solid-state design with Na-ion's material cost advantages. Groups at MIT, TU Munich, and Chinese Academy of Sciences are leading this area.

- **High-voltage electrolytes:** Development of ether- and carbonate-based electrolytes with sodium salts ($NaPF_6$, NaFSI, NaTFSI) enabling stable operation up to 4.5 V, unlocking higher-voltage cathode chemistries and improving energy density toward 200 Wh/kg at the cell level.

- **Cell-to-pack (CTP) integration:** CATL and other manufacturers are applying CTP technology to Na-ion packs — eliminating module-level packaging and integrating cells directly into the pack structure — to partially compensate for the lower cell-level energy density and achieve competitive pack-level energy density for EV applications.

- **Manganese-based cathode dominance:** Post-2023 research consensus is converging on Mn-rich, Ni-free layered oxide cathodes as the most promising pathway to high-energy-density, low-cost, cobalt-free Na-ion cells, with CATL's second-generation cell, Faradion, and multiple Chinese producers pursuing this direction.

- **AI-accelerated materials discovery:** Machine learning models trained on Na-ion cathode and electrolyte datasets are being used to screen thousands of compositions for ionic conductivity, structural stability, and electrochemical window — significantly accelerating the identification of next-generation Na-ion materials.

Environmental Impact

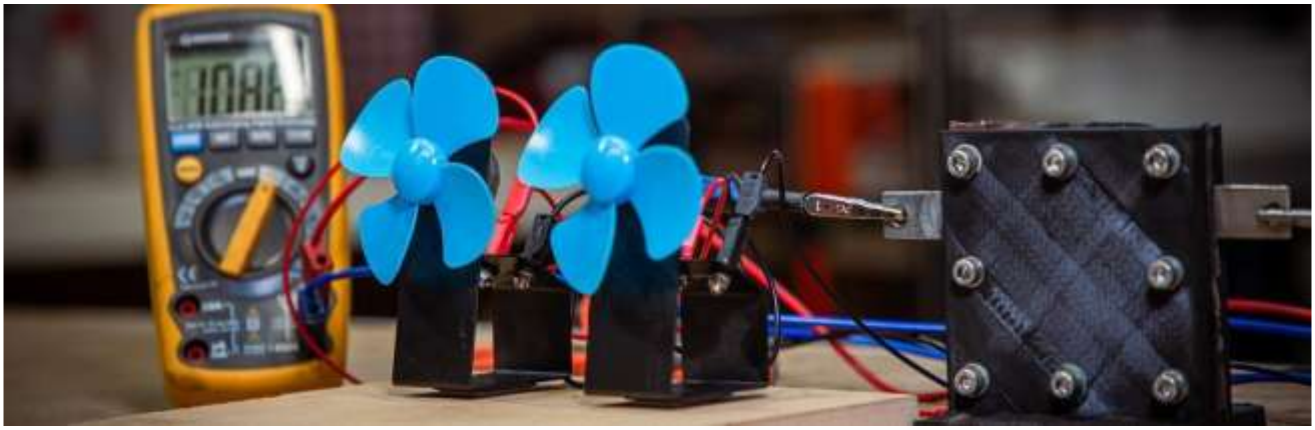
- **Elimination of critical mineral mining impact:** By requiring no cobalt (eliminating associated artisanal mining in the DRC), no lithium (reducing brine extraction pressure in South America's Atacama Desert), and no nickel, Na-ion batteries offer a dramatically reduced raw material environmental footprint compared to conventional NMC Li-ion batteries — one of the most significant sustainability advantages of the technology.

- **Sodium sourcing:** Sodium for Na-ion batteries is sourced primarily from sodium carbonate (soda ash) derived from trona mineral deposits (abundant in Wyoming, USA; Kenya; China) or synthesized via the Solvay process. The environmental impact of sodium carbonate production is substantially lower than lithium carbonate extraction from brine or spodumene ore.

- **Carbon anode sourcing:** Hard carbon for Na-ion anodes is currently derived from synthetic precursors (resins, sucrose) or biomass (coconut shells, cellulose), with biomass-derived hard carbon offering a potentially sustainable and carbon-neutral feedstock pathway — contrasting with synthetic graphite in Li-ion anodes (produced at high temperatures from petroleum coke).
- **Manufacturing compatibility:** The ability to use existing Li-ion manufacturing equipment for Na-ion production reduces the additional capital-embedded carbon in new battery factory construction, as manufacturing lines require adaptation rather than replacement.
- **End-of-life and recyclability:** Na-ion battery recycling infrastructure is in early development. Unlike Li-ion, the lower intrinsic material value of Na-ion cells (no cobalt or lithium to recover) reduces the economic incentive for recycling, potentially creating end-of-life management challenges. However, the lower toxicity of sodium, iron, and manganese compared to cobalt and nickel reduces the environmental risk of improper disposal. Recycling process development is an active area of research.
- **Lifecycle GHG advantage:** When deployed in renewable energy integration and EV applications, Na-ion batteries' lower embodied carbon in raw material extraction — combined with the ability to manufacture with existing infrastructure — gives them a favorable lifecycle greenhouse gas profile compared to NMC Li-ion, particularly when powered by renewable energy during manufacturing.

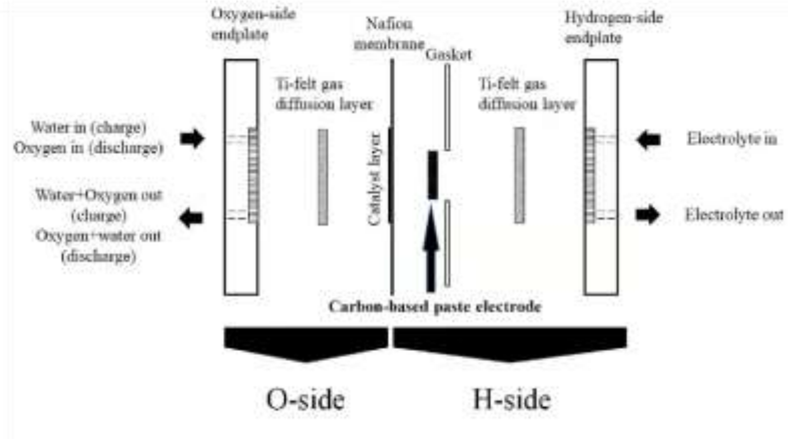
iv. PROTON BATTERY

Overview



Proton batteries are a class of rechargeable batteries in which protons (H+) serve as charge carriers. Protons are the smallest and lightest ions, which makes them ideal for high-performance batteries. Proton batteries are also non-toxic and environmentally friendly.

Working Principle



Inner schematic of the proton battery

A proton battery consists of a proton-conducting electrolyte, a negative electrode, and a positive electrode. During discharge, protons are transferred from the negative electrode to the positive electrode, through the electrolyte. The electrolyte is typically a liquid or solid polymer that allows protons to move freely.The most common negative electrode materials for proton batteries are carbon-based materials, such as activated carbon and graphene. These materials have high conductivity and can accommodate a high density of protons.

The most common positive electrode materials for proton batteries are transition metal oxides and hydroxides. These materials have high conductivity and can react with protons to store energy.

The proton battery functions like a reversible fuel cell. When charging, it takes in water, separates hydrogen ions, and releases oxygen. Unlike other systems, it stores these hydrogen ions directly in a special carbon electrode soaked in acid. To discharge, oxygen is added, producing water and releasing energy.

Chemical Reaction

$H_2 \leftrightarrow 2H^+ + 2e^-$

Researching Universities/Institutions/Companies

India: Indian Institute of Technology Madras, Indian Institute of Science, Indian Institute of Technology Bombay, Indian Institute of Technology Delhi, National Institute of Technology Tiruchirappalli, National Institute of Technology Karnataka, Central Electrochemical Research Institute, Indira Gandhi Centre for Atomic Research, Bhabha Atomic Research Centre.

United States: California Institute of Technology, University of California Berkeley, University of California Los Angeles, University of Michigan, Stanford University, University of Texas at Austin, Massachusetts Institute of Technology, Argonne National Laboratory, National Renewable Energy Laboratory, and Lawrence Berkeley National Laboratory.

Europe: University of Cambridge, University of Oxford, University of Münster, Helmholtz Zentrum Berlin für Materialien und Energie, Fraunhofer Institute for Solar Energy Systems, CNRS, and CEA, Faraday Institution and CELEST.

Asia: University of Tokyo, Kyoto University, City University of Hong Kong, Hong Kong Polytechnic University, University of Science and Technology of China, and Peking University, CATL, BYD, Samsung SDI, LG Chem, and Panasonic.

Other research groups: University of New South Wales and University of São Paulo.

Largest Acquired Capacity

As of 2026, proton battery technology remains in the early research and prototype stage, and there are currently no large-scale commercial proton battery energy storage systems (BESS) with capacities comparable to lithium-ion or other advanced battery technologies. Earlier claims associating large-scale systems (such as 100 MW/100 MWh) with proton batteries are inaccurate, as such deployments are typically based on alternative chemistries like metal-air systems developed by companies such as Form Energy. In contrast, proton batteries are still being developed primarily at laboratory and pilot scales, with ongoing research focused on improving energy density, efficiency, and scalability. Therefore, as of 2026, the largest "acquired capacity" for proton batteries cannot be defined in commercial terms, as the technology has not yet reached grid-scale deployment and remains under active investigation in academic and experimental research environments.

Specific Capacity

It has a specific energy density of 245 Wh/kg.

Cost of Making

Recent research suggests that proton battery technology has the potential to achieve very low energy storage costs in the future. Studies associated with the National Renewable Energy Laboratory indicate that advanced next-generation battery systems, including proton-based concepts, could theoretically reach costs of around $10 per kWh under ideal large-scale conditions, particularly for long-duration energy storage. Similarly, research conducted at RMIT University has demonstrated early-stage proton battery prototypes with the potential for significantly lower costs compared to conventional batteries, based on inexpensive and abundant materials.

However, as of now, these cost estimates remain theoretical and based on laboratory-scale research, as proton battery technology has not yet reached commercial deployment or validated industrial-scale cost benchmarks. In comparison, commercially available lithium-ion battery systems currently cost approximately $90–110 per kWh (₹7,500–₹9,000 per kWh), reflecting mature production technologies and global supply chains.

Space to Implement

It is estimated that proton batteries would require approximately 20-30% more space than lithium-ion batteries for an equivalent energy storage capacity.

Positives and Challenges

Positives:

- **Moderate to high energy density (potential):** Proton batteries have the potential to achieve competitive energy density, especially for stationary energy storage, though current prototypes are still below advanced lithium-ion levels.
- **Non-toxic and environmentally friendly:** Proton batteries use abundant and safe materials such as carbon and water, avoiding heavy metals like cobalt and nickel, making them more sustainable and eco-friendly.
- **Fast charging and discharging:** Proton batteries can enable rapid charge–discharge cycles due to fast proton transport mechanisms, making them suitable for applications requiring quick energy delivery.
- **Long cycle life (potential):** Early research indicates that proton batteries could achieve long cycle life with minimal degradation, although this is still being validated in laboratory conditions.

Challenges:

- **High development cost:** Proton batteries are currently in the research stage, and costs remain high due to limited manufacturing scale, experimental materials, and lack of industrial infrastructure, although future costs are expected to decrease with advancement.
- **Electrolyte and materials challenges:** Developing high-performance proton-conducting electrolytes with good stability, efficiency, and durability is a major technical hurdle, limiting overall battery performance.
- **Not yet commercially available:** As of 2026, proton batteries are still in the laboratory and prototype phase, with no large-scale commercial deployment or market-ready products.

- **Low technological maturity:** Compared to lithium-ion batteries, proton batteries have limited real-world testing and validation, making their long-term reliability uncertain.
- **Scalability issues:** Transitioning from small-scale prototypes to industrial-scale production remains a significant challenge due to design and engineering limitations.

Present Scenario

- Proton batteries are currently in the early research and prototype stage, with no large-scale commercial deployment as of 2026.
- Most development is being carried out in academic institutions such as RMIT University, where initial working prototypes have been demonstrated.
- The technology is gaining attention as a potential low-cost and sustainable alternative to conventional batteries, especially for stationary energy storage.
- Compared to lithium-ion batteries, proton batteries still have lower technological maturity and limited real-world testing.

Latest Developments

- **Energy density improvement:** Ongoing research aims to increase energy density to levels comparable with or exceeding lithium-ion batteries.
- **Advanced materials development:** Efforts are focused on developing high-performance proton-conducting electrolytes and improving electrode materials.
- **Scalability and commercialization:** Future work will focus on scaling from laboratory prototypes to industrial-scale production and real-world deployment.
- **Cost reduction:** Proton batteries have the potential to become very low-cost energy storage solutions due to the use of inexpensive and abundant materials.
- **Integration with renewable energy:** Proton batteries are expected to play a role in long-duration energy storage and grid stabilization, supporting renewable energy systems.

Proton batteries, though still in the early stages of development, have the potential to significantly impact a wide range of sectors, including stationary energy storage, electric mobility, consumer electronics, aerospace applications, medical devices, and grid support systems. These emerging batteries offer the prospect of safe and sustainable energy storage using abundant materials such as carbon and water, along with fast charge discharge capabilities due to rapid proton transport mechanisms. While their current energy density and scalability are still under development, ongoing research, particularly at institutions like RMIT University, suggests that proton batteries could provide a low cost, environmentally friendly alternative to conventional battery technologies in the future. However, as of 2026, their widespread adoption depends on overcoming challenges related to performance optimization, durability, and commercial scalability.

Environmental Impact

- **Positive impact:** Proton batteries are considered environmentally friendly as they use abundant, non-toxic materials such as carbon and water, reducing reliance on critical metals like cobalt and nickel.
- **Reduced mining impact:** Since they avoid heavy metals, proton batteries could significantly reduce the environmental damage associated with mining and resource extraction.
- **Low toxicity and safer disposal:** The materials used are generally safer, which could simplify end-of-life disposal and recycling compared to conventional batteries.
- **Lower environmental risk:** Reduced risk of fire, leakage, or hazardous waste makes proton batteries a safer option for large-scale applications.

v. SOLID-STATE BATTERY

Overview

A solid-state battery replaces the flammable liquid electrolyte with a solid ionic conductor, enabling lithium metal anodes and significantly higher safety. These batteries target a practical energy density of 400–600 Wh/kg roughly twice that of conventional Li-ion — with theoretical potential exceeding 1,000 Wh/kg. The solid electrolyte comes in three main types: oxides (LLZO garnet), sulfides (Li_6PS_5Cl argyrodite), and halides (Li_3InCl_6), each carrying different conductivity and manufacturing tradeoffs. The market, valued at around USD 650 million in 2024, is projected to reach USD 8 billion by 2030 at a CAGR of 40–45%. While already commercial in thin film applications for medical and IoT devices, automotive pilot production is underway in 2025–2026, with mass EV deployment targeted between 2027 and 2030.

Working Principle

Li^+ ions move through the electrolyte from anode to cathode during discharge and reverse on charge — just like conventional Li-ion batteries. The key difference is that ions travel through a solid lattice via vacancy hopping and grain boundary diffusion instead of a liquid solvent. This enables the use of a lithium metal anode, since solid electrolytes physically suppress dendrite growth, unlocking an energy density of 3,860 mAh/g compared to graphite's 370 mAh/g. The critical challenge, however, remains the solid-solid interface resistance between the electrolyte and electrodes, which must stay consistently low through repeated volume-change cycles.

Chemical Reaction

$LiC_6 + CoO_2 \rightarrow C_6 + LiCoO_2$

Researching Universities/Institutions/Companies

USA: QuantumScape (VW partnership), Solid Power (BMW/Ford), Factorial Energy (Stellantis/Mercedes), SES AI (GM/Honda), Argonne & Oak Ridge National Labs, MIT, Stanford, UC San Diego.

Europe: ProLogium (Mercedes; gigafactory in France), Toyota Motor Europe, BMW, Volkswagen, Fraunhofer Institute, University of Oxford, Imperial College London.

Asia: Toyota (largest SSB patent holder; 1,200 km range EV target 2027–28), Samsung SDI, CATL, Panasonic, TDK, Murata, LG Energy Solution, Tsinghua University, Peking University.

India: IIT Madras, IIT Bombay, IISc Bangalore, CECRI — DST-funded solid electrolyte research.

Specific Capacity

Practical cell energy density: 400–600 Wh/kg (commercial targets); 500 Wh/kg demonstrated by CATL condensed battery (2023).

Cost of Making

- **Current (2024–2026):** USD 800–2,000/kWh (≈ INR 67,000–1,67,000/kWh) — primarily due to Li metal anode, solid electrolyte processing, and low volume.
- **2030 target:** USD 80–120/kWh at GWh scale — approaching current Li-ion costs.
- **Sulfide electrolyte material:** USD 50–200/kg now; projected USD 10–30/kg at scale.
- **Main cost drivers:** Dry-room infrastructure (−40°C dew point for sulfide), Li metal foil, ceramic sintering (oxide type), low yield.

Positives and Challenges

Positives:

- **No thermal runaway:** Solid electrolyte is non-flammable — eliminates Li-ion fire risk entirely.

- **2× energy density:** Enables EVs with double the range at equivalent battery mass.
- **Ultra-fast charging:** <15 min to 80% — vs. 30–60 min for Li-ion.
- **Long cycle life:** 5,000–10,000+ cycles vs. Li-ion's 1,000–3,000.
- **Wide temperature range:** −40°C to 100°C — superior for aerospace and Arctic applications.
- **No leakage:** Critical for medical implants, satellites, and hermetically sealed devices.

Challenges:

- **Interface resistance:** Solid-solid contact between electrolyte and electrodes degrades with cycling — #1 engineering hurdle.
- **Dendrite risk:** Li dendrites still form through grain boundaries at high current; requires ultra-dense electrolyte membranes.
- **Sulfide moisture sensitivity:** H_2S gas hazard — needs expensive dry-room manufacturing.
- **Ceramic brittleness:** LLZO cracks during roll-to-roll manufacturing; hard to make thin (<30 μm).
- **High cost:** Currently 8–20× more expensive than Li-ion per kWh.
- **Manufacturing scale:** No GWh-scale SSB production achieved yet with acceptable yield.

Present Scenario (2025–2026)

- **Commercial today:** TDK & Murata thin-film SSBs in hearing aids, medical implants, IoT sensors.
- **Automotive pilot:** Solid Power, QuantumScape, Factorial Energy, ProLogium delivering cells to OEMs for integration testing.
- **Biggest milestone:** CATL's 500 Wh/kg condensed battery flew in China's Shenlong-2 electric aircraft (2024).

- **Toyota target:** Solid-state EV with 1,200 km range and 10-min fast charge by 2027–2028.
- **Market:** USD 650M (2024) → USD 8B (2030); growing at ~40–45% CAGR.

Future Developments

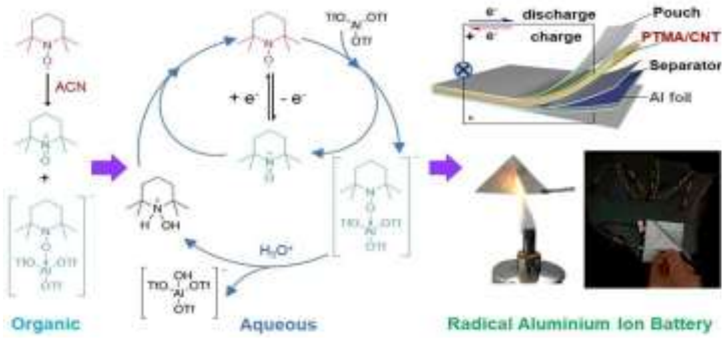
- **Halide electrolytes:** Room-temperature processing, 1–3 mS/cm conductivity, no H_2S risk — most manufacturing-friendly emerging class.
- **Anode-free cells:** No dedicated Li anode — Li deposits from cathode on first charge; maximizes energy density (QuantumScape approach).
- **Bipolar stacking (Toyota):** Cells share current collectors — less inactive material, higher pack energy density.
- **AI-driven discovery:** ML models accelerating new solid electrolyte composition screening (Google DeepMind GNoME, Materials Project).
- **Gigafactories:** Solid Power (Colorado), ProLogium (France) targeting GWh production by 2026–2028; cost target USD 80–120/kWh by 2030.

vi. ALUMINIUM RADICAL BATTERY

Overview

Aluminium radical batteries are a type of metal-ion battery that uses aluminium as the anode and a stable radical as the cathode. They are considered to be a more sustainable and environmentally friendly alternative to lithium-ion batteries, as aluminium is a more abundant element and the electrolytes used in aluminium radical batteries are water-based and non-toxic. However, aluminium radical batteries have been challenging to develop due to the slow movement of Al^{3+} ions in the electrolyte.

Working Principle



During discharge, Al^{3+} ions are released from the anode and travel through the electrolyte to the cathode, where they are reduced to Al. At the cathode, the stable radical is oxidised to a dictation. During charging, the reverse reaction occurs.

Chemical Reaction

$Al + 2H_2O + TEMPO \rightarrow Al(OH)_3 + TEMPOH + H_2O$

In this reaction, aluminum metal is oxidized to aluminum hydroxide, and the stable radical TEMPO is reduced to TEMPOH. The electrons released by the oxidation of aluminum are used to reduce TEMPO.

Researching Universities/Institutions/Companies

India: Research on aluminium-based and organic radical batteries is being conducted at Indian Institute of Technology Bombay, Indian Institute of Technology Madras, Indian Institute of Science, Jawaharlal Nehru Centre for Advanced Scientific Research, and Indian Institute of Petroleum. Additional contributions come from the Council of Scientific and Industrial Research labs and the International Advanced Research Centre for Powder Metallurgy and New Materials, focusing on next-generation battery chemistries and materials.

North America: Key research institutions include University of Illinois at Urbana Champaign, Stanford University, University of California Berkeley, University of Maryland College Park, and Northwestern University. Additional leading research is conducted at Massachusetts Institute of Technology and Argonne National Laboratory. Companies such as Ambri are exploring alternative metal-based battery systems related to aluminium concepts.

South America: Research efforts are led by University of São Paulo, with growing interest in low-cost and sustainable battery materials.

Europe: Leading institutions include University of Oxford, University of Cambridge, Imperial College London, Karlsruhe Institute of Technology, Technical University of Munich, National Centre for Scientific Research, and Grenoble Institute of Technology. Additional research networks such as Helmholtz Association and Fraunhofer Society are actively working on advanced battery chemistries.

Asia: Major contributions come from Tsinghua University, Peking University, Chinese Academy of Sciences, Kyoto University, University of Tokyo, Seoul National University, and Pohang University of Science and Technology. Emerging industrial research is also being explored by companies such as Samsung SDI and Panasonic.

Australia: Research is conducted at University of Melbourne, Monash University, University of Queensland, and RMIT University, focusing on sustainable and next-generation battery materials including aluminium-based systems.

Largest Capacity Acquired

As of 2026, aluminium-radical battery technology remains in the research and experimental stage, and there are currently no large-scale commercial deployments or grid-level battery energy storage systems (BESS) based on this chemistry. Earlier references to large-capacity systems (such as 100 MW / 1000 MWh) are not applicable to aluminium-radical batteries, as such projects are associated with other emerging technologies like iron-air systems developed by Form Energy. Aluminium-radical batteries are still being investigated primarily in laboratory settings, with research focusing on improving energy density, cycle life, and electrolyte stability. Therefore, as of 2026, the largest capacity for aluminium-radical batteries cannot be defined in commercial terms, since the technology has not yet progressed beyond prototype or small-scale experimental validation.

Specific Capacity

Aluminium radical batteries can theoretically store up to 2000 Wh/kg.

Positives and Challenges

Positive:

- **High theoretical energy density:** Aluminium-based batteries have a high theoretical energy density due to the multi-electron transfer capability of aluminium; however, current aluminium-radical prototypes are still working toward achieving practical energy densities comparable to lithium-ion systems.
- **Low cost potential:** Aluminium is abundant, widely available, and inexpensive, making these batteries potentially much cheaper than lithium-ion batteries once scalable manufacturing is achieved.
- **Improved safety:** Aluminium-radical batteries are generally considered safer and less flammable, as many designs use non-volatile or aqueous electrolytes, reducing the risk of fire and thermal runaway.
- **Environmental friendliness:** These batteries can use non-toxic and sustainable materials, lowering environmental impact compared to batteries that rely on critical metals like cobalt and nickel.
- **Long lifespan (potential):** Early research suggests that aluminium-based batteries could achieve long cycle life and durability, though long-term performance is still under investigation and not yet fully validated at scale.

Challenges:

- **Early-stage technology:** Aluminium-radical batteries are still in the research and prototype phase, with no commercial-scale deployment as of 2026, and significant technical challenges remain before commercialization.

- **Lower practical power density:** Compared to lithium-ion batteries, current aluminium-based systems often exhibit lower power density, limiting their suitability for high-power applications such as high-performance electric vehicles.

- **Electrode degradation and stability issues:** Aluminium electrodes can suffer from corrosion, dendrite formation, and structural degradation, leading to reduced capacity and cycle life over time; improving electrode stability remains a key research focus.

- **Electrolyte limitations:** Developing efficient and stable electrolytes that enable reversible aluminium-ion transport is challenging and affects overall battery performance.

- **Scalability challenges:** Transitioning from laboratory prototypes to large-scale manufacturing is difficult due to material compatibility, system design, and engineering constraints.

- **Limited real-world validation:** Long-term durability, efficiency, and safety performance are still not fully validated under practical operating conditions.

Present Scenario

- Aluminium-radical batteries are currently in the early research and laboratory prototype stage, with no commercial deployment as of 2026.

- Research is being actively conducted in institutions such as the Chinese Academy of Sciences, Massachusetts Institute of Technology, and Stanford University, focusing on improving electrochemical performance and material stability.

- The technology is gaining attention as a low-cost and sustainable alternative to lithium-ion batteries due to the abundance of aluminium.

- However, compared to lithium-ion and cobalt-free batteries, aluminium-radical batteries have low technological maturity and limited real-world testing.

Latest Developments

- **Energy density improvement:** Ongoing research aims to increase practical energy density to make aluminium-radical batteries competitive with lithium-ion systems.

- **Advanced electrode materials:** Development of stable and corrosion-resistant electrodes to improve cycle life and performance.
- **Electrolyte innovation:** Research is focused on designing efficient and stable electrolytes that enable better aluminium-ion transport and reversibility.
- **Scalability and commercialization:** Efforts are underway to scale the technology from laboratory prototypes to industrial production and real-world applications.
- **Cost reduction potential:** Due to the low cost of aluminium, these batteries could become one of the most economical energy storage solutions in the future.
- **Integration with renewable energy:** Aluminium-based batteries may play a role in large-scale, long-duration energy storage, supporting renewable energy systems.

Overall, aluminium-radical batteries have strong potential as a future energy storage technology due to their use of abundant materials, low cost potential, improved safety, and environmental advantages compared to conventional lithium-ion batteries. However, claims of significantly higher practical energy density are still under investigation, as current prototypes have not yet reached the performance levels of mature lithium-ion systems. As of 2026, aluminium-radical batteries remain in the early research and development stage, with key challenges including electrolyte optimization, electrode stability, and scalability needing to be addressed before commercialization.

Research in this field is progressing rapidly, with ongoing efforts at institutions such as the Chinese Academy of Sciences and Massachusetts Institute of Technology focusing on improving performance and durability. As the technology matures, it is expected that aluminium-radical batteries could see significant advancements in efficiency, lifespan, and cost-effectiveness, making them a promising candidate for sustainable and large-scale energy storage applications in the future.

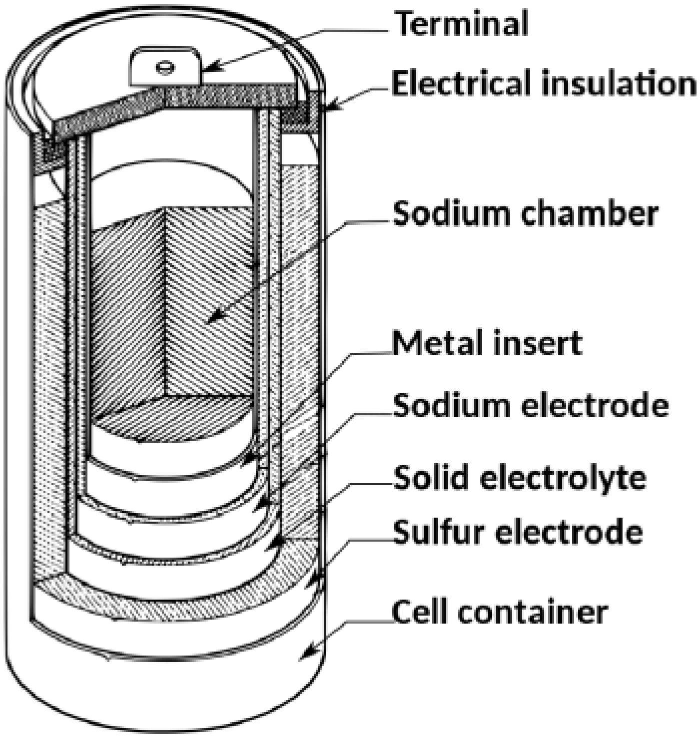
Environmental Impact

- **Positive impact:** Aluminium is abundant, recyclable, and widely available, reducing dependence on scarce and environmentally problematic materials like cobalt and nickel.

- **Lower toxicity:** Aluminium-based systems can use non-toxic and safer materials, making them environmentally friendly and easier to handle.
- **Reduced mining impact:** Aluminium is already widely mined and recycled, which can reduce the additional environmental burden compared to new mining operations.
- **Recyclability:** Aluminium has a well-established recycling infrastructure, improving sustainability and supporting a circular economy.
- **Manufacturing impact:** While aluminium production is energy-intensive, increasing use of renewable energy can help reduce its overall carbon footprint.

vii. SODIUM-SULPHUR BATTERY

Overview



A sodium-sulfur (NaS) battery is a type of molten-salt rechargeable battery that uses liquid (molten) sodium as the negative electrode, liquid (molten) sulfur as the positive electrode, and a solid beta-alumina ceramic ($\beta''\text{-}Al_2O_3$) membrane as both the electrolyte and separator. NaS batteries operate at high temperatures of 300–350°C, at which both sodium and sulfur are in a molten liquid state, enabling efficient ion transport through the ceramic electrolyte. First developed by Ford Motor Company in the 1960s and later commercialized by NGK Insulators Ltd. (Japan) in partnership with Tokyo Electric Power Company (TEPCO), NaS batteries are one of the most mature large-scale electrochemical energy storage technologies available. They are widely used for grid-scale energy storage, load leveling, renewable energy integration, and peak shaving due to their high energy density, long cycle life, and use of abundant raw materials.

Working Principle

Sodium-sulfur batteries operate through electrochemical reactions between molten sodium and molten sulfur at a high operating temperature of 300–350°C. During discharge, sodium at the negative electrode is oxidized, releasing electrons into the external circuit and sodium ions (Na^+) that migrate through the solid beta-alumina ceramic electrolyte toward the positive electrode. At the positive electrode, sulfur is reduced by accepting electrons and reacts with the incoming sodium ions to form sodium polysulfides (Na_2Sx, where $x = 3$ to 5). During charging, an external voltage reverses the process —

sodium polysulfides at the positive electrode decompose, releasing sodium ions that migrate back through the electrolyte and are deposited as molten sodium at the negative electrode, while sulfur is regenerated at the positive electrode. The solid beta-alumina ceramic electrolyte is selectively permeable to sodium ions, allowing efficient ion transfer while preventing direct chemical contact between the two electrodes. The battery must be maintained at its operating temperature using internal heating elements, either from waste heat generated during cycling or from external heaters, which is a key operational consideration for NaS systems.

Chemical Reaction

$2Na + xS \rightarrow Na_2S_x$ (sodium polysulfides, $x = 3–5$)

Researching Universities/Institutions/Companies

America: Argonne National Laboratory, Pacific Northwest National Laboratory, Sandia National Laboratories, National Renewable Energy Laboratory, Massachusetts Institute of Technology, University of Texas at Austin, University of Michigan, Ceramatec Inc. (now part of CoorsTek), Ambri Inc., GE Energy Storage, Primus Power, University of California Berkeley, University of Wisconsin-Madison.

Europe: Fraunhofer Institute for Ceramic Technologies and Systems (IKTS), German Aerospace Center (DLR), Helmholtz-Zentrum Berlin für Materialien und Energie, Technical University of Munich, RWTH Aachen University, University of Southampton, Imperial College London, CEA (France), FIAMM (Italy), University of Münster.

Asia: NGK Insulators Ltd. (Japan) — the world's leading commercial NaS battery manufacturer, Tokyo Electric Power Company (TEPCO, Japan), National Institute of Advanced Industrial Science and Technology (AIST, Japan), Kyoto University, Tokyo Institute of Technology, Osaka University, Samsung SDI (South Korea), POSCO (South Korea), Tsinghua University (China), Shanghai Institute of Ceramics — Chinese Academy of Sciences, Central Electrochemical Research Institute (India), Indian Institute of Technology Madras, Indian Institute of Technology Bombay, Indian Institute of Science, Bhabha Atomic Research Centre (India).

Largest Acquired Capacity

As of 2026, sodium-sulfur (NaS) battery technology is one of the most established and widely deployed large-scale electrochemical energy storage technologies globally, with NGK Insulators Ltd. having installed over 600 MW of NaS battery systems worldwide since the early 2000s. The largest individual NaS installations include the Abu Dhabi grid-scale energy storage facility in the UAE, which comprises a 648 MWh NaS battery system — one of the largest electrochemical energy storage projects in the world at the time of its deployment. Additional large installations exist in Japan, the United States, and the Middle East, with capacities ranging from 1 MWh to over 50 MWh per site. In Japan alone, over 200 MW of NaS battery capacity has been deployed for grid stabilization, load leveling, and renewable energy integration. The global cumulative installed capacity of NaS batteries has exceeded 5 GWh, with ongoing projects expanding deployment in regions with high renewable energy targets. More recently, newer NaS chemistries operating at intermediate temperatures (150–250°C) are being developed by companies such as NGK and research institutions to improve energy density, safety, and operational flexibility.

Specific Capacity

150–240 Wh/kg (gravimetric energy density); volumetric energy density approximately 150–300 Wh/L. Advanced NaS battery designs and next-generation intermediate-temperature variants aim to achieve 200–300 Wh/kg. The theoretical specific energy of a NaS battery is approximately 760 Wh/kg based on the full sodium-sulfur electrochemical couple.

Cost of Making

The cost of NaS battery systems (including the battery module, thermal management, power conditioning, and balance-of-plant) is estimated at approximately 00–500 per kWh (₹25,000–₹42,000 per kWh) for large-scale installations, with NGK Insulators reporting costs trending downward with scale. The relatively higher cost compared to lithium-ion batteries is attributed to the specialized high-temperature ceramic electrolyte manufacturing, thermal insulation requirements, and safety systems needed for high-temperature operation. However, NaS batteries offer a significantly lower cost of electricity storage over their lifetime due to their long cycle life (4,500+ cycles), high round-trip efficiency, and zero self-discharge during standby. Ongoing research and manufacturing scale-up are expected to bring NaS battery costs below 00 per kWh in the coming years, making them increasingly competitive for long-duration energy storage applications.

Space to Implement

- **Grid-scale energy storage:** NaS battery systems for utility-scale applications (1–100 MWh) are deployed in containerized or building-integrated formats, typically requiring 0.5–5 cubic meters per MWh of usable storage, depending on system design and thermal insulation. Compared to lithium-ion systems, NaS installations require additional space for thermal management and safety enclosures.
- **Renewable energy integration:** Wind and solar farms use NaS batteries in modular skid-mounted configurations, with a typical 1 MW / 7.2 MWh NaS module (as produced by NGK) requiring a footprint of approximately 80–120 square meters, including auxiliary systems.
- **Industrial load leveling:** NaS battery banks for industrial facilities (1–10 MWh) are housed in dedicated battery rooms or outdoor weatherproof enclosures, typically occupying 0.3–2 cubic meters per MWh of storage.
- **Telecom and remote off-grid power:** Smaller NaS battery systems (10–500 kWh) for remote or island grids require compact, insulated enclosures of approximately 0.5–5 cubic meters, with integrated heating and thermal management.
- **Substation-level power quality and peak shaving:** NaS systems installed at electrical substations are housed in purpose-built, climate-controlled battery buildings or large containerized systems ranging from tens to hundreds of cubic meters depending on total capacity.

Positives and Challenges

Positives:

- **High energy density:** NaS batteries offer a high gravimetric energy density of 150–240 Wh/kg, approximately 3–5 times higher than lead-acid batteries and competitive with many lithium-ion chemistries, enabling compact large-scale storage installations.

- **Long cycle life:** NaS batteries are rated for over 4,500 charge-discharge cycles at 100% depth of discharge (DoD), corresponding to approximately 15 years of daily cycling, which is among the best of any large-scale battery technology.
- **High round-trip efficiency:** NaS batteries achieve round-trip energy efficiencies of 75–90%, which is competitive with other electrochemical storage technologies for grid applications.
- **Abundant and low-cost raw materials:** Both sodium and sulfur are extremely abundant, inexpensive, and globally available, with no dependence on scarce or geopolitically sensitive materials such as cobalt, lithium, or nickel.
- **Zero self-discharge during standby:** When the battery is in a cold (non-operational) state, there is no self-discharge, making NaS batteries well-suited for applications requiring long standby periods between discharge cycles.
- **Scalability:** NaS battery systems are highly modular and scalable, with individual modules that can be stacked and combined to achieve capacities from hundreds of kWh to hundreds of MWh, making them suitable for a wide range of grid-scale applications.
- **No aqueous electrolyte:** The solid ceramic electrolyte eliminates risks of electrolyte leakage, corrosion, and water-related degradation common in aqueous battery systems.

Challenges:

- **High operating temperature:** NaS batteries must be maintained at 300–350°C during operation, requiring continuous heating (consuming approximately 10–15% of stored energy) and sophisticated thermal management systems, increasing system complexity and cost.
- **Safety risks:** At high operating temperatures, molten sodium is highly reactive with water and air, and molten sulfur is flammable. A failure of the ceramic

electrolyte can result in direct contact between sodium and sulfur, causing fire or explosion hazards, necessitating robust containment and safety systems.

- **Slow startup time:** NaS batteries require a startup heating period of several hours to reach operating temperature from a cold state, limiting their responsiveness in applications requiring immediate power availability.
- **High manufacturing complexity:** The precision fabrication of the beta-alumina solid electrolyte ceramic tubes requires specialized, high-temperature sintering processes and stringent quality control, contributing to high manufacturing costs.
- **Limited low-temperature flexibility:** NaS batteries are not suitable for applications requiring ambient-temperature operation, transportation energy storage (EVs), or portable electronics due to their high operating temperature requirement.
- **End-of-life management:** Disposal of spent NaS batteries involves handling reactive sodium and sulfur compounds safely, requiring specialized procedures and facilities, though sodium and sulfur are less toxic than heavy metals used in other battery chemistries.

Present Scenario

- Sodium-sulfur batteries are commercially proven and deployed at grid scale, with NGK Insulators Ltd. remaining the dominant global manufacturer and supplier of NaS battery systems.
- NaS batteries are widely used for load leveling, wind and solar energy integration, emergency backup power, and peak shaving in Japan, the United States, the United Arab Emirates, and several European countries.
- The technology has demonstrated reliable long-term performance in real-world utility-scale installations over more than two decades of commercial operation.
- Newer intermediate-temperature NaS battery designs (operating at 150–250°C) are under active development, aimed at improving safety, reducing thermal management energy losses, and broadening application potential.

- Growing global demand for long-duration energy storage (LDES) solutions is increasing interest in NaS batteries as a cost-effective, scalable alternative to lithium-ion systems for multi-hour to multi-day storage applications.

Latest Developments

- Intermediate-temperature NaS batteries: Research is progressing toward NaS batteries operating at 150–250°C using advanced solid or quasi-solid electrolytes, reducing thermal management energy losses and improving safety.
- Room-temperature sodium-sulfur (RT-NaS) batteries: Emerging research at institutions such as Stanford University and several Asian universities is exploring sodium-sulfur batteries operating at or near room temperature using novel liquid and solid electrolytes, which could dramatically expand application potential.
- Advanced electrolyte materials: Development of higher-conductivity, more mechanically robust beta-alumina ceramics and alternative solid electrolytes (e.g., NASICON-type materials) to improve performance and reduce manufacturing costs.
- Improved cell design: Research into advanced cell geometries, electrode architectures, and thermal insulation materials to reduce heat losses and improve round-trip efficiency beyond 90%.
- Cost reduction through manufacturing scale-up: Expansion of NaS battery manufacturing capacity, particularly in Asia and the Middle East, is expected to drive Integration with renewable energy systems: NaS batteries are increasingly being explored for long-duration (8–12 hour) energy storage paired with large-scale wind and solar installations, filling a niche that lithium-ion systems are less suited for economically.

Environmental Impact

- **Positive impact:** NaS batteries use sodium and sulfur, both of which are abundant, globally available, and non-critical materials, avoiding the ethical and environmental concerns associated with cobalt mining and lithium extraction.

- **Lower toxicity:** Sodium and sulfur are far less toxic than lead, cobalt, or nickel, reducing environmental risks from battery leakage or improper disposal compared to many other battery chemistries.

- **Energy consumption during operation:** The requirement to maintain high operating temperatures (300–350°C) means that NaS batteries consume a portion of their stored energy as heat — approximately 10–15% — which reduces net energy efficiency and increases operational carbon footprint unless waste heat is recovered or renewable energy is used for heating.

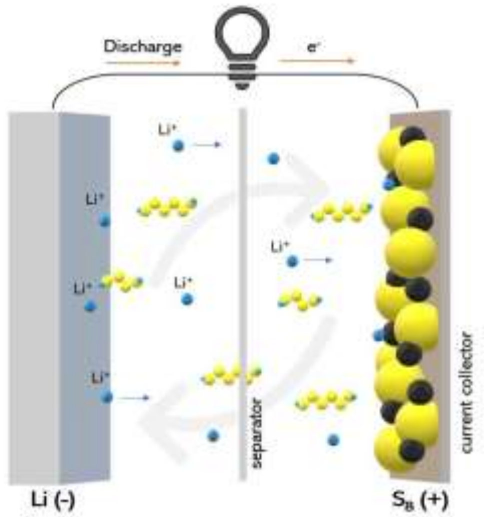
- **Recyclability:** Sodium and sulfur from end-of-life NaS batteries can be recovered and reused, and the ceramic electrolyte components can be processed for material recovery, though large-scale NaS recycling infrastructure is still developing globally.

- **Manufacturing impact:** The high-temperature sintering processes required for beta-alumina ceramic electrolyte production are energy-intensive, but the long operational lifetime (15+ years) and high cycle count of NaS batteries partially offset these initial environmental costs over the battery's full lifecycle.

- **Lifecycle benefits:** When used for renewable energy integration and grid stabilization, NaS batteries help displace fossil fuel peaking plants, contributing to significant reductions in greenhouse gas emissions over their operational lifetime.

viii. LITHIUM-SULPHUR BATTERY

Overview



A lithium-sulfur (Li-S) battery is a next-generation rechargeable battery that uses a lithium metal anode, an elemental sulfur (S_8) cathode, and an electrolyte — typically a liquid ether-based solution or, in advanced designs, a solid-state electrolyte. Li-S chemistry is fundamentally different from lithium-ion (Li-ion) batteries: instead of intercalating lithium ions into a host crystal lattice, it relies on a conversion reaction between lithium and sulfur to store and release energy. This gives Li-S batteries a theoretical energy density of approximately 2,600 Wh/kg — up to 10 times higher than conventional Li-ion batteries (~250 Wh/kg). Sulfur is an extremely abundant, low-cost industrial byproduct with no dependence on critical minerals such as cobalt or nickel, making Li-S a strategically important technology for sustainable energy storage. First seriously researched in the 1960s and intensively developed since 2010, Li-S batteries have as of 2024–2025 achieved their first real-world deployments on the International Space Station (ISS), high-altitude unmanned aircraft, and defense drone platforms. The global Li-S battery market, valued at approximately USD 32 million in 2024, is projected to reach USD 209 million by 2029, driven by aerospace, defense, and electric vehicle applications.

Working Principle

Unlike lithium-ion batteries where lithium ions slot into crystal lattice sites (intercalation), Li-S chemistry is based on an electrochemical conversion reaction. During discharge, the lithium metal anode is oxidized — lithium atoms lose electrons and release lithium ions (Li+) that migrate through the electrolyte toward the sulfur cathode. Simultaneously, electrons flow through the external circuit to power the connected load. At the sulfur cathode, elemental sulfur is reduced by accepting electrons and reacting with Li+ ions. This conversion does not proceed in a single step; instead, sulfur is reduced through a cascade of intermediate lithium polysulfide species — from long-chain, soluble species (Li2S8, Li2S6, Li2S4) to insoluble final products (Li2S2, Li2S). The central engineering challenge of Li-S chemistry is the polysulfide shuttle effect: the soluble intermediate polysulfides dissolve into the liquid electrolyte and migrate from the cathode to the lithium anode, where they react irreversibly, consuming active material and causing continuous capacity fade, anode corrosion, and low coulombic efficiency. Additional challenges include sulfur's extremely low electronic conductivity (~10 to the power of -30 S/cm), which requires conductive host frameworks; an approximately 80% volume expansion of the cathode as sulfur converts to Li2S; and lithium dendrite growth at the anode, which can cause internal short circuits. During charging, an external voltage reverses all reactions — Li2S is oxidized back to sulfur at the cathode, and lithium ions are reduced and deposited as lithium metal at the anode. Post-2023 research has focused heavily on solid-state electrolytes, advanced cathode host materials, and anode protection strategies to suppress the shuttle effect and achieve practical long-cycle-life Li-S cells.

Chemical Reaction

$2Li + S \rightarrow Li_2S$ ($\Delta G = -2.24$ eV, $V_0 \approx 2.15$ V)

Researching Universities/Institutions/Companies

America: Argonne National Laboratory (Lewis acid electrolyte additive; redox-active interlayer research); National Renewable Energy Laboratory; Lawrence Berkeley National Laboratory; Pacific Northwest National Laboratory; NASA Glenn Research Center (SABERS program — solid-state Li-S cells exceeding 500 Wh/kg for electric aviation); Massachusetts Institute of Technology; Stanford University; University of California San Diego (self-healing sulfur iodide cathode, Nature 2024); University of Texas at Austin (Manthiram group — leading Li-S reviews); University of Michigan; Lyten Inc. (3D graphene composite cathode; gigafactory planned near Reno, Nevada, up to 10 GWh/year); Sion Power (Li-S cells tested on Airbus HAPS aircraft); Zeta Energy (joint EV development with Stellantis, 2024); AEVEX Aerospace (defense UAS Li-S integration); QuantumScape.

Europe: University of Cambridge; University of Oxford; Imperial College London; Fraunhofer Institute for Chemical Technology (Germany); Helmholtz-Zentrum Berlin fur Materialien und Energie; Technical University of Munich; RWTH Aachen University;

University of Munster; CEA (France); CNRS (France); Faraday Institution (UK); CELEST Center for Electrochemical Energy Storage (Germany); Airbus SE (HAPS aircraft Li-S demonstration with Sion Power 11-day continuous flight achieved); University of Southampton.

Asia: Peking University (Professor Quanquan Pang — LBPSI glass electrolyte, 25,000-cycle life at room temperature, 432 mAh/g at 150C); Tsinghua University; University of Science and Technology of China; Shanghai Institute of Ceramics — Chinese Academy of Sciences; Kyoto University; Tokyo Institute of Technology; Seoul National University; POSCO (South Korea); Samsung SDI (South Korea); CATL (China, Li-S research division); BYD (China); Indian Institute of Technology Madras; Indian Institute of Technology Bombay; Indian Institute of Science; Central Electrochemical Research Institute (India); Defence Research and Development Organisation (India).

Middle East and Others: Khalifa University, UAE (Covalent Organic Framework sulfur host dual confinement strategy, 80% capacity retention after 500 cycles); University of New South Wales (Australia); University of Waterloo (Canada); Stellantis (Italy/USA joint EV Li-S development with Zeta Energy, targeting 2030 commercial deployment).

Largest Acquired Capacity

Lithium-sulfur battery technology remains primarily in the advanced research, prototype, and early commercial stage, with deployments concentrated in aerospace, defense, and specialty applications rather than large-scale grid or automotive energy storage. The most notable real-world deployments include: the demonstration of Li-S batteries on the International Space Station (ISS) in 2025, validating performance in a space environment; the Airbus High Altitude Pseudo-Satellite (HAPS) aircraft powered by Sion Power Li-S cells achieving an unprecedented 11-day continuous flight; and Lyten's delivery of Li-S battery packs for defense unmanned aerial systems (UAS) in 2024. In terms of planned commercial scale, Lyten has announced a lithium-sulfur gigafactory near Reno, Nevada, targeting up to 10 GWh of annual production capacity — representing the first major commercial-scale manufacturing commitment for Li-S technology globally. NASA's SABERS (Solid-state Architecture Batteries for Enhanced Rechargeability and Safety) program has demonstrated solid-state Li-S cells exceeding 500 Wh/kg in laboratory conditions for electric aviation applications. The global Li-S battery market was valued at approximately USD 32 million in 2024. No GWh-scale grid or EV deployment of Li-

S batteries has been achieved as of 2026, with mass-market EV deployment targeted for approximately 2030 by leading industry players including Lyten and Stellantis-Zeta Energy.

Specific Capacity

Theoretical energy density: approximately 2,600 Wh/kg (based on the full Li-S electrochemical couple). Practical energy density (pouch cells, 2024–2025): 300–450 Wh/kg approximately 1.5–2 times higher than the best commercial Li-ion cells. Advanced solid-state Li-S cells demonstrated by NASA SABERS have exceeded 500 Wh/kg under laboratory conditions. Sulfur cathode specific capacity: 1,675 mAh/g (theoretical); lithium anode specific capacity: 3,860 mAh/g (theoretical). Nominal cell voltage: 2.1–2.15 V. The LBPSI glass electrolyte developed at Peking University demonstrated a fast-charging capacity of 432 mAh/g at an extreme rate of 150C, with 80.2% capacity retention after 25,000 cycles — the highest cycle life result reported for Li-S chemistry to date (2024). Volumetric energy density is constrained by sulfur's low tap density and the porous host structures required, remaining below that of equivalent Li-ion designs at the cell level.

Cost of Making

The cost of Li-S battery cells and packs varies significantly by application and cell format. Sulfur itself is an extremely low-cost raw material an abundant industrial byproduct of petroleum refining and natural gas processing with prices typically below USD 0.10 per kg, representing a major cost advantage over lithium-ion cathode materials (cobalt: ~USD 30,000/tonne; nickel: ~USD 15,000/tonne; lithium carbonate: ~USD 13,000–20,000/tonne as of 2024–2025). However, current Li-S cell manufacturing costs remain high — estimated at USD 400–800 per kWh (Rs. 33,000–67,000 per kWh) for advanced pouch cell formats — primarily due to the cost of lithium metal anodes, specialized electrolyte and separator materials, low manufacturing volumes, and yield challenges associated with early-stage production. Solid-state Li-S cells carry an additional cost premium for solid electrolyte fabrication. As manufacturing scales — particularly with Lyten's planned 10 GWh gigafactory — costs are projected to decline significantly toward USD 100–150 per kWh by 2030, at which point Li-S would be cost-competitive with current lithium-ion for high-energy-density applications.

Space to Implement

- **Space and satellite systems:** Li-S batteries selected for ISS demonstration (2025) and satellite applications. Individual satellite battery packs (10–200 Ah) are compact, lightweight units optimized for vacuum and radiation environments, typically occupying 0.002–0.05 cubic meters. The high energy density reduces satellite battery mass by 30–50% compared to equivalent Li-ion systems, with significant launch cost savings.

- **High-altitude and long-endurance unmanned aircraft:** Li-S battery packs for HAPS platforms (such as the Airbus Zephyr powered by Sion Power Li-S cells) are integrated into ultra-thin, flexible wing structures, typically requiring 0.01–0.2 cubic meters of battery volume. The 11-day continuous flight demonstrated by Airbus would not have been achievable at equivalent weight with Li-ion.

- **Defense unmanned aerial systems (UAS) and drones:** Li-S battery packs for military drone platforms (1–20 kWh) require approximately 0.01–0.15 cubic meters, with the primary advantage being a 30–40% reduction in battery weight versus equivalent Li-ion packs, extending mission endurance and range.

- **Electric vertical take-off and landing (eVTOL) aircraft:** Li-S battery systems for eVTOL applications (20–100 kWh) will require approximately 0.1–0.5 cubic meters, with advanced cell-to-pack integration. The combination of high energy density and high peak power capability (for take-off) makes Li-S a favored technology candidate for this rapidly growing market.

- **Electric vehicles (future, ~2030):** EV Li-S battery packs (40–120 kWh) are projected to require approximately 0.4–1.2 cubic meters — similar to or slightly smaller than current Li-ion packs — while delivering significantly greater range due to higher gravimetric energy density. The lower volumetric energy density of Li-S compared to high-nickel Li-ion partially offsets the weight advantage at the pack level.

- **Portable electronics and wearables (research stage):** Li-S cells for consumer electronics would occupy very small volumes (0.00001–0.002 cubic meters), with the primary benefit being reduced device weight and extended battery life, though cycle life improvements are needed before commercial viability in this segment.

- **Grid-scale energy storage (research/future):** While not currently deployed at grid scale, Li-S batteries' low sulfur cost and high energy density make them a long-term candidate for stationary storage where weight is less critical. Grid-scale Li-S installations would require hundreds to thousands of cubic meters of housing for multi-MWh to GWh-scale systems, similar to current Li-ion BESS configurations.

Positives and Challenges

Positives:

- **Exceptional theoretical energy density:** Li-S batteries offer a theoretical energy density of approximately 2,600 Wh/kg — 5 to 10 times higher than conventional Li-ion batteries (~250 Wh/kg) — and practical cell-level energy densities of 300–500 Wh/kg already surpass the best commercial Li-ion cells, enabling transformative weight and size reductions in energy storage systems.
- **Abundant and ultra-low-cost cathode material:** Sulfur is an extremely abundant industrial byproduct of petroleum refining and natural gas processing, available globally at costs below USD 0.10 per kg. This represents a fundamental raw material cost advantage over cobalt- and No critical mineral dependencies: Li-S batteries require no cobalt, nickel, or manganese — the critical minerals that drive ethical, geopolitical, and supply chain concerns in Li-ion battery production — making Li-S intrinsically more sustainable and supply-chain resilient.
- **Wide operating temperature range:** Li-S batteries, particularly solid-state variants, can operate at temperatures as low as −70°C — far below the practical limits of most Li-ion chemistries — making them uniquely suitable for aerospace, arctic, and high-altitude applications.
- **High specific capacity of both electrodes:** The sulfur cathode (1,675 mAh/g) and lithium metal anode (3,860 mAh/g) both have far higher specific capacities than Li-ion equivalents (graphite anode: ~370 mAh/g; NMC cathode: ~140–200 mAh/g), providing a strong thermodynamic basis for high energy density.
- **Improved safety in solid-state variants:** Solid-state Li-S batteries eliminate flammable liquid electrolytes, significantly reducing fire and thermal runaway risk

compared to conventional liquid-electrolyte batteries — a critical advantage for aviation and defense applications.

- **Breakthrough cycle life in research:** The LBPSI glass electrolyte demonstrated at Peking University achieved 80.2% capacity retention after 25,000 cycles (2024) — if translatable to practical cell formats, this would match or exceed the best Li-ion cycle life, eliminating Li-S's most significant commercial limitation.

Challenges:

- **Polysulfide shuttle effect:** The dissolution of intermediate lithium polysulfide species (Li_2S_4–Li_2S_8) into liquid electrolytes and their migration from cathode to anode causes irreversible active material loss, anode corrosion, and continuous capacity fade — the central engineering challenge of Li-S chemistry that all major research efforts are focused on addressing.

- **Limited practical cycle life:** Current commercially available Li-S cells achieve only 300–500 charge-discharge cycles — significantly below Li-ion's 1,000–2,000+ cycles for consumer applications — restricting near-term deployment to applications with finite mission profiles (aerospace, defense) where shorter cycle life is acceptable.

- **Volume expansion of cathode:** Sulfur expands approximately 80% by volume as it converts to Li_2S during discharge, causing mechanical stress and fracturing of cathode structures, which accelerates capacity fade and reduces cell longevity.

- **Low electronic conductivity of sulfur:** Elemental sulfur is an electrical insulator ($\sim 10^{-30}$ S/cm), requiring complex conductive host frameworks (carbon, graphene, MXenes) to enable electron transport through the cathode, adding manufacturing complexity and cost.

- **Lithium dendrite growth:** Lithium metal anodes are prone to forming needle-like dendrites during charging, which can penetrate the separator and cause dangerous internal short circuits, requiring protective coatings, solid electrolytes, or other mitigation strategies.

- **High manufacturing cost and complexity:** Current Li-S cell costs of USD 400–800 per kWh are significantly above Li-ion costs (0–110 per kWh), reflecting the immature manufacturing base, lithium metal anode challenges, and specialized materials required. Solid-state variants carry an additional cost premium.

- **Scaling challenges for solid-state electrolytes:** Producing solid-state electrolyte membranes (e.g., sulfide argyrodite, LBPSI glass) with consistent quality, high ionic conductivity, and mechanical robustness at commercial scale remains a major engineering challenge not yet solved at production volumes.

Present Scenario

- Lithium-sulfur batteries have transitioned from a laboratory curiosity to a technology achieving first commercial deployments in aerospace and defense applications, with Lyten delivering Li-S battery packs for defense UAS in 2024 and Li-S cells demonstrated on the ISS in 2025.

- The global Li-S battery market is valued at approximately USD 32 million in 2024, dominated by aerospace, defense, and specialty applications. The market is projected to grow at a CAGR of approximately 45%, reaching USD 209 million by 2029.

- Lyten has announced plans for the world's first Li-S battery gigafactory, located near Reno, Nevada, with a planned annual capacity of up to 10 GWh, targeting both Major peer-reviewed breakthroughs since 2023 — including UC San Diego's self-healing sulfur iodide cathode (Nature, 2024), Peking University's 25,000-cycle LBPSI electrolyte (2024), and Argonne National Laboratory's redox-active interlayer have significantly advanced the scientific foundation for practical Li-S cells.

- Stellantis announced a joint EV development agreement with Zeta Energy in 2024, targeting commercial Li-S EV batteries around 2030, signaling growing automotive industry commitment to the technology.

- NASA's SABERS program has demonstrated solid-state Li-S cells exceeding 500 Wh/kg, establishing Li-S as the leading candidate for next-generation electric aviation energy storage.

- In India, the Indian Institute of Technology Madras, IIT Bombay, Indian Institute of Science, and Central Electrochemical Research Institute are active in Li-S materials research, supported by the Department of Science and Technology and the National Mission on Transformative Mobility and Battery Storage.

Latest Developments

- **Solid-state electrolytes (primary thrust):** Replacing liquid electrolytes with solid-state alternatives — particularly sulfide argyrodites (Li_6PS_5Cl), LBPSI glass, and halide electrolytes — eliminates polysulfide dissolution at the source. Chlorinated argyrodite ($Li_{6-x}PS_{5-x}Cl_{1-x}$) was recommended as a standardized benchmark solid electrolyte in a landmark 2024 Nature Chemical Engineering paper (Kim et al.).
- **Advanced cathode host materials:** Covalent Organic Frameworks (COFs) such as the chalcone-linked nanographene COF developed at Khalifa University, MXenes (2D transition metal carbides), and MBenes (2D transition metal borides) provide both physical confinement and chemical anchoring of polysulfides, with metallic conductivity and catalytic activity to accelerate sulfur conversion.
- **Self-healing cathode materials:** UC San Diego's sulfur iodide material (Nature, 2024) demonstrated that electrically conductive, self-healing cathodes can spontaneously repair volume-expansion-induced cracks, restoring mechanical integrity and conductivity without external intervention — a landmark step toward durable solid-state Li-S cells.
- **Sparingly solvating electrolytes (SSEs):** A major 2025 research trend involves designing electrolytes that deliberately minimize polysulfide solubility through solvation structure modulation, enabling lean-electrolyte operation with low electrolyte-to-sulfur ratios — a prerequisite for high practical energy density and long cycle life.
- **Lithium metal anode engineering:** Protective coatings (LiF, Li_3N, artificial SEI layers), composite anode structures, and 3D host frameworks are being developed to suppress dendrite growth, control volume change, and stabilize the anode interface during cycling.
- **AI and machine learning acceleration:** Machine learning models are being applied to predict solid electrolyte ionic conductivity, screen electrolyte

compositions, and optimize electrode architectures, significantly accelerating the research cycle. 3D printing enables fabrication of composite cathodes with precisely controlled porosity and sulfur loading.

- **Gigafactory scale-up:** Lyten's planned 10 GWh gigafactory near Reno, Nevada, represents the first commercial-scale manufacturing commitment, with production scale-up expected to drive Li-S cell costs from the current USD 400–800/kWh toward USD 100–150/kWh by 2030.
- **Room-temperature and intermediate-temperature variants:** Research into Li-S cells operating efficiently at room temperature with solid or quasi-solid electrolytes is progressing rapidly, with the goal of broadening applications beyond aerospace to EVs and consumer electronics.

Environmental Impact

- **Positive impact — elimination of critical minerals:** Li-S batteries require no cobalt, nickel, or manganese, directly eliminating the environmental damage, water depletion, ecosystem destruction, and human rights concerns associated with cobalt mining in the Democratic Republic of Congo and nickel mining in Russia, Indonesia, and the Philippines. This represents a fundamental environmental sustainability advantage over conventional Li-ion chemistries.
- **Abundant and low-impact cathode material:** Sulfur used in Li-S batteries is sourced primarily as an industrial byproduct of petroleum refining and natural gas sweetening — a material that would otherwise require costly and environmentally burdensome disposal. Repurposing this waste sulfur stream as a battery cathode reduces net industrial waste and associated emissions.
- **Lithium mining considerations:** Li-S batteries still require lithium metal anodes, and lithium mining (particularly brine extraction in South America's Lithium Triangle) involves significant water use and ecological disturbance in water-stressed desert ecosystems. Advances in lithium recycling and anode efficiency (reducing lithium excess) are critical to mitigating this impact.
- **Manufacturing energy footprint:** Current Li-S cell manufacturing involves energy-intensive processes for lithium metal production (electrolytic), solid

electrolyte sintering (for solid-state variants), and high-purity electrolyte synthesis. As with Li-ion, the environmental benefit of Li-S batteries is maximized when manufacturing is End-of-life and recycling: Li-S battery recycling infrastructure is not yet developed at scale. Sulfur from spent Li-S batteries can in principle be recovered and reused or processed as industrial sulfur, while lithium recovery from spent cells is possible using hydrometallurgical methods adapted from Li-ion recycling. As production volumes grow, dedicated Li-S recycling processes will need to be established.

- **Lifecycle greenhouse gas reduction:** When deployed in electric vehicles, aviation, and grid storage applications powered by renewable energy, Li-S batteries' higher energy density means fewer batteries (and less material) are needed for a given energy storage requirement, resulting in lower lifecycle material extraction, processing, and manufacturing emissions compared to equivalent Li-ion systems.
- **Safety and environmental risk:** Lithium metal is highly reactive with water and air, requiring careful handling during manufacturing and end-of-life processing. Solid-state Li-S variants reduce this risk by eliminating flammable liquid electrolytes, and sulfur itself is non-toxic, but robust safety and disposal protocols remain essential for responsible lifecycle management.

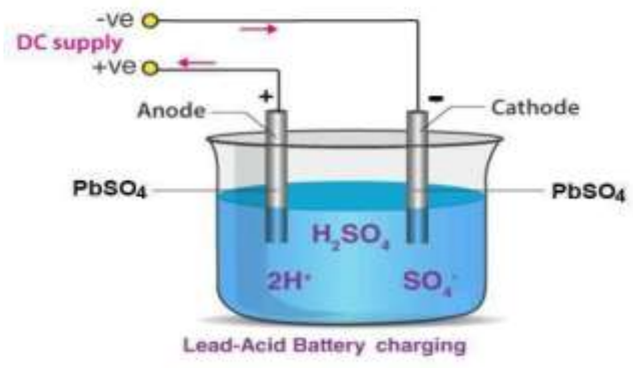
ix. LEAD ACID BATTERY

Overview

A lead-acid battery is the oldest type of rechargeable battery, invented in 1859 by French physicist Gaston Planté. It consists of lead (Pb) plates as the negative electrode, lead dioxide (PbO_2) as the positive electrode, and a dilute sulfuric acid (H_2SO_4) solution as the electrolyte. During discharge, both electrodes react with the sulfuric acid to produce lead sulfate ($PbSO_4$), releasing electrical energy. During charging, this reaction is reversed. Lead-acid batteries are widely used in automotive starter batteries, uninterruptible power supplies (UPS), grid energy storage, forklifts, and backup power systems due to their low cost, reliability, and ability to deliver high surge currents.

Working Principle

Lead-acid batteries operate through electrochemical reactions between lead, lead dioxide, and sulfuric acid. During discharge, the negative lead (Pb) electrode is oxidized and releases electrons, while the positive lead dioxide (PbO_2) electrode is reduced by accepting electrons. Sulfate ions (SO_4^{2-}) from the electrolyte combine with both electrodes to form lead sulfate ($PbSO_4$), and water is produced, diluting the electrolyte. During charging, an external voltage reverses this process — lead sulfate is converted back to lead and lead dioxide, and the sulfuric acid concentration is restored. This



reversible electrochemical cycle allows lead-acid batteries to store and release electrical energy repeatedly.

Chemical Reaction

$Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$

Research Universities / Institutions / Companies

America: Argonne National Laboratory, National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory, Sandia National Laboratories, University of California Berkeley, Massachusetts Institute of Technology, University of Michigan, EnerTech Environmental, East Penn Manufacturing (Deka Batteries), EnerSys, Crown Battery, C&D Technologies.

Europe: Fraunhofer Institute for Chemical Technology, EUROBAT (Association of European Automotive and Industrial Battery Manufacturers), Bettenbourg Battery Research Centre (Luxembourg), FIAMM (Italy), Exide Technologies (Germany/Europe), Hoppecke Batteries (Germany), Sonnenschein (Germany), Tudor Group (Spain/Sweden).

Asia: Central Electrochemical Research Institute (India), Indian Institute of Technology Madras, Indian Institute of Technology Bombay, Indian Institute of Science, Defence Research and Development Organisation (India), Amara Raja Batteries (India), Exide Industries (India), GS Yuasa (Japan), Panasonic (Japan), Furukawa Battery (Japan), Tianneng Power (China), Chaowei Power (China), Leoch International (China), Beijing Shoto Group (China).

Largest Capacity Acquired

Lead-acid battery technology continues to hold a significant share of the global stationary energy storage market, particularly in telecommunications backup, UPS systems, and grid support. While lead-acid batteries have been largely superseded by lithium-ion at the utility-scale grid level, large-scale deployments of valve-regulated lead-acid (VRLA) and advanced lead-acid (ALABC) batteries still operate in capacities ranging from tens to hundreds of MWh, particularly in telecom infrastructure and industrial facilities across the United States, India, and Southeast Asia. Advanced lead-acid systems incorporating carbon additives and improved plate designs have achieved capacities of up to 30–100 MWh in certain stationary applications. The global installed base of lead-acid batteries for energy storage and backup remains in the multi-GWh range when aggregated across all installations worldwide, reflecting the technology's continued relevance due to low cost, recyclability, and established supply chains.

Specific Capacity

30–50 Wh/kg (conventional flooded lead-acid); advanced lead-acid and lead-carbon batteries can achieve 50–70 Wh/kg under optimized conditions. The volumetric energy density is approximately 60–110 Wh/L.

Cost of Making

Lead-acid batteries remain among the most cost-effective rechargeable battery technologies. As of 2025–2026, the cost of lead-acid battery packs for stationary and automotive applications ranges from approximately $100–150 per kWh (₹8,000–₹12,500 per kWh) for standard flooded types, and $150–250 per kWh (₹12,500–₹21,000 per kWh) for VRLA (valve-regulated lead-acid) and advanced lead-acid variants. Automotive starter batteries remain significantly cheaper per unit due to mature, high-volume manufacturing. Lead-acid batteries also benefit from high recyclability, with over 99% of lead recovered and reused in many markets, which helps offset raw material costs.

Space to Implement

- **Automotive starter batteries:** Standard lead-acid car batteries (typically 45–100 Ah, 12V) require a very compact volume of approximately 0.005–0.012 cubic meters, fitting directly into engine compartments.
- **Stationary / UPS backup systems:** Lead-acid battery banks for telecom towers and data center UPS systems (1–100 kWh) typically occupy 0.5–5 cubic meters, depending on the number of battery strings and configuration.
- **Industrial motive power (forklifts):** Traction lead-acid battery packs (typically 24V–80V, 100–1,000 Ah) require approximately 0.3–1.5 cubic meters and are built into the counterweight section of forklifts.

- **Residential backup power:** Lead-acid battery systems for home backup (1–10 kWh) typically require 0.2–1.0 cubic meters and are often installed in utility rooms or garages.
- **Grid-scale stationary storage:** Large lead-acid battery energy storage systems require substantially more space than equivalent lithium-ion installations — roughly 30–50% more volume for the same energy capacity — making them less space-efficient for grid-scale deployments.
- **Electric two-wheelers (legacy):** Lead-acid battery packs used in older electric scooters and e-rickshaws (approximately 1–3 kWh) occupy around 0.05–0.20 cubic meters, though they are increasingly being replaced by lithium-ion systems.

Positives and Challenges

Positives:

- **Low cost:** Lead-acid batteries are among the cheapest rechargeable batteries available, with well-established manufacturing processes and abundant raw materials, making them accessible for a wide range of applications.
- **High recyclability:** Lead-acid batteries have one of the highest recycling rates of any consumer product — over 95–99% of the lead, plastic, and acid is recoverable and reused, supporting a well-developed circular economy.
- **High surge current capability:** Lead-acid batteries can deliver very high instantaneous currents, making them ideal for engine starting, ignition, and other high-demand applications.
- **Reliable and proven technology:** With over 160 years of use, lead-acid batteries are a mature, well-understood technology with extensive global infrastructure for manufacturing, maintenance, and recycling.
- **Good performance in extreme temperatures:** Flooded lead-acid batteries operate across a wide temperature range (−40°C to 50°C) and are relatively tolerant of overcharging compared to some newer chemistries.

- **No memory effect:** Unlike nickel-cadmium batteries, lead-acid batteries do not suffer from the memory effect, and partial discharges do not permanently reduce capacity if managed properly.

Challenges:

- **Low energy density:** Lead-acid batteries have significantly lower energy density (30–50 Wh/kg) compared to lithium-ion batteries (200–300 Wh/kg), resulting in larger and heavier battery packs for the same stored energy.
- **Limited cycle life:** Conventional flooded lead-acid batteries typically offer only 300–500 charge cycles under standard conditions, which is considerably lower than lithium-ion (1,000–3,000 cycles) and LFP (3,000–7,000+ cycles).
- **Heavy weight:** The use of dense lead plates makes these batteries the heaviest of common battery chemistries, limiting their use in weight-sensitive applications such as electric vehicles and portable electronics.
- **Maintenance requirements:** Flooded lead-acid batteries require periodic water top-up, electrolyte checks, and equalization charging, increasing maintenance burden compared to sealed or lithium-ion batteries.
- **Environmental and health concerns:** Lead is a toxic heavy metal, and improper disposal or recycling of lead-acid batteries poses serious environmental and health risks, including soil and water contamination.
- **Slow charging:** Lead-acid batteries generally require 8–16 hours for a full charge, with fast-charging options limited to avoid damaging plate sulfation and shedding.
- **Sulfation:** If left partially or fully discharged for extended periods, lead sulfate crystals can harden on the electrodes, permanently reducing capacity — a common failure mode in improperly maintained batteries.

Present Scenario

- Lead-acid batteries remain the dominant battery technology globally by installed volume and value in specific segments, particularly automotive starter batteries, UPS systems, and industrial motive power.

- Despite competition from lithium-ion batteries, lead-acid technology continues to hold a significant share of the global battery market, estimated at over 40% by revenue as of 2025–2026, primarily due to low cost, recyclability, and established infrastructure.
- Advanced lead-acid (ALA) and lead-carbon (LC) variants are being developed and deployed to improve energy density, cycle life, and fast-charging performance, enabling use in hybrid vehicles and grid energy storage.
- In developing markets such as India, Southeast Asia, and Africa, lead-acid batteries remain the primary energy storage technology for off-grid solar systems, telecom towers, and backup power due to their affordability and local availability.
- Major manufacturers such as Exide Industries, Amara Raja Batteries, EnerSys, and East Penn Manufacturing continue to invest in production capacity and technology improvements.

Latest Developments

- **Advanced lead-carbon batteries:** Incorporating activated carbon or graphene into the negative electrode improves charge acceptance, reduces sulfation, and extends cycle life to 1,000–3,000 cycles — approaching lithium-ion performance for stationary applications.
- **Bipolar lead-acid technology:** Innovative designs using bipolar plates reduce internal resistance, improve energy and power density, and enable lighter, more compact battery systems.
- **Enhanced recycling processes:** Next-generation hydrometallurgical and bioleaching recycling methods are being developed to improve efficiency, reduce environmental impact, and recover more valuable materials from end-of-life batteries.
- **Improved electrode and separator materials:** Research into advanced plate grids, expanders, and separators aims to improve battery efficiency, lifespan, and performance under partial state-of-charge (PSoC) cycling.

- **Hybrid systems:** Lead-acid batteries combined with supercapacitors or lithium-ion cells in hybrid configurations offer improved performance for high-demand applications such as start-stop vehicles and renewable energy storage.

Environmental Impact

- **Positive impact (recycling):** Lead-acid batteries support one of the world's most effective recycling systems. In North America and Europe, over 99% of lead-acid batteries are collected and recycled, recovering lead, plastic, and sulfuric acid for reuse — making them a model for circular economy principles.

- **Toxicity concerns:** Lead is a neurotoxin and poses serious environmental and public health risks if batteries are improperly disposed of, particularly in regions with inadequate recycling infrastructure. Improper smelting of lead-acid batteries is a major source of lead pollution in developing countries.

- **Water and land contamination:** Battery acid (sulfuric acid) leakage from damaged or improperly handled batteries can contaminate soil and groundwater, requiring careful handling and storage.

- **Energy-intensive production:** Manufacturing lead-acid batteries is energy-intensive,with significant CO_2 emissions associated with lead smelting, plate processing, and assembly.

- **Lifecycle environmental balance:** While individual lead-acid batteries have a higher environmental impact per kWh stored compared to some alternatives, their high recyclability and long global track record of responsible recycling partially offset these concerns, especially in mature markets with strict waste regulations.

x. NICKEL-CADMIUM BATTERY

Overview

Nickel–Cadmium (Ni-Cd) batteries are rechargeable electrochemical batteries that use nickel oxide hydroxide as the positive electrode and cadmium as the negative electrode. They were one of the earliest widely used rechargeable battery technologies and are known for their robust performance, strong tolerance to deep discharge, long cycle life, and ability to operate in extreme temperatures. Ni-Cd batteries were extensively used in portable electronics, aviation equipment, emergency lighting, medical devices, and industrial power tools. However, due to environmental concerns related to the toxicity of cadmium, their use in consumer products has declined and is now restricted in many countries. Despite this, Ni-Cd batteries are still used in specialized applications where high reliability, durability, and performance in harsh conditions are required.

Working Principle

A Nickel-Cadmium battery is an energy storage system based on electrochemical charge-discharge reactions between a nickel-based cathode and a cadmium anode, with potassium hydroxide as the electrolyte. During discharge, the cadmium electrode is oxidized and the nickel electrode is reduced, producing electrical energy for the external circuit. During charging, the reaction is reversed and the active materials are restored to their original state. This reversible process gives Ni-Cd batteries their long cycle life and ability to work under repeated deep discharge conditions.

Chemical Reaction

$Cd + 2NiO(OH) + 2H_2O \rightleftharpoons Cd(OH)_2 + 2Ni(OH)_2$

Researching Universities/Institutions/Companies

India: Powergrid Corporation of India Limited, Central Electrochemical Research Institute, Indian Institute of Technology Madras, Indian Institute of Technology Bombay, and industrial battery service companies involved in UPS and station backup systems.

Asia: Japanese industrial battery manufacturers and utilities continue to support Ni-Cd systems in rail, backup power, and emergency applications.

Europe: Organizations working on battery regulation, recycling, and replacement technologies are pushing Ni-Cd out of portable applications because of cadmium restrictions.

North America: Industrial UPS and backup-power suppliers still support Ni-Cd for harsh-environment applications, especially where high reliability is required.

Largest Acquired Capacity

Ni-Cd batteries are still used in large backup and industrial systems rather than in mainstream consumer electronics. Recent market information shows continued demand in UPS, rail, telecom, and power-sector backup applications. A major 2024–2025 milestone includes the Cairo Metro Line 4 project, where Saft was contracted to supply MRX nickel-technology batteries for 92 trains to ensure critical backup for doors and air conditioning. In India, Volks Energie secured a significant 2025 project to assist the Power Grid Corporation of India Ltd. (PGCIL) in transitioning critical substation backup from lead-acid to more dependable Ni-Cd systems.

Specific Capacity

Ni-Cd batteries typically offer about 40 to 60 Wh/kg (Practical) of specific energy, depending on the design and application. This is lower than lithium-ion and Ni-MH systems, but their strength lies in durability, fast discharge, and resistance to abuse rather than energy density. Ni-Cd has high-rate discharge capability.

Cost of Making

The cost of producing 1 kWh of energy storage capacity using a nickel-cadmium (Ni-Cd) battery typically ranges between \$300 to \$600 (application-dependent), with some estimates placing it closer to \$1,000 per kWh depending on the application.

Space to Implement

Ni-Cd batteries generally need more space than lithium-ion batteries for the same energy capacity because their energy density is lower. They are therefore used mainly in places where compact size is less important than long service life, such as industrial UPS units, emergency lighting, railway systems, and power plants.

Positives and Challenges

The positives of nickel-cadmium batteries include long cycle life, good high-rate discharge capability, wide operating temperature range, good recycling efficiency, and strong tolerance to deep discharges. They are also mechanically robust and perform well in demanding industrial environments.

The challenges of nickel-cadmium batteries include cadmium toxicity, stricter regulation, high initial cost, lower energy density than newer battery chemistries, exhibit memory effect where repeated partial discharge reduces capacity and the need for proper recycling and disposal. As a result, many portable applications are shifting to Ni-MH, lithium-ion, or LiFePO4 alternatives.

Applications

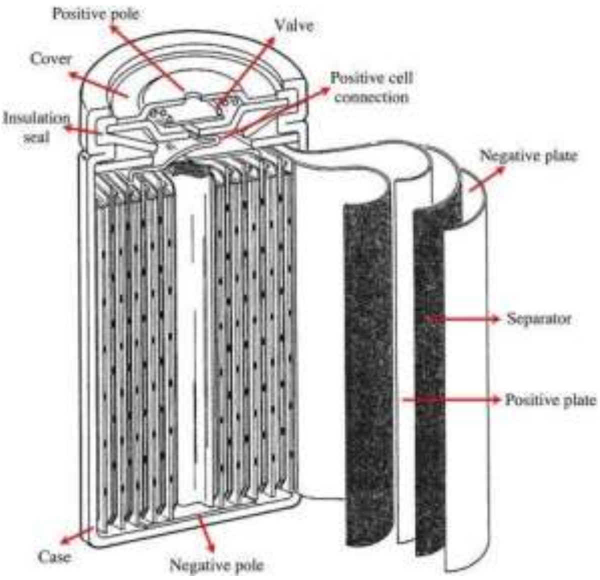
Ni-Cd batteries excel in high-discharge applications requiring reliability under extreme conditions. They power emergency lighting, backup systems, and critical aerospace/military equipment. Public transportation like aviation and railways uses them for engine starts and failover power.

Latest Developments

Recent research on Nickel–Cadmium batteries focuses mainly on environmental management, recycling technologies, and performance improvements. Scientists are developing improved recycling methods to recover valuable materials such as nickel and cadmium from used batteries, reducing environmental impact and supporting circular economy practices. Advanced electrode designs and improved separators are also being investigated to enhance cycle life and charging efficiency. Additionally, research is being conducted on reducing the memory effect and improving charge acceptance through better battery management systems. Although Ni-Cd technology is considered mature, these improvements help extend its use in critical applications such as aerospace systems, emergency power supplies, and industrial equipment. Ni-Cd is being upgraded in industrial backup systems, especially for critical power applications where long life and reliability matter more than energy density. There is also more focus on recycling and end-of-life handling because cadmium is hazardous and recovery helps reduce environmental impact.

xi. NICKEL-METAL HYDRIDE BATTERY

Overview



Nickel–Metal Hydride (Ni-MH) batteries are rechargeable electrochemical energy storage systems developed as an improvement over nickel–cadmium (Ni-Cd) batteries. In this battery, hydrogen is stored in a metal alloy at the negative electrode while nickel oxyhydroxide acts as the positive electrode material. Ni-MH batteries offer higher energy density, reduced toxicity, and improved environmental safety compared to Ni-Cd batteries. They are widely used in hybrid electric vehicles, consumer electronics, medical equipment, and renewable energy storage applications. Recent technological developments have improved the cycle life, energy density, and self-discharge characteristics of Ni-MH batteries, making them more reliable and efficient for modern energy storage systems.

Working principle

A Nickel–Metal Hydride battery works based on reversible electrochemical charge-discharge reactions that occur between a positive electrode cathode made of nickel oxyhydroxide and a negative electrode anode made of a hydrogen-absorbing alloy, usually a rare-earth based alloy. The electrodes are separated by a porous separator and immersed in an alkaline electrolyte, commonly potassium hydroxide, which helps ionic transport during operation. During discharge, hydrogen stored in the negative electrode is released and reacts at the positive electrode, producing electrical energy. During charging, the process is reversed, and hydrogen is absorbed back into the alloy electrode. This reversible process makes Ni-MH batteries suitable for repeated cycling in applications where durability matters more than compact size.

Chemical Reaction

$NiOOH + MH \rightleftharpoons Ni(OH)_2 + M$

Researching Universities / Institutions / Companies

India: Indian Institute of Technology Madras, Indian Institute of Science, Indian Institute of Technology Bombay, Indian Institute of Technology Delhi, Central Electrochemical Research Institute, National Institute of Technology Karnataka.

Asia: Tsinghua University, Peking University, University of Tokyo, Kyoto University, National University of Singapore, Seoul National University, Panasonic, Toyota, and other hybrid-vehicle supply-chain companies.

Europe: University of Cambridge, University of Oxford, Fraunhofer institutes, and battery recycling and materials companies working on hydrogen-absorbing alloys and separator improvements.

North America: Stanford University, Massachusetts Institute of Technology, University of California, Berkeley, and companies exploring advanced Ni-MH recycling and long-life storage systems.

Largest Acquired Capacity

Ni-MH batteries are still most strongly associated with hybrid vehicles rather than very large grid-scale lithium-style deployments. The market continues to grow because of hybrid vehicle demand, industrial backup use, and recycling-driven material recovery rather than because of very large single-battery installations. As of late 2024, the largest industrial implementations for Ni-MH have transitioned toward modular railway systems. For example, Panasonic has deployed modular Ni-MH storage systems for railway vehicles that offer maintenance-free operation over long lifecycles without the logistics restrictions associated with “dangerous goods” labeling.

Specific Capacity

The specific energy of Ni-MH batteries is typically around 60 to 120 Wh/kg, depending on cell design and application, with modern cells optimized more for durability and safety than for extreme energy density. This places them below most lithium-ion chemistries but still suitable for many hybrid and moderate-power uses.

Cost of Making

The production cost of a Nickel–Metal Hydride (Ni-MH) battery has generally stabilized around $250 to over $500 per kWh.

Space to Implement

Ni-MH batteries generally require more space than lithium-ion batteries for the same energy capacity because of their lower energy density. They are therefore better suited to hybrid vehicles, power tools, portable electronics, and industrial systems where a slightly larger battery pack is acceptable.

Hybrid Vehicle Packs: 0.5 - 1.2 m^3.

Industrial Modular Units: 1.5 - 3.0 m^3 per MWh (utilizing new stacked bipolar designs).

Positives and Challenges

The positives of nickel-metal hydride batteries include high reliability, good safety, wide temperature tolerance, long cycle life, and reduced toxicity compared with nickel-cadmium batteries. They also remain practical in hybrid electric vehicles because they can handle repeated charge-discharge cycling and high power demand.

The challenges of Ni-MH batteries include lower energy density than lithium-ion batteries, higher weight and volume for the same capacity, and gradual self-discharge in conventional cells. Another limitation is that raw material cost and supply for nickel and rare-earth alloy components can affect manufacturing economics.

Applications

Ni-MH batteries offer higher capacity than Ni-Cd with less toxicity, suiting consumer and industrial devices. Common in portable appliances like blood pressure monitors, flashlights, power tools, and hybrid vehicles. They also support solar lighting, toys, and electronics such as cameras and game consoles.

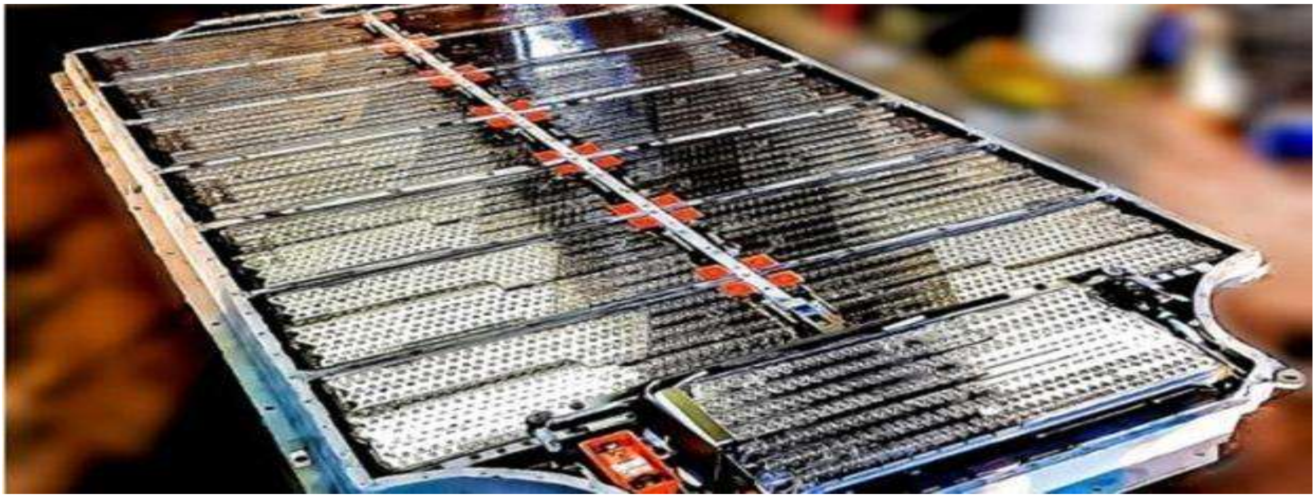
Latest Developments

Recent advancements in Ni-MH battery technology focus on improving performance and sustainability. The most important development in Ni-MH technology is the improvement of low-self-discharge and ultra-low-self-discharge cells, which can retain a much larger share of their charge during storage. New separator and electrode designs have improved stability, reduced self-discharge, and increased practical shelf life.

Another major development is the growing focus on recycling and circular manufacturing, especially recovery of nickel and rare-earth materials from end-of-life hybrid vehicle batteries. In the market, Ni-MH is still relevant in hybrid electric vehicles, backup power systems, and consumer electronics due to their safety, durability, and cost-effectiveness, and demand is supported by its mature supply chain, safety profile, and dependable performance in warm and cold climates.

xii. COBALT-FREE LITHIUM-ION BATTERY

Overview



Cobalt-free lithium-ion batteries are a type of lithium-ion battery that does not use cobalt in the cathode. Cobalt is a costly and environmentally harmful material, so the development of cobalt-free lithium-ion batteries is seen as a way to make lithium-ion batteries more affordable and sustainable.

Working Principle

Cobalt-free lithium-ion batteries are a type of lithium-ion battery that does not use cobalt in the cathode. Cobalt is a costly and environmentally harmful material, so the development of cobalt-free lithium-ion batteries is seen as a way to make lithium-ion batteries more affordable and sustainable.

Cobalt-free lithium-ion batteries work in the same way as traditional lithium-ion batteries. The cathode material reacts with the electrolyte to store lithium ions, which can then be released when the battery is discharged. The anode material is usually graphite, which provides a place for the lithium ions to go when they are released from the cathode.

The main difference between cobalt-free lithium-ion batteries and traditional lithium-ion batteries is the cathode material. Cobalt-free cathode materials are less expensive and environmentally harmful than cobalt, but they may not have the same performance characteristics.

Chemical Equation

$LiFePO_4 + LiC_6 \rightarrow Li_2FePO_4 + C_6Li_2FePO_4 + C_6 \rightarrow LiFePO_4 + LiC_6$

Researching Universities/Company

Africa: Research efforts in sustainable and cobalt-free battery materials are being carried out at Stellenbosch University, University of Cape Town, and University of Pretoria, with increasing focus on local mineral processing and battery material development.

Asia: Major contributions come from Tsinghua University, Peking University, University of Tokyo, Kyoto University, Seoul National University, Indian Institute of Technology Bombay, Indian Institute of Technology Delhi, and National University of Singapore. Industry leaders such as CATL, BYD, Samsung SDI, LG Chem, and Panasonic are actively developing cobalt-free chemistries such as LFP and next-generation cathodes.

Australia: Institutions such as University of Melbourne, University of Sydney, Queensland University of Technology, and RMIT University are advancing research in sustainable battery materials and cobalt-free alternatives.

Europe: Leading research is conducted at University of Cambridge, University of Oxford, Imperial College London, Karlsruhe Institute of Technology, Technical University of Munich, Paris-Saclay University, and University of Bordeaux. Additional major initiatives include Fraunhofer Society, Helmholtz Association, and Northvolt, which focus on sustainable and cobalt-free battery production.

North America: Key institutions include Stanford University, Massachusetts Institute of Technology, University of California Berkeley, University of California Los Angeles, University of Texas at Austin, Cornell University, University of Waterloo, and McGill University. Research is strongly supported by institutions such as Argonne National Laboratory and National Renewable Energy Laboratory. Companies like Tesla and QuantumScape are also exploring cobalt-free and next-generation battery chemistries.

South America: Research efforts are led by University of São Paulo, State University of Campinas, and University of Buenos Aires, with growing interest in sustainable battery materials and local resource utilization.

Largest Acquired Capacity

As of 2026, cobalt-free lithium-ion batteries primarily based on lithium iron phosphate (LFP) chemistry are widely deployed in large-scale energy storage systems. Several battery energy storage system (BESS) projects around the world now exceed 1–3 GWh (gigawatt-hours) in total capacity, particularly in the United States and China. Major deployments using LFP batteries have been led by companies such as CATL, BYD, and Tesla, with large installations like the Moss Landing energy storage facility in California reaching multi-GWh scale. These systems demonstrate that cobalt-free lithium-ion technology has become the dominant choice for grid-scale storage, due to its lower cost, improved safety, and long cycle life. Unlike earlier smaller projects in the hundreds of MWh range, current deployments reflect rapid scaling, with new installations increasingly designed for multi-gigawatt-hour capacity to support renewable energy integration and grid stability.

Specific Capacity

Researchers have reported specific energy capacities of up to 300 Wh/kg for cobalt-free lithium-ion batteries.

Cost for making

Current estimates place battery pack costs at approximately $80–100 per kWh (₹6,500–₹8,500 per kWh) under typical market conditions, with leading manufacturers such as CATL and BYD achieving even lower costs at scale. These reductions are driven by improvements in supply chains, cell-to-pack technologies, and widespread adoption of LFP chemistry. As a result, cobalt-free lithium-ion batteries are now among the most cost-effective energy storage solutions, widely used in electric vehicles and grid-scale applications.

Positives and Challenges

Positives:

- **Lower cost:** Cobalt-free lithium-ion batteries, especially lithium iron phosphate (LFP), are more cost-effective due to the elimination of expensive cobalt and reduced dependence on nickel, with current costs reaching $80–100 per kWh at scale.

- **More environmentally friendly:** These batteries are more sustainable as they avoid cobalt mining, which is associated with environmental degradation and ethical concerns, and instead use more abundant and less harmful materials such as iron and phosphate.
- **Improved safety:** Cobalt-free lithium-ion batteries (particularly LFP) are thermally stable and less prone to thermal runaway, making them safer for electric vehicles and large-scale energy storage systems.
- **Longer cycle life:** They offer excellent durability, often achieving 3,000–7,000+ charge cycles, which is significantly higher than many cobalt-based chemistries.
- **Good thermal and chemical stability:** These batteries perform reliably under a wider range of operating conditions, with better resistance to overheating and degradation.
- **Adequate energy density:** While generally lower than high-nickel cobalt-based batteries, modern cobalt-free lithium-ion batteries still provide sufficient energy density for most applications, especially in EVs and grid storage.

Challenges:

- **Lower energy density (compared to high-nickel chemistries):** Cobalt-free lithium-ion batteries, especially LFP, generally have lower energy density than cobalt-containing NMC/NCA batteries, which can limit driving range in high-performance electric vehicles.
- **Temperature sensitivity:** These batteries tend to show reduced performance in low-temperature conditions, affecting charging speed and efficiency in colder climates.
- **Higher internal resistance (in some designs):** Certain cobalt-free chemistries can exhibit higher internal resistance, which may impact power output and fast-charging performance, although improvements are ongoing.
- **Larger size and weight for same capacity:** Due to lower energy density, achieving the same energy storage often requires larger and heavier battery packs compared to cobalt-based alternatives.

- **Rapid scaling challenges:** Although now widely adopted, further scaling to meet global demand requires significant expansion of manufacturing capacity and supply chains.
- **Technology optimization still ongoing:** While commercially mature (especially LFP), continuous improvements are still needed in energy density, fast charging, and cold-weather performance to match or exceed high-nickel batteries.

Present Scenario

- Cobalt-free lithium-ion batteries, especially lithium iron phosphate (LFP), are now widely commercialized and rapidly growing in electric vehicles and energy storage systems.
- Major manufacturers such as CATL, BYD, and Tesla have adopted cobalt-free chemistries at large scale.
- These batteries are increasingly preferred due to their lower cost, improved safety, and long cycle life, making them dominant in grid-scale storage and entry-to-mid-range EV markets.
- Global production capacity for cobalt-free batteries has expanded significantly, particularly in Asia, supporting large-scale deployment of renewable energy systems.

Environmental Impact

- **Positive impact:** Cobalt-free lithium-ion batteries reduce environmental and ethical concerns by eliminating cobalt, which is associated with pollution, high water usage, and mining-related social issues.
- **Use of abundant materials:** These batteries rely on iron and phosphate, which are more abundant and environmentally friendly compared to cobalt and nickel.
- **Lower environmental risk:** Improved thermal stability reduces the risk of fires and hazardous incidents, making them safer for large-scale applications.
- **Recycling benefits:** Easier and safer recycling processes are possible, although large-scale recycling infrastructure is still developing globally.

- **Manufacturing impact:** While still energy-intensive, efforts to use renewable energy in production are helping reduce the overall carbon footprint.

Latest Developments

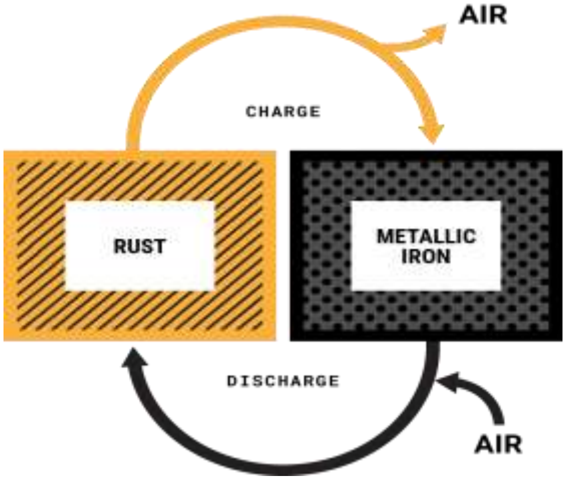
- **Energy density enhancement:** Ongoing research aims to improve energy density to better compete with high-nickel batteries while maintaining safety and cost advantages.
- **Advanced cell design:** Innovations such as cell-to-pack and cell-to-chassis technologies are improving space efficiency and performance.
- **Fast charging improvements:** Development of ultra-fast charging capabilities while maintaining battery life and safety.
- **Global expansion:** Continued scaling of production and supply chains to meet growing demand for EVs and renewable energy storage.
- **Recycling and circular economy:** Increasing focus on closed-loop recycling systems to recover materials and reduce environmental impact.

Overall, cobalt-free lithium-ion batteries offer several important advantages over cobalt-containing batteries, including lower cost, improved safety, longer cycle life (especially in LFP chemistry), and greater environmental sustainability due to the elimination of cobalt. These benefits have led to rapid adoption in electric vehicles and large-scale energy storage systems by companies such as CATL, BYD, and Tesla.

However, challenges remain, including lower energy density compared to high-nickel cobalt-based batteries, reduced performance in low temperatures, and the need for further improvements in fast-charging capabilities. Despite these limitations, cobalt-free lithium-ion batteries are no longer an emerging concept but a commercially mature and rapidly expanding technology. Ongoing research and industrial development are focused on enhancing energy density, improving performance, and optimizing manufacturing processes, and the technology is expected to play a central role in the future of sustainable energy storage.

xiii. IRON-AIR BATTERY

Overview



Iron-air batteries are a long-duration energy storage technology that uses iron, water, and oxygen from air to store and release electricity through a reversible rusting and de-rusting process. Iron–Air batteries are gaining significant attention in recent years because they use abundant, low-cost, and environmentally friendly materials. Unlike many other battery technologies, iron is widely available and inexpensive, making Iron–Air batteries suitable for large-scale and long-duration energy storage applications, especially for renewable energy systems such as wind and solar power. Due to their potential for very low cost and long-duration energy storage, Iron–Air batteries are being actively researched and developed for grid-scale energy storage (100-hour batteries), especially where energy needs to be delivered for many hours or even multiple days, rather than for portable devices.

Working Principle

Iron–Air battery is a type of metal–air electrochemical energy storage system that operates based on the reversible oxidation of iron in the presence of oxygen from the air. During discharge, iron reacts with oxygen and water in the electrolyte to produce iron hydroxide while releasing electrons that generate electrical energy. During charging, the reverse reaction occurs, converting iron hydroxide back into metallic iron.

Chemical Reactions

$2Fe + O_2 + 2H_2O \rightleftharpoons 2Fe(OH)_2$

Researching Universities/Institutions/Companies

India: Indian Institute of Technology Madras, Indian Institute of Science, and grid-storage research groups working on long-duration storage integration.

North America: Form Energy, Google, Xcel Energy, and utility partners developing multi-day storage projects in the United States.

Europe: Delft University of Technology and FuturEnergy Ireland, involved in the first international iron-air project announcement.

Other research groups: universities and labs studying corrosion control, electrode design, and multi-day storage economics.

Largest Acquired Capacity

A major 2024 milestone was the commissioning of the first commercial 100-hour system at a Georgia Power site. Furthermore, in early 2025, Google committed approximately $1 billion for a massive 30 GWh system to power its data centers. Another landmark project in Lincoln, Maine, is currently under construction (planned for 2028) which aims to be the largest battery installation in the world by energy capacity at 8,500 MWh.

Specific Capacity

Iron-air batteries are designed for very long duration storage, with commercial targets of about 100 hours of discharge at full power. Their specific energy is not the main selling point; instead, the focus is on low cost per stored kilowatt-hour and long duration. Theoretical energy density is high (700 – 1,200 Wh/kg), but practical system-level density is lower (200 – 400 Wh/kg) due to the heavy iron and aqueous electrolyte.

Cost of Making

Iron-air batteries are being developed as an ultra-low-cost storage option using abundant materials such as iron, water, and air. Iron-air batteries are designed for long-duration grid storage, aiming for a production cost of around $20/kWh (technology target), which is roughly 1/10th the cost of lithium-ion batteries. While some estimations place initial manufacturing costs between $120-$150/kWh, the technology utilizes cheap, abundant materials (iron, air, water), positioning it as a highly cost-effective solution for grid energy.

Space to Implement

Iron-air battery systems are extremely heavy and require significant land because they are built for stationary, large-scale installations and long duration rather than compactness. They are therefore best suited for utility substations, renewable energy farms, and data-center support sites with large available land or building area.

Standard Module: A 10-module product building block is roughly 9.5' x 8' x 40' (similar to a shipping container).

Utility Scale: Approximately 0.5 acres of land is required per Megawatt (MW) of power capacity due to the size of the water treatment and electrolyte management systems.

Positives and Challenges

The positives of iron-air batteries include very low material cost, long-duration energy storage (multi-day storage), non-flammable electrolyte, zero risk of thermal runaway, and suitability for multi-day grid backup, round-Trip Efficiency (RTE) is approximately 40–60%. They also use widely available materials, which reduces supply-chain pressure compared with lithium-based systems.

The challenges of iron-air batteries include low power density, large physical size, slower charge and discharge behavior, lower round-trip efficiency and the technology is still in the development and early commercialization stage. Another challenge is that the system is mainly useful for fixed grid applications and not for transport or portable electronics.

Applications

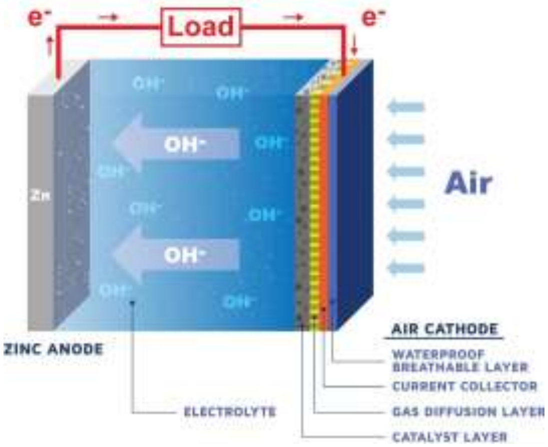
Iron-Air batteries provide long-duration, low-cost storage using abundant materials like iron and air. Key for grid stabilization, renewable energy storage from solar/wind, and backup power. They suit remote communities and potentially electric vehicles for extended range.

Latest Developments

Recent research and technological developments have focused on improving the performance, efficiency, and durability of Iron–Air batteries. Researchers are developing advanced air electrodes and catalysts to improve oxygen reduction and oxygen evolution reactions, which are critical for battery efficiency. The most important recent development is the move from pilot demonstrations to major commercial announcements. In 2026, Form Energy and FuturEnergy Ireland announced the first overseas multi-day iron-air project, showing that the technology is now spreading beyond the United States. Another major development is the announcement of very large grid-scale systems, including the 300 MW/30 GWh Google-Xcel project in Minnesota. In addition, the first grid-connected iron-air battery in Europe was reported in 2025 at Delft University of Technology, which marked a key step in proving the technology in real grid conditions.

xiv. ZINC-AIR BATTERY

Overview



Zinc–Air batteries are a type of metal–air electrochemical battery that uses zinc as the anode and oxygen from the air as the cathode reactant. Unlike conventional batteries that store both reactants internally, Zinc–Air batteries use oxygen from the surrounding air, which significantly reduces the weight and increases the energy density of the battery. These batteries are widely used in hearing aids, medical devices, small electronics, and backup power systems due to their high energy density and relatively low cost. In recent years, Zinc–Air batteries have gained attention as a potential technology for large-scale energy storage and electric vehicle applications because zinc is abundant, inexpensive, and environmentally friendly.

Working Principle

The operation of a Zinc–Air battery is based on electrochemical reactions between zinc metal and oxygen from the air in the presence of an alkaline electrolyte, typically potassium hydroxide (KOH). During discharge, zinc is oxidized at the anode, releasing electrons, while oxygen from the air is reduced at the cathode. These reactions generate electrical energy that can be used to power devices. In rechargeable zinc-air batteries, the reaction is reversed during charging, allowing zinc to be regenerated.

Chemical Reactions

$2Zn + O_2 \rightleftharpoons 2ZnO$

Researching Universities/Institutions/Companies

India: Indian Institute of Technology Madras, Indian Institute of Science, and battery research groups working on low-cost stationary storage.

Europe: ZSW, Sunergy partners, ANR-supported research groups, and European universities developing rechargeable zinc-air prototypes.

North America: e-Zinc, Zinc8 Energy Solutions, and utility-linked demonstration projects for behind-the-meter storage and renewables integration.

Asia: Research teams in China, Japan, and South Korea working on catalysts, electrolytes, and cycle-life improvement.

Largest Acquired Capacity

Zinc-air systems are mostly in demonstration and niche commercial use, being proposed for grid and commercial storage, with one example being a planned 40 kW system supporting a 1 MW solar array. Another commercial direction is long-duration storage projects designed for 8 hours or more, and some companies report targets around 20,000 hours of operating life.

Specific Capacity

Zinc-air batteries have a very high theoretical energy density which exceeds 1,000 Wh/kg and 300 to 400 Wh/kg (Practical).

Cost of Making

Zinc-air batteries are highly cost-competitive, with manufacturing costs already reported as low as US$100 per kWh, and some projections for large-scale utility systems aiming for as low as $45/kWh (future target).

Space to Implement

Zinc-air batteries generally need more space than lithium-ion batteries for the same practical storage capacity, especially in stationary systems. They are therefore best suited for residential backup, commercial buildings, microgrids, and renewable energy storage where area is available.

Utility Scale: Approximately 0.4 to 0.7 acres per MW for long-duration storage.

Containerized Solutions: Standard 20ft or 40ft containers are used for modular grid-edge support.

Positives and Challenges

The positives of zinc-air batteries include high energy density, low material cost, good safety, and environmental friendliness due to abundant zinc. They are also promising for long-duration stationary storage and backup applications.

The challenges of zinc-air batteries include limited rechargeability in many designs, dendrite growth on the zinc anode, drying or flooding of the air electrode, sensitivity to environmental conditions, and performance is affected by humidity (risk of drying out or flooding) and CO_2 (forming carbonates in the electrolyte). These issues still make cycle life and charging efficiency the main barriers to large-scale adoption.

Applications

Zinc-Air batteries deliver high energy density, often in primary (non-rechargeable) forms for small devices. Widely used in hearing aids, watches, calculators, and cameras replacing mercury cells. Larger versions target electric vehicles, grid storage, and remote warning lights.

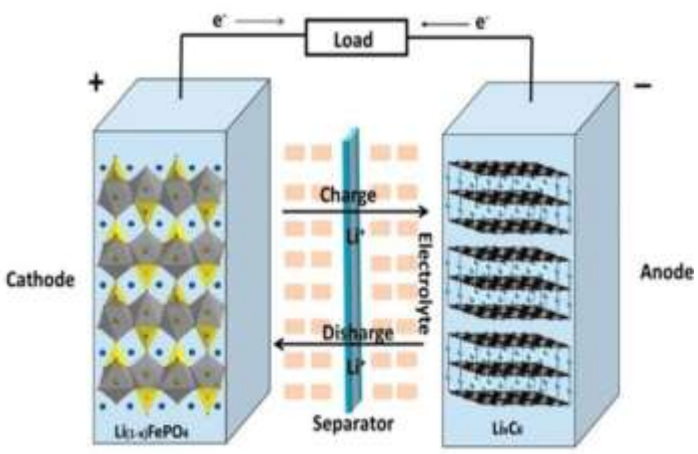
Latest Developments

Recent research focused on improving the efficiency, rechargeability, and durability of Zinc–Air batteries. Scientists are developing advanced air cathode catalysts to improve oxygen reduction and oxygen evolution reactions, which are essential for rechargeable systems. The most important recent development is the move toward rechargeable zinc-air systems for stationary energy storage and renewable integration. The EU-funded HIPERZAB project and the ZABAT project are both focused on improving cyclability, sustainability, and life-cycle cost for grid and residential use.

Nanostructured electrode materials and improved electrolyte formulations are also being studied to enhance cycle life and energy efficiency. Researchers are exploring solid-state and hybrid Zinc–Air battery systems that reduce electrolyte leakage and improve stability. In addition, several companies and research institutions are investigating the use of Zinc–Air batteries for large-scale renewable energy storage and electric mobility applications, which could significantly expand the role of this technology in future energy systems.

xv. LITHIUM IRON PHOSPHATE BATTERY

Overview



Lithium Iron Phosphate, commonly known as LFP, is one of the most commercially mature and widely used battery chemistries in the world today. It has gained strong acceptance in stationary energy storage systems and mainstream electric vehicles due to its excellent safety, long life cycle, and lower material cost. Compared with many other lithium-ion chemistries, LFP is known for being highly stable and reliable, making it a preferred choice for large-scale and long-term applications.

Working Principle

The battery operates through the movement of lithium ions between the cathode and anode during charging and discharging cycles. During discharge, lithium ions move from the lithium iron phosphate cathode to the anode, releasing electrical energy. During charging, the ions return to the cathode. The strong phosphate bond structure of the cathode remains highly stable throughout this process, which reduces degradation and improves battery durability over time.

Chemical Reaction

$$Li_xC_6 + FePO_4 \rightleftharpoons C_6 + LiFePO_4$$

Largest Acquired Capacity

LFP batteries are widely used in utility-scale energy storage projects. One major example is the Moss Landing Energy Storage Facility in California, which has a capacity of around 300 MW / 1.2 GWh. China also leads global deployment, with cumulative battery energy storage installations exceeding 100 GWh, much of which uses LFP chemistry due to its affordability and safety.

Specific Capacity

LFP batteries generally operate at a nominal voltage of about 3.2 volts per cell. Their specific energy typically ranges between 90 and 160 Wh/kg depending on design and application. With modern improvements, some advanced cells can now achieve values close to 210 Wh/kg, making them increasingly competitive in the energy storage market.

Space Needed

LFP batteries offer moderate energy density, so they require more space compared to high-density chemistries such as NMC. At the system level, energy density may range around 15–20 kWh per square meter. A standard 20-foot battery container can typically deliver around 5–7 MWh of storage capacity, depending on design configuration.

Energy Storage Cost

One of the strongest advantages of LFP technology is its cost-effectiveness. Battery pack prices are generally below $60 per kWh in some markets, making them significantly cheaper than many NMC equivalents. This lower cost has made LFP highly attractive for grid-scale storage, commercial systems, and affordable electric vehicles.

Advantages

LFP batteries provide excellent cycle life, often exceeding 2,000 to 6,000 charge-discharge cycles while maintaining high-capacity retention. They are highly stable even at elevated temperatures, with very low risk of thermal runaway. The chemistry uses abundant and lower-cost materials such as iron and phosphate, making it environmentally and economically favorable. LFP is also widely suitable for stationary storage systems and commercial EV applications.

Challenges

Despite many benefits, LFP batteries have certain limitations. Their lower nominal voltage of around 3.2 V reduces gravimetric energy density compared to some alternatives. They may also experience weaker performance in low-temperature environments. In addition, they are generally heavier per kWh than NMC or NCA battery chemistries, which can be a drawback where weight and compactness are critical.

xvi. Lithium Nickel Manganese Cobalt Oxide Battery

Overview

Lithium Nickel Manganese Cobalt Oxide, commonly known as NMC, is one of the most widely used lithium-ion battery chemistries, especially in electric vehicles. It is highly valued for its excellent balance of energy density, power capability, and operational versatility. Because it combines multiple performance strengths in one chemistry, NMC has become a preferred option for EV manufacturers, portable electronics, power tools, and even some grid-scale storage systems.

Working Principle

The NMC battery uses a cathode made from a blend of nickel, manganese, and cobalt, where each material contributes a specific benefit. Nickel increases energy density, manganese improves structural stability, and cobalt enhances conductivity and performance. These materials can be mixed in different ratios, such as NMC 811, which contains 80% nickel. During charging and discharging, lithium ions move between the graphite anode and the NMC cathode through an electrolyte, generating and storing electrical energy efficiently.

Current Research

Recent research in NMC technology is focused on increasing capacity while reducing dependence on expensive cobalt. High-nickel NMC variants such as NMC 9-series are being developed to achieve energy densities above 300 Wh/kg. Researchers are also working on single-crystal cathodes to improve cycle life and reduce cracking during repeated charging. Another major area of development is combining NMC with solid-state electrolytes to enhance safety and future performance.

Largest Capacity Installations

NMC chemistry dominates a significant portion of the global electric vehicle battery market and is used by many major automotive manufacturers. Large-scale production facilities operated by leading companies such as CATL, LG Energy Solution, Panasonic, and Samsung SDI manufacture NMC batteries in gigawatt-hour quantities annually. This chemistry continues to power millions of EVs worldwide and remains central to the expanding lithium-ion battery industry.

Specific Capacity

NMC batteries typically operate at a nominal voltage of around 3.6 to 3.7 volts per cell. Their specific energy usually ranges from 150 to 260 Wh/kg depending on composition and design. Advanced cells from premium manufacturers can reach around 350 Wh/kg, making NMC one of the highest energy-density mainstream battery chemistries available today.

Space Needed

One of the major strengths of NMC batteries is their compact design. They offer high volumetric energy density, allowing more energy to be stored in smaller physical space. This makes them ideal for electric vehicles and portable devices where size and weight are important design constraints.

Energy Storage Cost

NMC battery costs have reduced significantly with mass production and technology improvements. Cell-level costs in recent years have approached around $100 per kWh depending on nickel, cobalt, and lithium market prices. However, fluctuations in raw material costs can still influence final battery pricing.

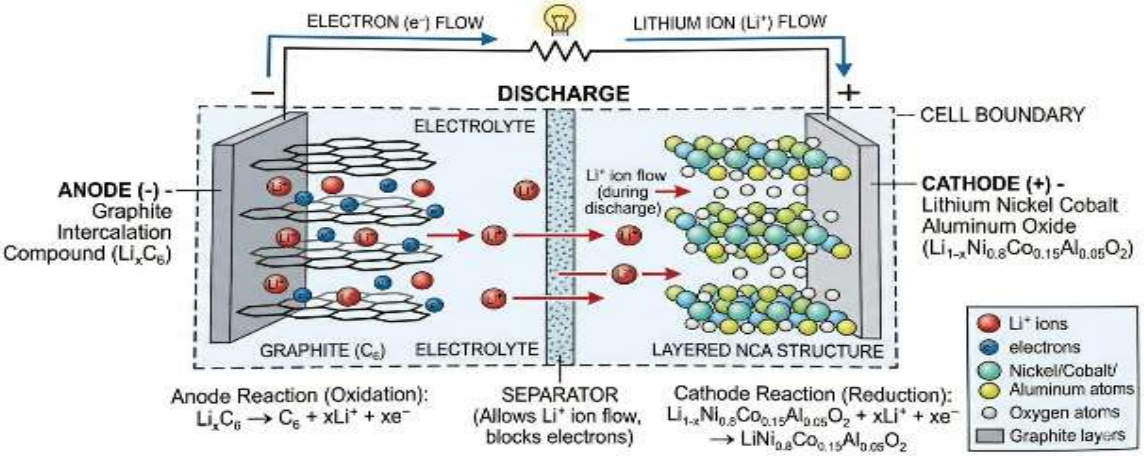
Advantages

NMC batteries are considered strong all-round performers because they balance high energy density, strong power output, and reasonable lifespan. They typically provide around 1,000 to 3,000 charge cycles depending on nickel content and usage conditions. They are available in multiple form factors such as cylindrical, prismatic, and pouch cells.

Their mature global supply chain and proven performance have made them a leading battery chemistry for EVs and commercial applications.

xvii. LITHIUM NICKEL COBALT AIUMINIUM OXIDE BATTERY

Overview



A high-energy-density lithium chemistry famously used by Tesla. Aluminum substitutes for manganese, providing structural stability, while high nickel content delivers superior energy density.

Working Principle

Lithium ions intercalate into the NCA cathode. Aluminum (typically ~5%) stabilises the lattice without contributing to capacity. High nickel content (typically 80%+) enables ~200 mAh/g specific capacity. Graphite anode in liquid organic electrolyte.

Chemical Reaction

$$Ni_{0.8}Co_{0.15}Al_{0.05}O_2 + C_6 \rightleftharpoons Li_{1-x}Ni_{0.8}Co_{0.15}Al_{0.05}O_2 + Li_xC_6$$

Current Research

Dry-electrode manufacturing to cut costs; reducing cobalt to near-zero (NCMA variants); single-crystal NCA for longer cycle life; coating strategies to reduce surface reactivity.

Largest Acquired Capacity

Tesla's gigafactories collectively represent the world's largest NCA deployment, powering Model S/X vehicles. Panasonic's new Kansas gigafactory (32 GWh/yr, opened July 2025) produces NCA cells.

Specific Capacity

~3.65 V nominal; 200–260 Wh/kg; theoretical specific capacity ~200 mAh/g. Space Needed Excellent — among the best energy-to-volume ratios available commercially.

Energy Storage Cost

~$90–110/kWh at cell level; cobalt dependency maintains elevated pricing.

Advantages

Highest practical energy density among commercial chemistries Excellent for weight-sensitive applications (aerospace, drones, premium EVs) Good high-rate discharge performance Mature manufacturing base (Panasonic, Samsung SDI) Challenges Chemically more volatile than NMC — requires robust cooling systems Shorter cycle life than NMC (500–1,500 cycles typically) Highly dependent on cobalt and nickel supply chains Thermal runaway risk if poorly managed.

Challenges

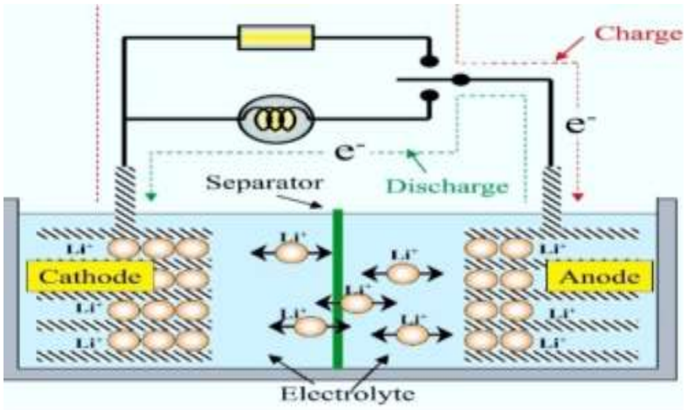
- Chemically more volatile than NMC requires robust cooling systems
- Shorter cycle life than NMC (500–1,500 cycles typically)
- Highly dependent on cobalt and nickel supply chains
- Thermal runaway risk if poorly managed

xviii. LITHIUM TITANATE BATTERY

Overview

A lithium-ion variant replacing the graphite anode with LiTi ion Trades energy density for extreme safety, ultralong cycle life, and ultrafast charging the endurance champion of lithium batteries.

Working Principle



Lithium titanate anode has a zero-strain crystal structure that prevents dendrite formation and eliminates SEI layer growth. This fundamental change enables extreme charge/discharge rates and exceptional longevity, though at the cost of lower voltage (~2.4 V) and energy density.

Overall Reaction

$$Li_4Ti_5O_{12} + 3LiCoO_2 \rightleftharpoons Li_7Ti_5O_{12} + 3Li_{0.67}CoO_2$$

Current Research

Nanostructured LTO anodes for improved rate capability; hybrid LTO/supercapacitor systems; applications in ultrafast-charging bus and rail networks; space power systems.

Largest Capacity

Toshiba's SCiB cells power multiple urban rail systems globally. Grid-scale LTO installations exist in Japan and China for frequency regulation.

Specific Capacity

~2.4 V nominal; 50–80 Wh/kg significantly lower than other lithium chemistries.

Energy Storage Cost

~$300–600/kWh — among the most expensive per kWh due to titanate material costs.

Advantages

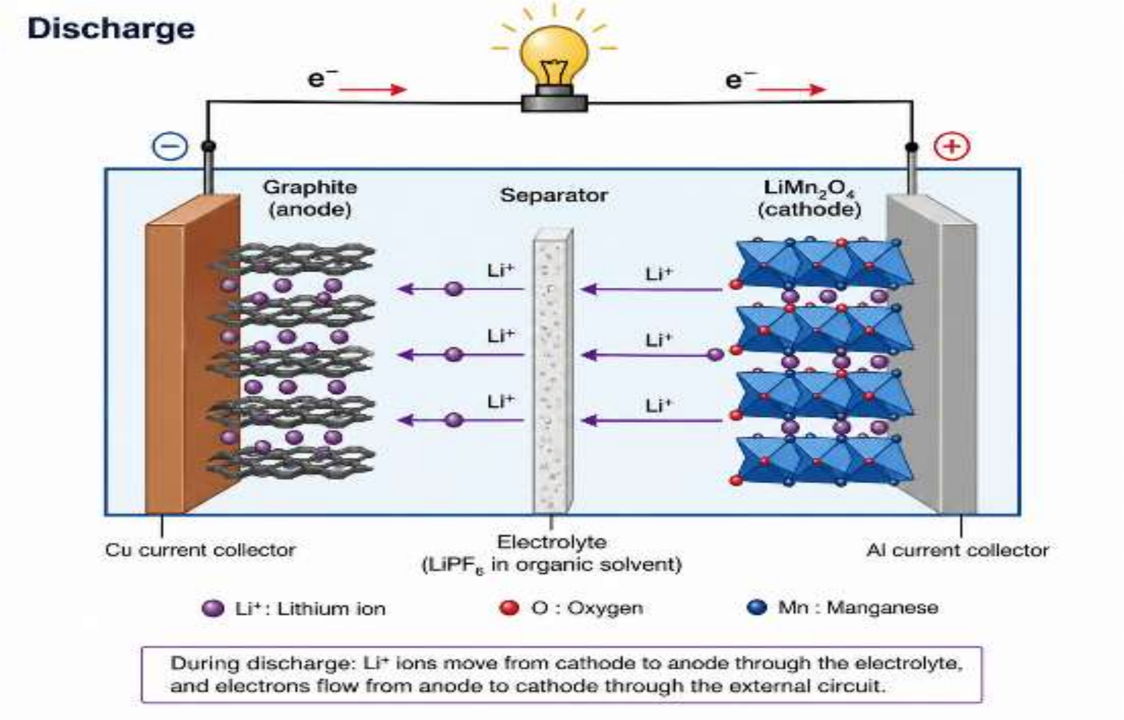
- 20,000+ full depth-of-discharge cycles with minimal fade
- Full charge in 5–15 minutes without risk
- Stable performance from −40°C to +60°C
- Inherently non-combustible -no thermal runaway even under abuse
- 15+ year operational lifespan in demanding applications

Challenges

- Very low energy density (50–80 Wh/kg) limits range/portability
- Very high cost per kWh prohibits mass-market deployment
- Lower nominal voltage reduces pack efficiency
- Limited large-scale commercial availability outside Japan

xix. LITHIUM MANGANESE OXIDE BATTERY

Overview



During discharge: Li⁺ ions move from cathode to anode through the electrolyte, and electrons flow from anode to cathode through the external circuit.

An early lithium-ion chemistry with a spinel crystal structure. Still relevant in power tools, medical devices, hybrid vehicles, and as a blending component with NMC.

Working Principle

$LiMn_2O_4$ adopts a cubic spinel lattice allowing three-dimensional lithium-ion diffusion. Manganese is inexpensive and non-toxic. Lithium inserts into/extracts from the spinel at ~4 V. Commonly blended with NMC to improve power delivery.

Chemical Reaction

$$LiMn_2O_4 + C_6 \rightleftharpoons Li_{1-x}Mn_2O_4 + Li_xC_6$$

Current Research

LMO is rarely pursued alone. Research focuses on NMC/LMO blends for improved power, Li-rich layered LMO derivatives for higher capacity, and Mn dissolution suppression via coatings and doping.

Largest Capacity

Used in early Nissan Leaf generations and numerous hybrid vehicles. Blended NMC/LMO packs are widespread in EVs. No significant standalone grid installations.

Specific Capacity ~4.0 V nominal; 100–150 Wh/kg; practical capacity ~100–120 mAh/g.

Space Needed

Moderate similar footprint to LFP per kWh. Energy Storage Cost ~$150–250/kWh; manganese is very cheap but overall system costs are moderate.

Advantages

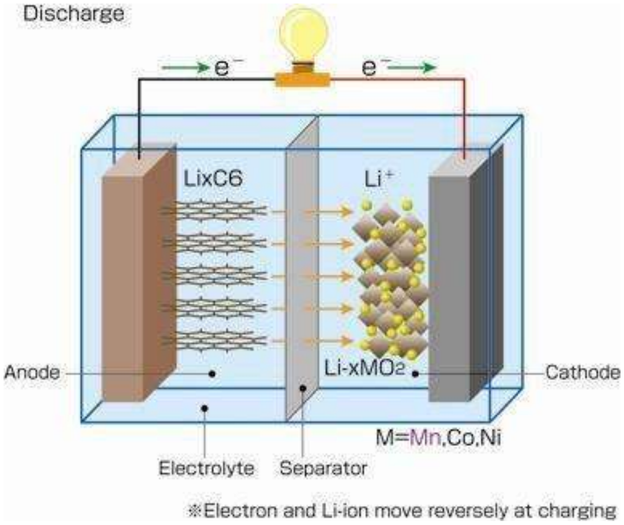
- High power output good rate capability for bursts
- Thermally more stable than NMC
- Uses low-cost, abundant manganese (~$2/kg)
- Simple cubic spinel structure is well understood
- Good safety profile in normal use conditions

Challenges

- Mn^{3}disproportionation causes capacity fade, especially at elevated temperatures
- Relatively poor cycle life (500–1,000 cycles)
- Manganese dissolution into electrolyte degrades performance over time
- Not suitable as sole chemistry for demanding long-cycle applications.

xx. NICKEL ZINC BATTERY

Overview



A rechargeable alkaline chemistry offering higher voltage and energy density than NiCd, using environmentally friendly, abundant materials. Bridging the gap between lead-acid and lithium.

Working Principle

Nickel oxyhydroxide cathode and zinc anode in potassium hydroxide electrolyte. Cell voltage ~1.6–1.8 V. During discharge, zinc oxidises at the anode while NiOOH reduces to $Ni(OH)_2$ at the cathode.

Chemical Reaction

$$\boldsymbol{Zn + 2NiOOH + 2H_2O \rightleftharpoons Zn(OH)_2 + 2Ni(OH)_2}$$

Current Research

Zinc morphology control to suppress dendrite growth; advanced separators to prevent zinc migration; improved cycle life for consumer and industrial EV applications. Companies like ZAF Energy Systems are commercialising NiZn for heavy industry.

Largest Capacity

Limited large-scale deployments; primarily specialty vehicles, UPS, military, and data centre backup. No GWh-scale grid installations. Specific Capacity ~1.6 V nominal; 60–90 Wh/kg at cell level; moderate power density. Space Needed Moderate — better than lead-acid, not competitive with lithium on volumetric energy density.

Energy Storage Cost

~$150–300/kWh; relatively low material cost but manufacturing adds expense.

Advantages

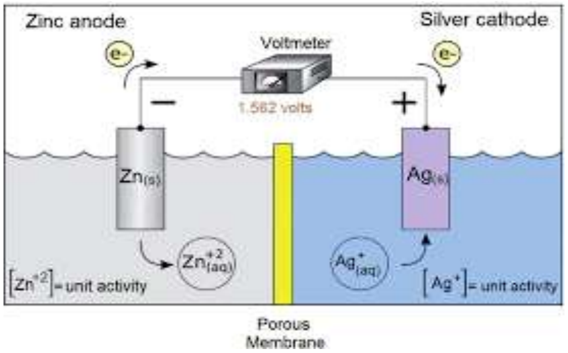
- Memory effect causes voltage depression over repeated cycling
- Zinc dendrite formation limits cycle life (200–400 cycles typically)
- Zinc anode shape change degrades performance over time
- Sensitive to overcharge; requires precise charge control

Challenges

- Memory effect causes voltage depression over repeated cycling
- Zinc dendrite formation limits cycle life (200–400 cycles typically)
- Zinc anode shape change degrades performance over time
- Sensitive to overcharge; requires precise charge control

xxi. SILVER ZINC BATTERY

Overview



A very high-energy-density primary or rechargeable battery used in niche high-performance applications where cost is secondary to performance and safety.

Working Principle

Silver oxide (Ag_2O or AgO) cathode reacts with a zinc anode in potassium hydroxide electrolyte. High cell voltage (~1.55 V) and exceptional gravimetric energy density. Silver provides an extremely stable, high-capacity cathode.

Overall reaction

$$\boldsymbol{Zn + AgO + H_2O \rightleftharpoons Zn(OH)_2 + Ag}$$

Current Research

Solid-state electrolytes for ultra-high energy density; silicon-dominant anodes; ZPower developing rechargeable AgZn for wearables and hearing aids; research into silver recovery and recycling. Largest Capacity No large-scale grid installations due to silver cost. Primary use in aerospace (spacecraft), submarines, torpedoes, and high-performance drones.

Specific Capacity

~1.55 V nominal; 100–200 Wh/kg (rechargeable); one of the highest practical energy densities among aqueous batteries.

Space Needed

Very compact for the energy delivered; widely used where volume is critical.

Energy Storage

Cost Extremely high $1,000–10,000/kWh depending on application; driven by silver prices (~$800+/kg).

Advantage

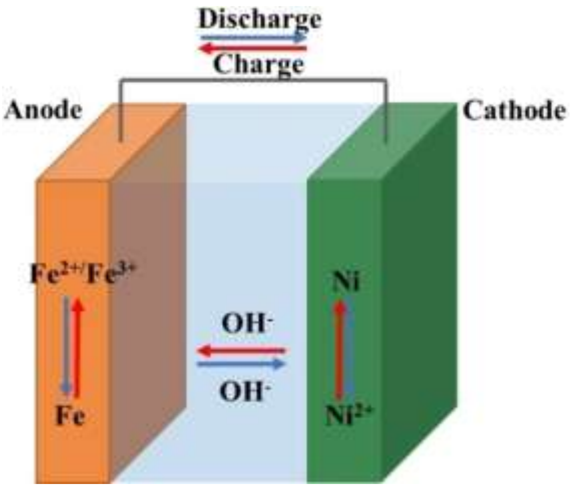
- Exceptional practical energy density
- Very flat discharge voltage profile
- Safe — aqueous chemistry, no thermal runaway risk
- Biocompatible — used in medical implants and devices
- Mission-critical reliability in aerospace and defense

Challenges

- Prohibitively high cost for mass-market applications
- Silver is rare and expensive
- subject to price volatility
- Rechargeable versions have very limited cycle life (50–200 cycles)
- Silver migration and dendrite formation degrade performance
- Not economically recyclable at commercial scale

xxii. NICKEL IRON BATTERY

Overview



One of the oldest rechargeable batteries, invented by Thomas Edison in 1901. Extraordinary durability and resilience — virtually indestructible, with lifespans of 30+ years.

Working Principle

Nickel oxyhydroxide cathode and iron anode inpotassium hydroxide electrolyte. Cell voltage ~1.2 V.Extremely tolerant to abuse overcharge, over-discharge, and physical damage cause no permanent damage to the cell chemistry.

Overall Cell reaction

$$Fe + 2NiOOH + 2H_2O \rightleftharpoons Fe(OH)_2 + 2Ni(OH)_2$$

Current Research

Improved electrolyte additives to reduce hydrogen gassing; nanostructured iron electrodes for better rate performance; renewed interest for off-grid solar storage where multi-decade life justifies high initial cost. Largest Capacity

Niche market — used historically in mining vehicles and railways. Modern companies like Iron Edison supply NiFe systems for off-grid homes and remote installations.

Specific Capacity

~1.2 V nominal; 30–50 Wh/kg — very low, among the poorest of rechargeable chemistries.

Space Needed

Very poor energy density requires roughly 3–5× more space than LFP per kWh.

Energy Storage Cost

~$400–800/kWh upfront; with 20–30+ year lifespans, levelised cost can be competitive.

Advantages

- Can last 30+ years with proper maintenance
- Tolerates deep discharge and neglect without permanent damage
- Made from abundant, non-toxic materials (nickel, iron)
- No permanent capacity loss from abuse cycling
- Very environmentally benign end-of-life

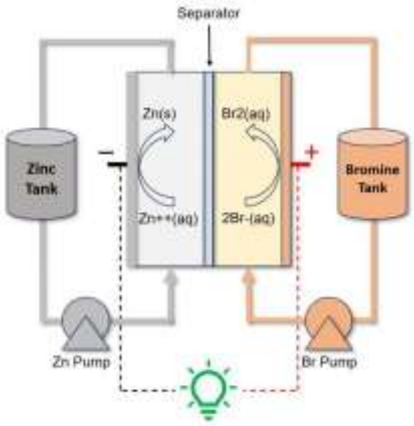
Challenges

- Very low energy density (30–50 Wh/kg)
- High self-discharge rate (~20–30% per month)
- Significant hydrogen gassing during charging — ventilation required

- Poor round-trip efficiency (~65–75%)
- Slow charging rate; high upfront cost

xxiii. ZINC BROMINE BATTERY

Overview



A hybrid flow battery storing energy in a liquid zinc bromide electrolyte solution. Power and energy can be independently scaled — attractive for medium- to large-scale stationary storage.

Working Principle

Zinc bromide aqueous solutions serve as both catholyte and anolyte. During charging, zinc plates onto the negative carbon electrode; bromine forms at the positive electrode and is complexed with organic agents to reduce vapour pressure. Discharge reverses the reaction. Current Research Improving bromine complexing agents to reduce toxicity and vapour pressure; better membrane materials; Primus Power continues commercial development. Focus on improved reliability and cost reduction

Overall Reaction

$$\boldsymbol{Zn + Br_2 \rightleftharpoons ZnBr_2}$$

Largest Capacity

Primus Power offers systems up to 25 kW/125 kWh. Grid-scale deployments remain limited compared to vanadium flow batteries.

Specific Capacity

~1.8 V nominal; 60–80 Wh/L electrolyte; system-level ~30–50 Wh/kg. Space needed is more compact than vanadium flow batteries but still requires substantial tank and pump infrastructure.

Energy Storage Cost

~$200–400/kWh at system level; moderate electrolyte cost but bromine handling adds safety infrastructure expense.

Advantages

- Scalable — energy and power independently sized
- Long theoretical cycle life (>2,000 cycles)
- 100% depth of discharge possible
- Bromine and zinc are low-cost abundant materials can be fully discharged for safe transport and storage

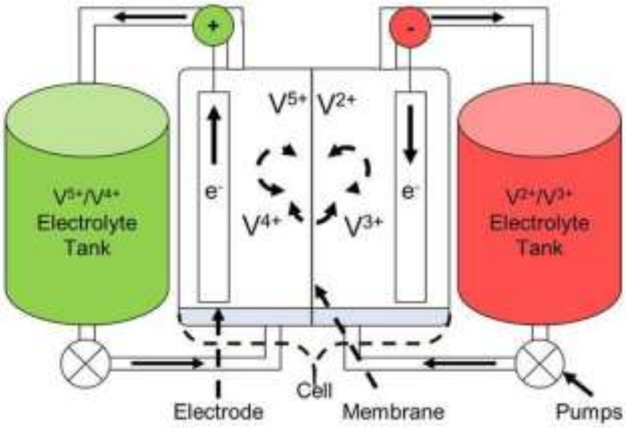
Challenges

Bromine is highly toxic, corrosive, and volatile — safety concerns

- Zinc dendrite formation limits long-term reliability
- Moderate round-trip efficiency (70–80%)
- Complex system management with pumps, membranes,
- Commercial deployment challenged — Redflow entered administration in 2024

xxiv. VANADIUM REDOX BATTERY

Overview



The most commercially mature flow battery chemistry, using vanadium ions in four oxidation states. The leading choice for long-duration grid storage where safety and longevity outweigh energy density.

Working principle

The V^{2+}/V^{3+} pair acts as the negative electrode; the V^{5+}/V^{4+} pair as the positive electrode. Both sides use vanadium, eliminating cross-contamination concerns. Electrolyte flows from external tanks through a cell stack where electrochemical reactions occur.

Chemical Reaction

$$\boldsymbol{V_2 + +VO_2 + \; + 2H + \rightleftharpoons V_3 + +VO_2 + +H_2O}$$

Current Research

Mixed-acid (sulfate/chloride) electrolytes to increase vanadium solubility and temperature range; organic flow battery alternatives to reduce costs; advanced electrode surface treatments; all-vanadium bipolar plate improvements.

Largest Capacity

A 175 MW / 700 MWh vanadium redox flow battery opened in China in 2024 — the world's largest flow battery installation.

Specific Capacity

~1.2 V nominal per cell; 25 Wh/L electrolyte; system-level ~15–25 Wh/kg. Space Needed Large footprint — approximately 15 kWh/m^2 vs 34 kWh/m^2 for lithium-ion at system level.

Energy Storage Cost

~$300–600/kWh currently; projected LCOS for 10-hr, 100 MW systems is ~$0.16/kWh.

Advantages

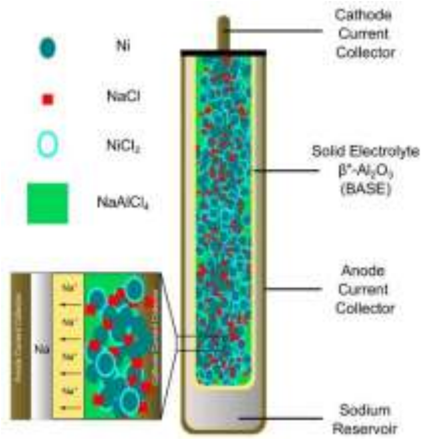
- 12,000–20,000+ charge cycles — effectively unlimited with electrolyte refresh
- Zero fire risk — fully aqueous, non-flammable chemistry
- Energy and power independently scalable by design
- Near-indefinite electrolyte life — vanadium never degrades
- Excellent for 4–12 hour grid storage applications

Challenges

- V_2O_2 costs >$30/kg — price volatility affects project economics
- Round-trip efficiency 75–85% — lower than lithium-ion
- Very large space requirements — not suitable for urban dense installations
- Complex pumping, membrane, and thermal management systems
- Vanadium precipitation at extreme temperatures without additives

xxv. SODIUM NICKEL CHLORIDE BATTERY

Overview



A molten salt battery based on common table salt and nickel. Known as the ZEBRA battery (Zeolite Battery Research Africa), developed in South Africa from 1985. High voltage and good energy density from earth-abundant materials.

Working Principle

Operates at 270–350°C. Sodium metal anode and $NiCl_2$ cathode are separated by a beta-alumina ceramic electrolyte. During discharge, sodium oxidises to Na_2, forming NaCl; $NiCl_2$ reduces to metallic Ni. Liquid $NaAlCl_2$ (secondary electrolyte) fills pores in the cathode.

Overall Chemical reaction

$$2Na + NiCl_2 \rightleftharpoons Ni + 2NaCl$$

Current Research

Lowering operating temperature with new electrolyte formulations; iron-doped cathodes (Na-$NiCl_2$/$FeCl_2$) for higher power density; intermediate-temperature designs at 150–200°C; planar cell geometries for better scalability.

Largest Capacity

The sole commercial manufacturer is FZSoNick (Switzerland). Installations in telecom backup, grid storage, and some EV applications. No GWh-scale deployments currently. Specific Capacity ~2.58 V per cell; 118 Wh/kg at cell level; 87 Wh/kg at battery system level.

Space Needed

Moderate — comparable to early lithium-ion; requires thick thermal insulation to maintain operating temperature.

Energy Storage Cost

~$300–500/kWh; limited manufacturing scale and ceramic electrolyte complexity maintain high costs.

Advantages

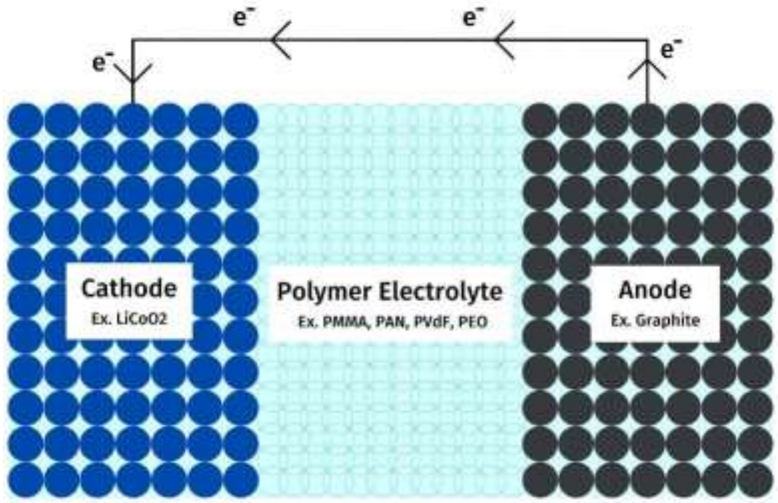
- Good pulse power capability for EVs and grid regulation
- Cell maintenance-free; very low self-discharge
- Resistant to overcharge intrinsic protection mechanism
- Safe failure mode: $NaAlCl_2 + Na \rightarrow$ salt + Al (non-hazardous)
- Uses abundant table salt and nickel no lithium, no cobalt

Challenges

- Must be kept hot at ~300°C continuous energy draw even at rest
- Only practical in large battery formats due to thermal management
- Brittle beta-alumina ceramic electrolyte susceptible to fracture
- Long warm-up time from cold state
- Very limited commercial availability single manufacturer

xxvi. LITHIUM POLYMER BATTERY

Overview



Not a distinct cathode chemistry but a packaging variant where liquid electrolyte is replaced with a polymer gel, enabling ultra-thin, flexible, and custom-shaped cells for consumer electronics and drones.

Working Principle

A polymer gel electrolyte replaces liquid organic electrolyte, allowing laminated pouch cell construction. Cathode is typically LCO or NMC; anode is graphite. The gel electrolyte enables custom shapes, thinner profiles, and eliminates the risk of electrolyte leakage.

Overall Chemical Reaction

$$\boldsymbol{LiCoO_2 + C_6 \rightleftharpoons Li_{1-x}CoO2_2 + Lix_xC_6}$$

Current Research

Solid-state polymer electrolytes (truly solid) to eliminate flammability; silicon anodes in pouch format; high-voltage polymer electrolytes for >4.5 V cells; thermal-resistant polymer matrices for EVs.

Largest Capacity

LiPo cells underpin billions of smartphones, laptops, drones, and wearables globally. No distinct single 'largest installation' as LiPo denotes format over chemistry.

Specific Capacity

~3.7 V nominal (LCO/NMC); 150–250 Wh/kg depending on cathode chemistry; very high volumetric energy density.

Space Needed

Excellent — thinnest available format; cells can be custom-shaped to fit any device cavity. Optimal for portable applications.

Energy Storage Cost

~$100–200/kWh at cell level; manufacturing is more complex than cylindrical/prismatic cells.

Advantages

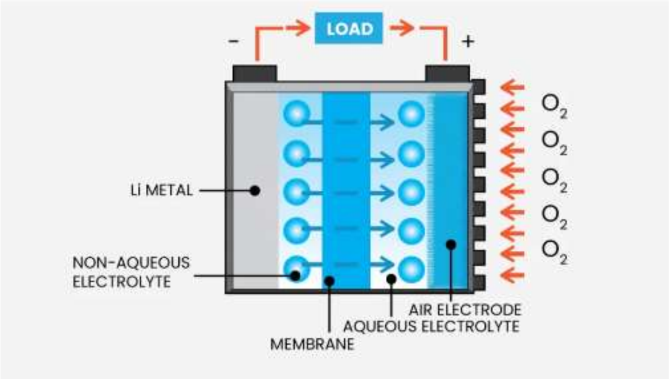
- Extremely thin and lightweight — can be made as thin as 1 mm
- Fully customisable shape for any application
- No rigid metal casing required
- Good energy density comparable to NMC
- Widely manufactured with mature supply chain

Challenges

- Less mechanically robust swells and deforms with age
- Gas generation (swelling) indicates degradation
- Puncture causes immediate fire risk
- Shorter cycle life than hard-case lithium cells
- Requires careful BMS to prevent thermal runaway

xxvii. LITHIUM AIR BATTERY

Overview



A next-generation, pre-commercial chemistry with the highest theoretical energy density of any battery system approaching the energy density of gasoline. Still primarily at the research stage.

Working Principle

Oxygen from the atmosphere acts as the cathode reactant. During discharge, Li_2oxidises at the anode; O_2reduces at a porous carbon cathode to form Li_2O_2 (2-electron) or LiO_2 (4-electron reaction). The theoretical specific energy excluding oxygen is ~40.1 MJ/kg comparable to gasoline.

Chemical Reaction

Li-Air (aprotic): $2Li + O_2 \rightleftharpoons Li_2O_2$

Li-Air (aqueous): $4Li + O_2 + 2H_2O \rightleftharpoons 4LiOH$

Current Research

A 4-electron Li_2O reaction approach developed by Illinois Institute of Technology and Argonne National Laboratory achieves much higher energy density. Solid-state ceramic-polymer electrolytes key to room-temperature operation. Research on air-cathode catalysts and lithium anode protection is active.

Largest Capacity

No commercial installations exist. Still at laboratory/prototype stage worldwide.

Specific Capacity

Theoretical: ~3,460 Wh/kg (excluding O_2); practical demonstrations: 200–500 Wh/kg.

Space Needed

Potentially the best of all chemistries if realised oxygen comes from ambient air, eliminating cathode weight entirely. Energy Storage Cost Currently not calculable at commercial scale research-stage costs are very high.

Advantages

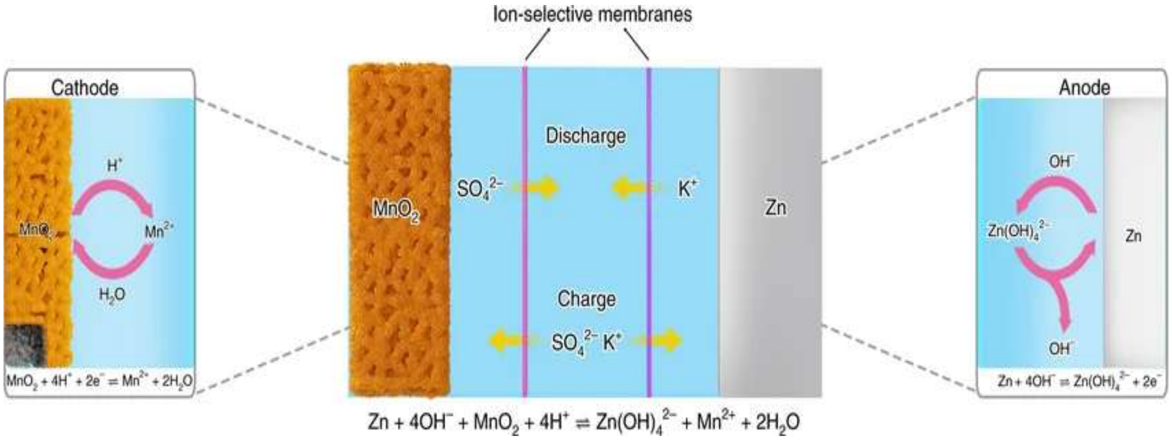
- Extraordinary theoretical energy density
- Lithium is the lightest metal available for battery use
- Oxygen cathode eliminates cathode material cost entirely
- Could revolutionise EVs and aviation if commercialized
- Active global research investment from major labs

Challenges

- Very limited cycle life typically fewer than 100 cycles in practice
- Dendrite formation at lithium anode causes short circuits
- Sensitivity to humidity and CO_2 contaminates air cathode
- Li_2O_2/Li_2O discharge products clog porous cathode
- No commercial product 10–20+ years from mass deployment

xxviii. ZINC MANGANESE DIOXIDE BATTERY

Overview



The most widely manufactured primary battery in history (standard alkaline AA/AAA cells). Rechargeable versions are emerging as cost-effective grid storage solutions using abundant, safe, non-toxic materials.

Working Principle

Zinc anode and manganese dioxide cathode in potassium hydroxide electrolyte. In alkaline cells, Zn oxidises at the anode; MnO_2 is reduced to MnOOH at the cathode. Rechargeable versions use tailored MnO_2 phases and limit cycling depth to maintain structural integrity.

Chemical Reaction

Alkaline Version (most common):

$$Zn + 2MnO_2 + 2H_2O \rightleftharpoons Zn(OH)_2 + 2MnOOH$$

Zinc-Carbon (Leclanché) Version:

$$Zn + 2MnO_2 + 2NH_4Cl \rightleftharpoons Zn(NH_3)_2Cl_2 + Mn_2O_3 + H_2O$$

Current Research

Urban Electric Power (UEP) and Eos Energy commercialising rechargeable Zn-MnO_2 for grid storage; zinc-ion batteries using mild aqueous electrolytes showing 500–1,000 cycles; new MnO_2 phases (α, β, γ, δ) studied for improved stability.

Largest Capacity

Eos Energy has deployed containerised Zn-MnO_2 systems (Eos Z3) at utility scale, with projects in the hundreds of MWh range across the US. Primary alkaline cells: billions of units annually.

Specific Capacity

~1.5 V nominal (primary); rechargeable ~1.2–1.5 V; primary cells 150–200 Wh/kg; rechargeable systems 80–120 Wh/kg at system level.

Space Needed

Moderate Eos systems achieve ~1 MWh per container at very competitive cost.

Energy Storage Cost

~$160/kWh for grid-scale Eos systems, very competitive. Primary cells cost ~$5–15/kWh (single-use).

Advantages

- Extremely low-cost raw materials — zinc and manganese are abundant
- Safe aqueous chemistry no fire risk whatsoever
- Wide operating temperature range
- Primary cells have very long shelf life (5–10 years)
- Rechargeable versions emerging as low-cost grid storage

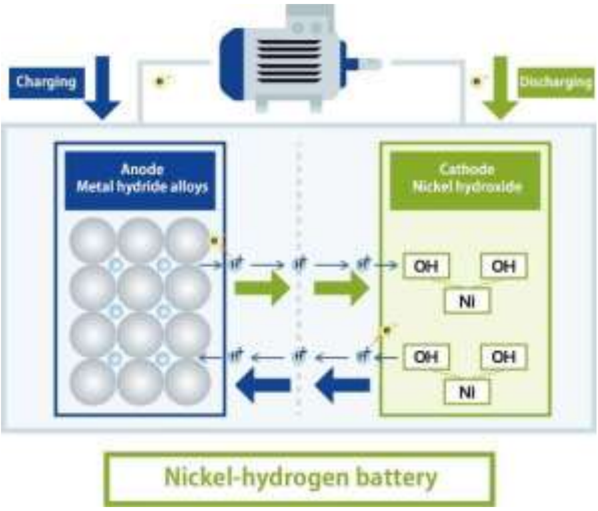
Challenges

- Rechargeable MnO_2 suffers from irreversible phase changes on deep cycling

- MnO_2dissolution in electrolytes degrades performance over time
- Zinc dendrite formation limits rechargeable cycle life (300–500 cycles)
- Lower round-trip efficiency (~80%) than lithium
- Primary cells are single-use , not rechargeable in standard form

xxix. NICKEL HYDROGEN BATTERY

Overview



A specialised aerospace battery combining a nickel electrode with gaseous hydrogen stored in a pressurised vessel. The dominant satellite power source for decades, with extraordinary cycle life.

Working Principle

Nickel oxyhydroxide cathode paired with gaseous hydrogen anode in KOH electrolyte. Hydrogen is stored at up to 1,200 psi in a pressurised vessel. During discharge, H_2 is oxidised at the anode; NiOOH is reduced to $Ni(OH)_2$ at the cathode. Cell voltage ~1.25V.

Overall reaction

$2NiOOH+H_2\rightleftharpoons 2Ni(OH)_2$

Current Research

Ambient-pressure aqueous NiH_2 systems (Stanford-developed) for grid storage eliminating pressurised vessels; hybrid systems combining NiH_2 with other chemistries; applications in 5G backup power and long-duration storage.

Largest Capacity

The Hubble Space Telescope used NiH_2 batteries for 19+ years (launched 1990, batteries replaced 2009) with the highest cycle count of any NiH_2battery in LEO. The ISS used NiH_2 until 2019.

Specific Capacity

75 Wh/kg; 60 Wh/dm³; specific power 220 W/kg; open-circuit voltage 1.55 V; average discharge voltage 1.25 V.

Space Needed

Very poor volumetric density large pressurised hydrogen vessels dominate the form factor. Impractical for terrestrial space-constrained applications. Energy Storage Cost ~\$500–2,000/kWh for aerospace-grade cells. Novel ambient-pressure versions could reach ~\$100–200/kWh.

Advantages

- 15+ year service life at 80% depth of discharge
- 20,000+ charge cycles with 85% energy efficiency
- Extremely reliable in extreme temperature environments (space)
- No memory effect — consistent performance throughout life
- No permanent degradation from overcharge or over-discharge

Challenges

- Bulky pressurised hydrogen vessel poor volumetric energy density
- High manufacturing cost for aerospace grade pressure vessels
- Complex hydrogen management and containment
- Largely obsolete for new space missions due to lithium-ion advances
- Terrestrial applications impractical without ambient-pressure redesign

ADVANCED CHEMICAL ENERGY STORAGE

Advanced Chemical Energy Storage (ACES) refers to a new generation of electrochemical energy storage technologies that are more efficient, durable, and environmentally friendly than conventional batteries. These systems are currently under development and early stages of commercialization, with strong potential to transform the way energy is stored and utilized.

One of the key advantages of ACES technologies is their high energy density, enabling a larger amount of energy to be stored within a smaller volume or mass. This makes them particularly suitable for applications such as portable electronics, electric vehicles, and other space-constrained systems. In addition, ACES batteries offer enhanced durability, as they can withstand a significantly higher number of charge–discharge cycles compared to traditional batteries, resulting in longer service life.

Another major advantage is improved safety and environmental compatibility. Conventional batteries often use flammable electrolytes and toxic materials, whereas many ACES systems are designed with non-flammable electrolytes, solid-state configurations, or environmentally benign components. This reduces risks such as fire hazards, thermal runaway, and environmental pollution.

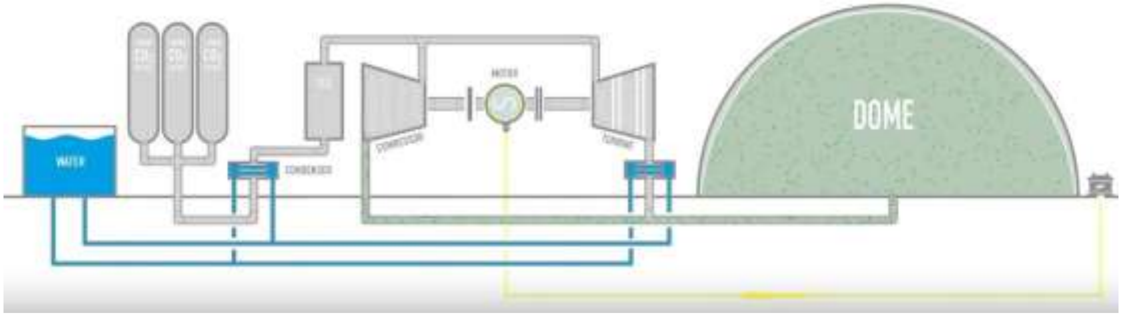
Overall, ACES technologies have the potential to revolutionize energy storage by supporting the integration of renewable energy sources, reducing dependence on fossil fuels, and enabling a more sustainable and low-carbon energy future.

i. CO2 BATTERY

Overview

The CO2 Battery, pioneered by Italian company Energy Dome, is a long-duration energy storage (LDES) system that uses carbon dioxide as its working fluid in a closed-loop thermodynamic cycle. No CO2 is released to the atmosphere. The system can dispatch energy for 8–24 hours, making it an ideal solution for solar and wind power smoothing, peak shaving, and providing 24/7 clean power to energy-intensive industries such as data centres.

Working principle



A CO_2 battery works on a closed-loop thermodynamic cycle in which energy is stored by compressing carbon dioxide and released by expanding it. During the charging phase, electrical energy (typically from renewable sources like solar or wind) is used to compress CO_2 gas to a high pressure, which increases its temperature. The gas is then cooled, converting it into a liquid, and the heat produced during compression is stored separately in a thermal storage system. In the storage phase, the CO_2 remains in a high-pressure liquid state in tanks, while the stored heat is retained for later use. When electricity is required, the system enters the discharging phase, where the liquid CO_2 is reheated using the stored thermal energy and allowed to expand back into gas. This high-pressure expanding gas drives a turbine connected to a generator, thereby producing electricity. The CO_2 is then recycled back into the system, making it a closed and emission-free process suitable for large-scale energy storage.

Researching University/Company

Energy Dome (Italy), University of Surrey (UK), Massachusetts Institute of Technology (MIT, USA), Pohang University of Science and Technology (POSTECH, South Korea), Politecnico di Milano (Italy), Tianjin University (China).

Largest Capacity Acquired

The Energy Dome CO2 battery, a 20 MW/200 MWh system in Ottana, Sardinia — reached full commercial operation in July 2025, successfully feeding power into the Italian grid. The technology is now scaling globally: India's NTPC is building one at its Kudgi power plant in Karnataka, and Alliant Energy in Wisconsin has approval for an installation capable of powering 18,000 homes. Google also partnered with Energy Dome in July 2025 to deploy the systems across its major data center locations in Europe, the US, and Asia-Pacific marking a significant vote of confidence in the technology's commercial viability.

Energy Density

66.7 kilowatt-hours per cubic meter (kWh/m^3)

Cost of making

The cost of a CO_2 battery system is approximately ₹16,000–₹21,000 per kWh

Applications

- Grid-scale energy storage: Used by utilities for storing large amounts of electricity and maintaining grid stability
- Renewable energy integration: Stores excess energy from solar and wind power and supplies it when generation is low

- Peak shaving and load shifting: Stores energy during low demand and releases it during peak demand
- Long-duration energy storage (LDES): Suitable for storing energy for several hours to days, unlike lithium-ion batteries
- Industrial power backup: Provides reliable backup power for industries and large facilities
- Microgrids and smart grids: Supports stable operation of decentralized energy systems
- Energy arbitrage: Stores electricity when prices are low and releases when prices are high

Positives

In addition to its long duration, the CO2 battery also has a number of other advantages, including:

- Cost-effective at scale: CO_2 batteries are becoming competitive with lithium-ion systems, especially for long-duration storage, with lower lifecycle costs.
- Uses readily available materials: Constructed using carbon dioxide, steel, water, and standard industrial equipment, avoiding rare or critical minerals.
- Environmentally safe: The system operates in a closed loop, meaning CO_2 is not released into the atmosphere, making it non-toxic and environmentally friendly.
- Long operational life: Expected lifetime of 20–30 years with minimal performance degradation compared to chemical batteries.
- Suitable for grid applications: Ideal for renewable energy integration, peak shifting, and grid stability

Challenges & Areas for Improvement

Despite progress, several challenges remain:

- Efficiency improvement: Current round-trip efficiency is about 70–80%, which is lower than lithium-ion batteries.

- Cost reduction with scale: Although costs are decreasing, further cost optimization through mass deployment is needed.

- Large land and infrastructure requirement: CO_2 batteries require significant physical space and industrial setup.

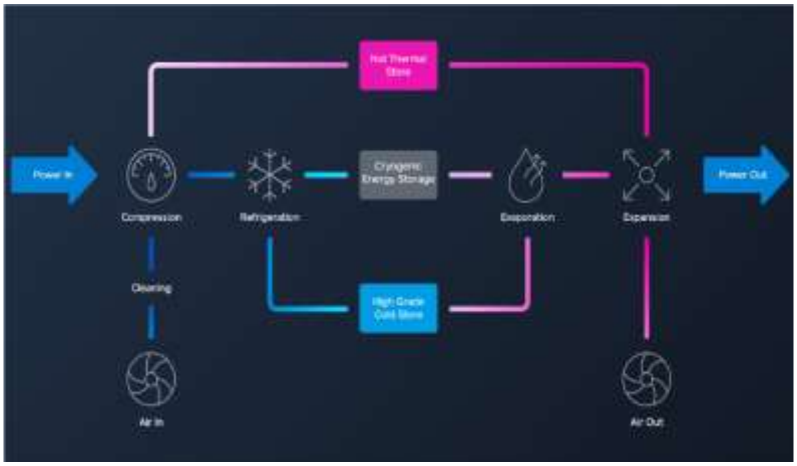
- Technology scaling: Ongoing efforts are focused on scaling systems to hundreds of MW and multi-GWh capacity.

The future of CO2 batteries

CO_2 batteries are emerging as a promising solution for future long-duration energy storage (LDES), especially with the rapid growth of renewable energy sources like solar and wind. As power systems increasingly rely on intermittent energy, CO_2 batteries can provide reliable storage for 8–24 hours or more, helping to stabilize the grid. With companies like Energy Dome moving from pilot projects to commercial-scale deployments across Europe, the USA, and Asia, the technology is expected to expand significantly in the coming years. Ongoing advancements are focused on improving efficiency, reducing costs, and scaling systems to larger capacities (hundreds of MW to GWh levels). Due to their use of abundant, non-toxic materials and long operational life, CO_2 batteries have strong potential to support decarbonization and sustainable energy systems, making them a key technology for the future of global energy infrastructure.

ii. HIGHVIEW POWER CRYO-BATTERY

Overview



The CRYOBattery™ developed by Highview Power is a long-duration energy storage system based on cryogenic (liquid air) technology. It works by using electricity to compress and cool air to about −196°C, converting it into a liquid that can be stored in insulated tanks. When power is needed, the liquid air is heated and allowed to expand back into gas, which drives a turbine connected to a generator to produce electricity. This system operates in a closed cycle, uses abundant and environmentally friendly air, and can store energy for hours to days, making it suitable for grid-scale applications. Although its efficiency (around 60–70%) is lower than lithium-ion batteries, the CRYOBattery offers advantages such as long operational life, large-scale capacity, and no dependence on rare materials, making it a promising solution for supporting renewable energy and improving grid stability.

Working Principle

The CRYOBattery developed by Highview Power works on a cryogenic thermodynamic cycle, where electrical energy is stored by converting air into a liquid at very low temperatures and later recovered by expanding it to generate electricity.

During the charging phase, atmospheric air is drawn in, filtered, and compressed using electrical energy. The compressed air is then cooled through multiple stages until it reaches around 196°C, at which point it becomes liquid air. The heat removed during this process is captured and stored in a thermal storage system to improve efficiency. In the storage phase, the liquid air is kept in insulated cryogenic tanks at low pressure. It can be stored for long durations (hours to days) with minimal energy loss.

During the discharging phase, the liquid air is pumped to high pressure and then reheated using the stored heat or ambient heat. As it warms, it rapidly expands back into gas, and this high-pressure gas drives a turbine connected to a generator, producing electricity. The system may also recover cold energy released during expansion to further enhance performance.

Thus, the CRYOBattery operates in a closed, clean cycle using air as the working fluid, making it suitable for large-scale, long-duration energy storage and integration with renewable energy systems.

Researching University/Company

Highview Power (UK), University of Birmingham (UK), University of Leeds (UK), University of Brighton (UK), supported by Innovate UK and the Energy Research Accelerator

Largest Acquired Capacity

Largest Capacity Acquired The largest CRYOBattery developed by Highview Power is the Hunterston project in Scotland, with a planned capacity of approximately 3.2 GWh (300 MW), making it the largest liquid air energy storage system currently under development.

Specific Capacity

Approximately 50 – 100 Wh/kg

Cost of Making

The cost of a CRYOBattery system is approximately ₹8,000–₹14,000 per kWh (₹8–14 crore per MWh)

Space for Implementation

A 5 MW / 50 MWh cryogenic energy storage system typically requires on the order of ~1,000 m² of core plant area, while a 50 MW / 250 MWh system may require around

~5,000 m². However, the actual land requirement depends on plant design, auxiliary systems, and site conditions, and can be significantly higher in practical installations.

Positives of CRYO Battery

- Long-duration energy storage
- Uses air -abundant and freely available resource
- Environmentally friendly -no emissions, non-toxic
- No requirement of rare or critical materials
- Cost-effective for large-scale applications
- High scalability- MW to GW level systems
- Can be installed anywhere- no geographic limitation needed
- Long operational life ~30–40 years
- Low degradation compared to chemical batteries
- Provides grid support services (frequency control, peak load management, backup power)
- Suitable for renewable energy integration

Challenges of CRYOBattery

- Lower efficiency compared to lithium-ion batteries ~60–70%
- High initial capital cost due to complex cryogenic systems
- Requires large infrastructure and space
- Energy loss during liquefaction -cooling to −196°C is energy intensive
- Dependence on efficient heat and cold recovery systems
- Slower response time compared to electrochemical batteries
- Technology still in early commercial stage

- Performance depends on availability of waste heat ambient conditions
- Scaling challenges for very large (multi-GWh) systems

Future of CRYO Battery

- Rapid growth in long-duration energy storage (LDES) demand (8–24+ hours)
- Expansion of projects by Highview Power in UK, USA, Europe, and Asia
- Movement from pilot plants → large commercial installations (100 MW to GW)
- Expected cost reduction due to mass deployment and standardization
- Improvement in efficiency using waste heat and cold recovery systems
- Increasing role in renewable energy integration solar & wind balancing
- Potential to replace fossil-fuel peaker plants
- Integration with smart grids and advanced control systems
- Growing support from governments and clean energy policies
- Development of multi-GWh storage projects for national grids

iii. AMMONIA ENERGY STORAGE

Overview

Ammonia Energy Storage is an advanced chemical energy storage technology in which energy is stored in the form of ammonia (NH_3). It is typically produced using renewable electricity through a process where hydrogen (generated by electrolysis) is combined with nitrogen from air. The stored ammonia can later be used to generate electricity by converting it back into hydrogen or by direct combustion in turbines. Ammonia is gaining attention as an energy carrier because it is easier to store and transport than hydrogen, having higher energy density and existing global infrastructure for handling and distribution. It can be stored in liquid form under moderate pressure or low temperature, making it suitable for large-scale and long-duration energy storage (LDES).

As of 2026, ammonia-based systems are under active development and pilot deployment for grid-scale storage, renewable energy integration, and industrial energy applications. Due to its scalability, transportability, and compatibility with existing infrastructure, ammonia is considered a promising solution for future sustainable energy systems.

Working principle

Ammonia Energy Storage operates on a Power-to-Ammonia-to-Power (P2A2P) cycle, where electrical energy is converted into chemical energy in the form of ammonia and later converted back into electricity.

During the charging (storage) phase, renewable electricity is used in an electrolyzer to split water into hydrogen and oxygen. The hydrogen is then combined with nitrogen (extracted from air) through a synthesis process (similar to the Haber–Bosch process) to produce ammonia (NH_3). This ammonia is stored in liquid form in tanks under moderate pressure or low temperature.

During the discharging (energy recovery) phase, the stored ammonia is either cracked back into hydrogen and nitrogen or used directly as a fuel. If cracked, the hydrogen is fed into a fuel cell or turbine to generate electricity. Alternatively, ammonia can be directly combusted in gas turbines to produce power. This cycle enables efficient storage of energy over long durations, with the advantage that ammonia is easier to store and transport compared to hydrogen, making it suitable for gridscale and seasonal energy storage applications.

Researching University/ Institutions

Research on ammonia-based energy storage is being carried out by several leading universities and research centers worldwide. Key contributors include the University of Minnesota, which operates pilot plants converting wind energy into ammonia for storage. In the United States, the University of North Dakota Energy & Environmental Research Center is actively developing ammonia-based energy storage systems (NH_3-BEST concept) for grid applications.

In Europe, institutions such as Cardiff University are involved in projects like FASTER, focusing on converting renewable energy into ammonia for storage and transport. Technical research is also supported by collaborative programs such as the ARENHA project (led by Technical University of Denmark), which focuses on ammonia synthesis, storage, and conversion back to energy.

Research Companies

Several companies are involved in developing and deploying ammonia-based energy storage and infrastructure. Key players include Technip Energies, which is working on large-scale ammonia production and energy projects. Energy companies such as Reliance Industries are investing heavily in green ammonia production for energy storage and fuel applications, including large international supply agreements. Additionally, infrastructure providers like Royal Vopak are developing ammonia storage and handling facilities for energy transition applications

Largest Capacity Acquired

Ammonia energy storage is implemented in large industrial systems, with projects such as NEOM (Saudi Arabia) and Kakinada (India) reaching hundreds of thousands to millions of tonnes per year of ammonia storage/production capacity.

Specific Capacity

Approximately 3,000 – 3,500 Wh/kg (based on NH_3 fuel energy)

Cost of making

Typical cost range: ₹20,000 – ₹35,000 per kWh (system-level estimate)

Positives

- High energy density compared to many storage systems
- Suitable for long-duration and seasonal energy storage
- Easier to store and transport than hydrogen
- Existing global infrastructure for storage and distribution
- Carbon-free energy carrier (when produced using renewable energy)
- Can be used for power generation, fuel, and energy storage
- Scalable for large industrial and grid applications
- Enables integration of renewable energy at large scale

Challenges

- High energy losses during conversion
- Toxic and hazardous nature of ammonia requires careful handling
- High initial cost for electrolyzers and synthesis systems
- Complex infrastructure for production and reconversion
- Lower overall efficiency compared to batteries

- Emissions risk (NOx formation) during combustion if not properly controlled
- Technology still in early deployment stage for energy storage applications

Future of Ammonia Energy Storage (NH_3-based)

Ammonia energy storage has strong future potential as a long-duration and seasonal energy storage solution. With the growth of renewable energy, it is expected to play a key role in large-scale energy storage, transport, and global energy trade. Advances in green hydrogen production, ammonia synthesis, and fuel conversion technologies will improve efficiency and reduce costs. Due to its ease of storage and existing infrastructure, ammonia is likely to become an important energy carrier in future sustainable and low-carbon power systems.

FLOW BATTERIES

Flow batteries are a class of rechargeable electrochemical energy storage systems in which energy is stored in liquid electrolytes that flow through one or more electrochemical cells from external storage tanks. This configuration enables the storage and discharge of large amounts of energy, as the total energy capacity is determined by the volume of the electrolyte, while the power output depends on the size of the cell stack.

Flow batteries are characterized by their long cycle life, typically exceeding 10,000–20,000 charge–discharge cycles, with minimal degradation in performance. Due to their non-flammable aqueous electrolytes and stable operation, they are considered highly suitable for grid-scale and long-duration energy storage applications.

A typical flow battery system consists of two main components: the electrochemical cell stack and the electrolyte storage tanks. The cell stack is the core unit where electrochemical reactions take place, converting chemical energy into electrical energy during discharge, and electrical energy back into chemical energy during charging. The electrolyte tanks store two separate liquid solutions known as the anolyte (negative electrolyte) and catholyte (positive electrolyte), which are circulated through the cell stack using pumps.

During the charging process, electrical energy supplied from an external source drives oxidation and reduction reactions in the electrolytes, storing energy in chemical form. During discharge, the reverse reactions occur, releasing stored chemical energy as electrical energy to supply the load. The two electrolytes remain physically separated by an ion-selective membrane, which allows ionic transfer while preventing direct mixing, thereby maintaining system efficiency and stability.

Recent developments up to 2026 have focused on improving electrolyte chemistry, reducing system costs, and enhancing efficiency. Newer flow battery technologies such as iron-based and organic electrolytes are being developed to provide lower-cost and more sustainable alternatives, further expanding their role in renewable energy integration and grid stabilization.

i. VANADIUM REDOX FLOW BATTERY (VRFB)

Overview

Vanadium Redox Flow Batteries (VRFBs) are advanced electrochemical energy storage systems that use vanadium ions in different oxidation states dissolved in liquid electrolytes to store and release energy. Unlike conventional batteries, the energy is stored in external electrolyte tanks, allowing independent scaling of power and energy capacity.

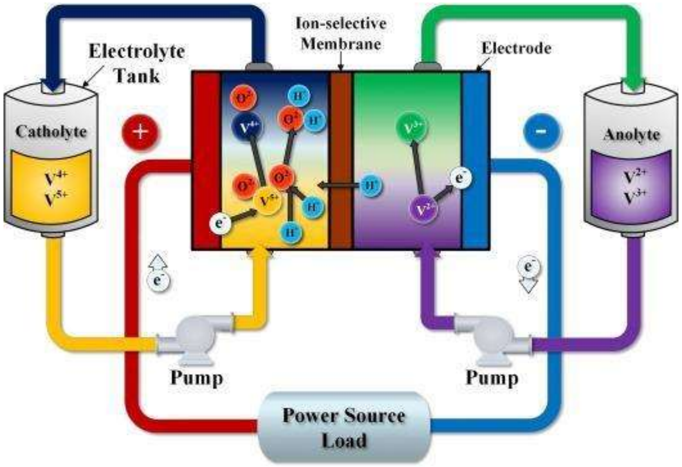
VRFBs are known for their exceptionally long lifespan, typically exceeding 20 years with more than 20,000 charge–discharge cycles, and their ability to operate with minimal degradation over time. Since both electrolytes use vanadium, the risk of cross-contamination is eliminated, improving durability and simplifying system maintenance.

These batteries are non-flammable and environmentally safer, as they use aqueous electrolytes, making them highly suitable for large-scale applications. Due to their scalability, reliability, and safety, VRFBs are widely used in grid-scale energy storage, especially for integrating renewable energy sources such as solar and wind.

VRFBs are considered the most mature and commercially deployed flow battery technology, playing a significant role in long-duration energy storage (LDES) systems.

Working Principle

A Vanadium Redox Flow Battery (VRFB) operates based on reversible oxidation reduction (redox) reactions of vanadium ions dissolved in liquid electrolytes. The system consists of two separate electrolyte tanks containing vanadium ions in different oxidation states, which are circulated through a cell stack by pumps. Inside the cell stack, the electrolytes flow through two half-cells separated by an ion-exchange membrane that allows only ions (mainly protons) to pass while preventing mixing of the electrolytes.



During charging, electrical energy from an external source drives oxidation reactions in the positive electrolyte (converting V^{4+} to V^{5+}) and reduction reactions in the negative electrolyte (converting V^{3+} to V^{2+}), thereby storing energy in chemical form.

During discharging, the reverse reactions occur: V^{2+} is oxidized back to V^{3+} and V^{5+} is reduced to V^{4+}, releasing electrons that flow through the external circuit to supply power to the load. This continuous circulation of electrolytes, combined with the membrane's selective ion transfer, enables efficient and stable energy storage and retrieval, with the unique advantage that both electrolytes use vanadium, eliminating cross-contamination issues and enhancing system durability.

Chemical Reaction

$VO_2^+ + 2H^+ + V^{2+} \rightleftharpoons VO^{2+} + V^{3+} + H_2O$

Research Universities/Institutions

Research and development of Vanadium Redox Flow Batteries is being actively carried out by leading universities and national laboratories across the world. In India, major contributions are made by Indian Institute of Science, Indian Institute of Technology Madras, Indian Institute of Technology Bombay, and CSIR-National Chemical Laboratory. In Asia, institutions such as Tsinghua University, University of Tokyo, and Nanyang Technological University are actively involved. In the United States, advanced research is carried out by Pacific Northwest National Laboratory, Argonne National Laboratory, and Massachusetts Institute of Technology. In Europe, key contributors include Delft University of Technology, Imperial College London, and German Aerospace Center. These institutions are focusing on improving electrolyte stability, membrane performance, efficiency, and cost reduction.

Research Companies

Several companies are leading the commercialization and technological advancement of VRFB systems. Major global players include Invinity Energy Systems, VRB Energy, Sumitomo Electric Industries, Rongke Power, and CellCube. Other important contributors include Largo Clean Energy and UniEnergy Technologies. These companies are involved in large-scale deployment, manufacturing, electrolyte supply, and development of advanced VRFB systems for grid-scale energy storage applications.

Largest Capacity Acquired

The largest Vanadium Redox Flow Battery (VRFB) installation currently in operation is the Dalian VRFB project in China, developed by Rongke Power. This project has an initial installed capacity of 100 MW / 400 MWh, commissioned in 2021, and is designed to be expanded to 200 MW / 800 MWh and beyond, making it one of the largest grid-scale electrochemical energy storage systems in the world.

Cost of Energy Storing

₹20,000 – ₹40,000 per kWh (system-level cost).

Space for Implementation

Approximately 150 – 250 sq.m for 1 MW / 4 MWh system

Specific Capacity

20 to 50 Wh/kg (Lithium-ion: 100–250 Wh/kg)

Applications

VRFBs are widely used for a variety of stationary and grid-scale energy storage applications, such as:

- Grid balancing and frequency regulation
- Peak shaving and load leveling
- Renewable energy storage (solar and wind integration)
- Backup power and uninterruptible power supply (UPS)

- Microgrids and smart grid systems
- Remote and off-grid power supply
- Utility-scale long-duration energy storage (LDES)
- Transmission and distribution support (substations)

Positives

- Long lifespan (20–25 years, >20,000 cycles)
- Low maintenance requirements
- High safety (non-flammable aqueous electrolyte)
- Environmentally friendly and recyclable electrolyte
- Independent scalability of power and energy
- Deep discharge capability (up to 100% DoD)
- Stable performance with minimal degradation over time
- Suitable for long-duration energy storage (LDES)

Challenges

- High initial capital cost
- Lower energy density compared to lithium-ion batteries
- Larger space requirement due to external tanks
- Pumping system increases system complexity
- Moderate efficiency (around 75–85%) compared to Li-ion
- Sensitivity to electrolyte impurities and temperature variations

Future of Vanadium Redox Flow Battery (VRFB)

VRFBs have a strong future in grid-scale and long-duration energy storage (LDES). With increasing use of renewable energy, they are expected to play a key role in solar and wind power integration. Ongoing improvements in cost reduction, efficiency, and large-scale deployment will make them more competitive. Their long life, safety, and scalability ensure that VRFBs will become an important technology in future sustainable power systems.

ii. ZINC- BROMINE FLOW BATTERY

Overview

Zinc–Bromine Flow Batteries (ZBFBs) are a type of hybrid redox flow battery that use zinc metal and bromine solution as active materials to store and release energy. Unlike conventional batteries, energy is stored in liquid electrolytes contained in external tanks, allowing flexible scaling of energy capacity.

ZBFBs are known for their higher energy density compared to other flow batteries, along with good cycle life and modular design. During operation, zinc is deposited and dissolved on the electrode, while bromine participates in reversible chemical reactions, enabling energy storage and discharge.

These batteries are non-flammable and relatively safe, making them suitable for stationary applications. As of 2026, ZBFBs are commercially used in telecom backup systems, microgrids, and medium-scale energy storage, and are considered a practical alternative to lithium-ion batteries for certain ESS applications where safety and durability are important.

Working Principle

A Zinc–Bromine Flow Battery (ZBFB) operates based on reversible electrochemical reactions between zinc and bromine in liquid electrolytes. The system consists of two electrolyte solutions stored in tanks and circulated through a cell stack using pumps. Unlike fully liquid flow batteries, ZBFB is a hybrid system where zinc metal is deposited on an electrode during operation.

During the charging process, electrical energy from an external source drives the movement of ions in the electrolyte. Zinc ions (Zn^{2+}) are reduced and deposited as solid zinc on the negative electrode, while bromide ions (Br^-) are oxidized to form bromine (Br_2) at the positive electrode. The energy is thus stored in the form of plated zinc and bromine solution.

During discharging, the reverse reactions occur. The deposited zinc is oxidized back into zinc ions, releasing electrons, while bromine is reduced back to bromide ions. These reactions generate electrical energy, which flows through the external circuit to supply power to the load.

The electrolytes are continuously circulated to maintain reaction efficiency, and a separator or membrane is used to prevent direct mixing of zinc and bromine while allowing ionic conduction. This reversible plating and stripping of zinc, along with bromine redox reactions, enables efficient energy storage and release in ZBFB systems.

Chemical Reaction

$Zn + Br_2 \rightleftharpoons ZnBr_2$

Researching Universities/Institutions

Research on Zinc–Bromine Flow Batteries is carried out by several universities, national laboratories, and collaborative research platforms worldwide. In India, institutions such as Indian Institute of Science, Indian Institute of Technology Madras, and CSIR-Central Electrochemical Research Institute are involved in electrochemical energy storage research.

In Asia, major research contributions come from Tsinghua University, University of Tokyo, and collaborative institutes linked with the Chinese Academy of Sciences, where early demonstration systems have been developed .

In the United States and Europe, research is supported by institutions such as Massachusetts Institute of Technology, Argonne National Laboratory, and The Faraday Institution, which focus on advanced battery technologies and large-scale energy storage systems.

Additionally, industry–academic collaboration plays a major role in this field. Research platforms involving universities like Huazhong University of Science and Technology and Wuhan University of Technology are actively working on improving zinc–bromine battery performance and cost through joint development programs .

Overall, global research efforts are focused on improving electrode stability, electrolyte performance, and prevention of zinc dendrite formation, which is a key challenge in Zinc–Bromine Flow Battery technology.

Research Companies

Key companies working on Zinc–Bromine flow battery technology include Eos Energy Enterprises, Redflow Limited, and TETRA Technologies. These companies focus on developing modular battery systems, electrolyte supply, and grid-scale energy storage solutions**.**

Largest Capacity Acquired

Zinc–Bromine flow batteries are typically deployed in modular systems, with single-site installations generally in the 1–20+ MWh range, while larger capacities are achieved through aggregation of multiple units.

Space to Implement

Approximately 1–2 sq.ft per kWh of storage capacity (≈ 90–180 m^2 for a 1MW/ 4MWh)

Specific Capacity

60 to 100 Wh/kg

Cost of making

₹30,000 – ₹40,000 per kWh

Applications

Zinc–Bromine Flow Batteries (ZBFBs) are used in a variety of stationary energy storage applications, such as:

- Telecom backup power systems
- Microgrids and distributed energy systems

- Renewable energy storage (solar and wind integration)
- Peak shaving and load management
- Backup power for commercial and industrial facilities
- Remote and off-grid power supply
- Medium-scale grid energy storage

Positives

- Higher energy density compared to most flow batteries
- Long cycle life and good durability
- High safety (non-flammable electrolyte)
- Deep discharge capability (up to 100% DoD)
- Modular and scalable design
- Suitable for harsh and high-temperature environments

Challenges

- Moderate to high initial cost
- Formation of zinc dendrites affecting performance
- System complexity due to pumps and electrolyte circulation
- Lower efficiency compared to lithium-ion batteries (~65–75%)
- Maintenance requirements higher than some other battery types

Future of Zinc–Bromine Flow Battery (ZBFB)

Zinc–Bromine Flow Batteries have a promising future in medium-scale and distributed energy storage systems. With increasing demand for safe and durable alternatives to lithium-ion batteries, ZBFBs are expected to play an important role in telecom backup, microgrids, and renewable energy integration. Ongoing improvements in cost reduction, dendrite control, and system efficiency will enhance their performance and reliability.

Due to their modular design and ability to operate in harsh conditions, ZBFBs are likely to see wider adoption in remote and off-grid applications in the coming years.

iii. IRON FLOW BATTERY (IFB)

Overview

Iron Flow Batteries (IFBs) are a type of redox flow battery that use iron-based electrolytes (Fe^{2+}/Fe^{3+}) to store and release energy. Energy is stored in liquid electrolytes contained in external tanks and circulated through a cell stack, allowing independent scaling of power and energy capacity. IFBs are gaining attention as a low-cost and sustainable alternative to other flow batteries because iron is abundant, inexpensive, and non-toxic. They are particularly suitable for long-duration energy storage (8–12+ hours) and grid-scale applications. These batteries offer long operational life (20+ years), high safety due to non-flammable aqueous electrolytes, and minimal environmental impact. As of 2026, IFBs are in the early commercial stage, with companies like ESS Inc. leading deployments for renewable energy storage and utility-scale applications. Due to their cost advantage and scalability, Iron Flow Batteries are expected to play a significant role in future energy storage systems, especially for large-scale renewable integration.

Working principle

An Iron Flow Battery (IFB) operates based on reversible redox reactions of iron ions (Fe^{2+}/Fe^{3+}) in aqueous electrolytes. The system consists of two electrolyte tanks containing iron-based solutions, which are circulated through a cell stack using pumps. Inside the cell stack, the electrolytes flow through two half-cells separated by an ion-exchange membrane that allows ions to pass while preventing mixing of the electrolytes.

During the charging process, electrical energy from an external source drives oxidation and reduction reactions. In the positive half-cell, ferrous ions (Fe^{2+}) are oxidized to ferric ions (Fe^{3+}), while in the negative half-cell, reduction reactions occur (often involving iron plating or hydrogen evolution depending on design), storing energy in chemical form.

During discharging, the reverse reactions take place. Ferric ions (Fe^{3+}) are reduced back to ferrous ions (Fe^{2+}), releasing electrons, while the negative side undergoes oxidation, generating electrical energy that flows through the external circuit to supply power to the load.

The continuous circulation of electrolyte and the reversible iron redox reactions enable stable and long-duration energy storage, making IFBs suitable for large-scale applications.

Chemical Reaction

$2Fe^{3+} + Fe \rightleftharpoons 3Fe^{2+}$

Researching Universities/Companies/Institutions

Research and development of Iron Flow Batteries (IFBs) is being carried out by several universities, research institutes, and national laboratories focusing on low-cost and long-duration energy storage technologies.

In the United States, major contributions come from University of California San Diego, which has collaborated with ESS Inc. to test and improve iron flow battery systems under programs like ARPA-E.

In Europe, institutions such as The Faraday Institution and Helmholtz Institute Ulm are actively involved in advanced electrochemical energy storage research, including flow battery technologies.

Additionally, various universities worldwide are working on iron-based redox chemistry, electrolyte optimization, and system design, contributing to the development of scalable and cost-effective flow battery systems for grid applications. Research efforts are mainly focused on improving efficiency, reducing hydrogen evolution losses, and enhancing long-term stability.

Major companies include ESS Tech, VoltStorage, Vionx Energy, and Invinity Energy Systems, working on long-duration iron flow battery technologies.

Largest Capacity Acquired

Iron Flow Battery projects are currently in the tens of MWh range (operational), with larger systems such as 500 MWh under development in Boxberg, Germany

Specific Capacity

20 to 40 Wh/kg

Cost of Making

₹15,000 – ₹25,000 per kWh

Space to Implement

Approximately 200 – 300 sq.m for a 1 MW / 4 MWh system

Applications

Iron Flow Batteries (IFBs) are mainly used for long-duration and large-scale energy storage applications, such as:

- Grid-scale energy storage and load leveling
- Renewable energy storage (solar and wind integration)
- Long-duration energy storage (8–12+ hours)
- Microgrids and distributed energy systems
- Backup power for utilities and industries
- Transmission and distribution support (substations)
- Remote and off-grid power supply

Positives

- Low cost due to abundant iron-based materials
- Long lifespan (20+ years, high cycle life)
- High safety (non-flammable, water-based electrolyte)
- Environmentally friendly and non-toxic
- Suitable for long-duration energy storage (8–12+ hours)
- Minimal degradation over time

- Scalable for large grid applications
- Low maintenance requirements

Challenges

- Lower energy density compared to lithium-ion batteries
- Larger space requirement due to electrolyte tanks
- Moderate efficiency (~60–70%) compared to other batteries
- Hydrogen evolution side reaction reduces efficiency
- Early-stage commercialization (limited deployments)
- Higher system complexity (pumps, flow control)
- Slower response compared to lithium-ion in some applications

Future of Iron Flow Battery (IFB)

Iron Flow Batteries have a strong future in long-duration energy storage (LDES) due to their low cost, safety, and abundant materials. As renewable energy usage increases, IFBs are expected to play a key role in grid-scale storage and solar/wind integration. Ongoing improvements in efficiency and large-scale deployment will enhance their commercial viability. In the coming years, IFBs are likely to become a cost-effective solution for large energy storage systems.

GRAVITATIONAL STORAGE

Gravitational energy storage (GES) is a type of energy storage that uses gravity to store energy. GES systems work by lifting a heavy object to a high elevation. The potential energy stored in the object is then converted to electrical energy when it is lowered back down.

GES systems are a promising technology for large-scale energy storage, as they can store large amounts of energy for long periods of time. They are also relatively inexpensive and reliable. GES systems are still under development, but they have the potential to play a major role in the transition to a clean energy future.

One of the most common types of GES systems is pumped hydro storage (PHS). PHS systems use two reservoirs at different elevations. When electricity is abundant, water is pumped from the lower reservoir to the upper reservoir. This stores energy in the form of potential energy. When electricity is needed, water is released from the upper reservoir to the lower reservoir, driving a turbine to generate electricity.

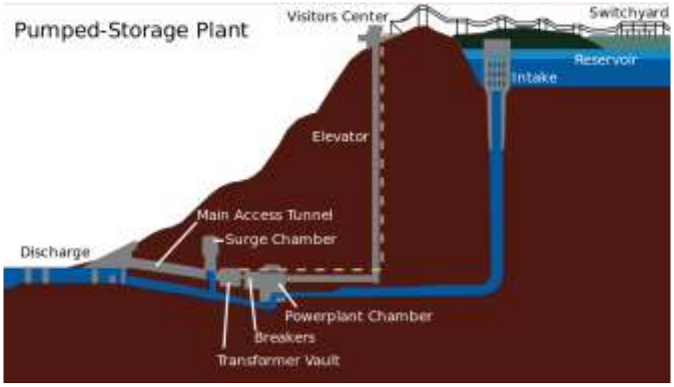
Another type of GES system is a gravity battery. Gravity battery systems use a crane or other lifting device to raise a heavy object to a high elevation. The potential energy stored in the object is then converted to electrical energy when it is lowered back down. Gravity battery systems are still in their early stages of development, but they have the potential to be more efficient and cost-effective than PHS systems.

GES systems have a number of advantages over other types of energy storage technologies, such as batteries. GES systems can store large amounts of energy for long periods of time without losing energy. They are also relatively inexpensive to build and maintain. Additionally, GES systems are not subject to the same environmental concerns as batteries, such as the use of hazardous materials.

GES systems have the potential to play a major role in the transition to a clean energy future. GES systems can help to integrate renewable energy sources into the grid and provide backup power during outages. GES systems can also help to reduce greenhouse gas emissions and improve air quality.

i. PUMPED HYDRO STORAGE

Overview



Pumped hydro storage (PHS) is a type of hydroelectric energy storage. It uses two reservoirs at different elevations to store energy. Water is pumped from the lower reservoir to the upper reservoir during off-peak hours, when electricity is plentiful and cheap. When electricity is needed, the water is released from the upper reservoir through turbines to generate electricity. PHS is the most common form of grid-scale energy storage in the world.

Working Principle

PHS works by using the potential energy of water to store electricity. When water is pumped from the lower reservoir to the upper reservoir, it gains potential energy. This potential energy is then converted into electricity when the water is released from the upper reservoir through turbines. The round-trip efficiency of PHS has improved with modern variable-speed pump-turbine units, now reaching 80–87% (up from the traditional ~80%). This means for every 100 kWh used to pump water, 80–87 kWh can be recovered.

Largest Capacity Acquired

The largest pumped hydro storage facility in the world is the Fengning Pumped Storage Power Station in Hebei Province, China, which reached full operation on 31 December 2024. It surpasses the previous record-holder, the Bath County Station in Virginia, USA (3 GW).

Researching Universities/Institutions/Companies

India: Indian Institute of Technology Bombay (India), Indian Institute of Technology Delhi (India)

Asia: Tsinghua University (China), Peking University (China), University of Tokyo (Japan), Kyoto University (Japan), Seoul National University (South Korea), National University of Singapore (Singapore)

North America: Stanford University (United States), Massachusetts Institute of Technology (United States), University of California, Berkeley (United States), University of California, Los Angeles (United States), University of Texas at Austin (United States), Cornell University (United States), University of Waterloo (Canada), McGill University (Canada)

Europe: University of Cambridge (United Kingdom), University of Oxford (United Kingdom), Imperial College London (United Kingdom), Karlsruhe Institute of Technology (Germany), Technical University of Munich (Germany), Paris-Saclay University (France), University of Bordeaux (France).

Specific Capacity

0.27 to 2.73 kWh/Kg.

Cost of Making

Global capital costs for PHS typically range from ~$1,438 to $4,243 per kW (approximately 1,20,000–3,55,000/kW at current exchange rates), varying widely by site conditions, geology, and scale. On a per-kWh basis, large-scale PHS costs approximately $165/kWh (~ 13,800/kWh) — a significant reduction from earlier estimates, driven by improved engineering and economies of scale. Recent Indian pumped hydro auctions (Maharashtra, 2024) revealed a levelized cost of storage as low as 3.2/kWh for 1,000 MW projectsSpace to Implement

The Bath County Pumped Storage Station in Virginia, USA, which has a generation capacity of 3 GW and a storage capacity of 24 GWh, covers an area of approximately 4,200 acres (1,700 hectares). Closed-loop off-river PHS designs, now gaining momentum, require significantly less land and impose fewer environmental constraints than traditional open-loop river-based systems.

Positives and Challenges

Positives of pumped storage system,

- PHS is a mature technology with a long track record of success.
- It is a scalable technology that can be used to store large amounts of energy.
- It is a reliable technology with a low risk of failure.
- It is a flexible technology that can be used to provide a variety of grid services.

Challenges of pump storage system

- PHS requires a large amount of land.
- It can be expensive to build and operate.
- It can have a negative impact on the environment.

Pumped hydro storage is playing an increasingly important role in providing peaking power and maintaining system stability in the power system of many countries. Pumped storage technology is the long term technically proven, cost effective, highly efficient and flexible way of energy storage on a large scale to store intermittent and variable energy generated by solar and wind.

ii. GRAVITY-BASED ENERGY STORAGE SYSTEM

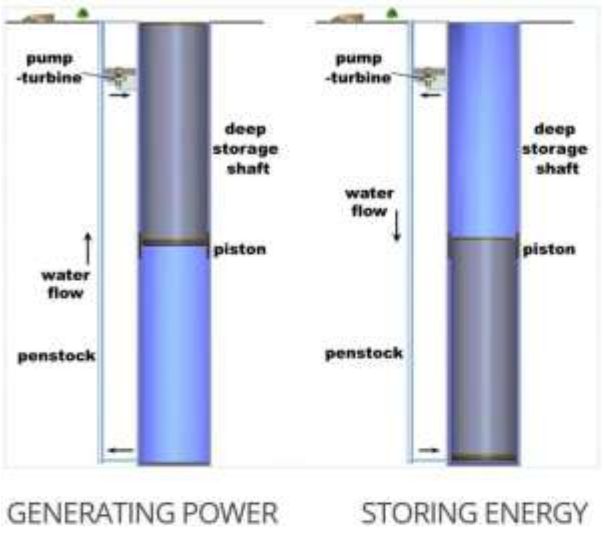
Overview

Gravity-based storage systems store energy by lifting a mass to a height. When the mass is released, it falls and its potential energy converted into is kinetic energy, which can then be used to generate electricity.

Working principle

During periods of excess energy generation, such as when there is an abundance of electricity from renewable sources like wind or solar, the surplus power is used to lift a heavy mass. This mass can be in the form of solid objects (like concrete blocks or heavy materials), water, or even lifting vehicles (e.g., trains or cars) to an elevated position. The energy is used to overcome the force of gravity and raise the mass to a higher level. As the mass is raised, it gains potential energy due to its increased height above a reference point, typically the ground or a lower reservoir. The potential energy is directly proportional to the height and mass of the object, as expressed by the equation: Potential Energy (PE) = Mass (M) x Gravitational Acceleration (g)x Height (h). When electrical power is required, the stored mass is allowed to descend, converting its potential energy into kinetic energy as it falls. The mass is guided through a controlled descent using a system of pulleys, cables, or a suitable mechanism to ensure a controlled and safe release. As the mass descends, it turns a generator or a mechanical device that converts the kinetic energy into electrical 86 energy. This electricity can be delivered to the grid or used for various applications. The efficiency of gravity energy storage systems is determined by the ratio of the electrical energy output during the discharge phase to the electrical energy input during the charge phase. Minimising losses during the energy conversion process and the descent phase is crucial for high round-trip efficiency.

There are two main types of gravity-based energy storage systems:



- Pumped-storage hydroelectricity is the most common type of gravity-based energy storage. In this system, water is pumped from a lower reservoir to a higher reservoir during times of excess energy production. When energy is needed, the water is released back to the lower reservoir, driving a turbine to generate electricity.
- Gravitational potential energy storage systems use other materials, such as concrete blocks or weights, to store energy. These systems are typically less efficient than pumped-storage hydroelectricity, but they can be used in a wider range of locations.

Researching Universities/Institutions/Companies

Asia:

- Energy Vault(Switzerland): 35 MWh/8 MW
- Gravitricity(Scotland): 2 MW/2 MWh
- University of California, Berkeley : gravity-based energy storage system that uses compressed air**.**

Largest Capacity

Acquired The largest capacity acquired by a gravity-based energy storage system is 25 MW/100 MWh. This system was developed by Energy Vault and is located in China.

Cost of Energy Storing

Costs for solid gravity energy storage systems vary by technology and scale. Energy Vault and similar companies target a cost range of approximately \$60–\$150/kWh (~ 5,000–12,500/kWh) at commercial scale, significantly lower than earlier estimates. Round-trip efficiency above 80% and zero storage degradation over time improve the long-term economics compared to chemical batteries.

Space needed to implement

A typical Pumped Hydro Storage plant requires about 10 acres of land per GWh of storage capacity. Solid Gravity Energy Storage systems require about 1-2 acres of land per GWh of storage capacity.

Positives and Challenges

- Gravity-based energy storage systems offer several advantages over other types of energy storage systems, including:
- They have a long life span and require little maintenance.
- They are relatively expensive to build.
- They can store large amounts of energy for long periods of time.

However, gravity-based energy storage systems also have some challenges, including:

- They are not as efficient as other types of energy storage systems.
- They can only be used in certain locations with the right terrain.
- They can have a visual and environmental impact.

Applications

- **Grid stabilisation:** It can help stabilise the electrical grid by balancing supply and demand, mitigating the intermittency of renewable energy sources.
- **Large-Scale Energy Storage:** It can be used for utility-scale energy storage to support large cities or industrial operations.

- **Renewable Integration:** Gravity storage can store excess energy from wind and solar farms, releasing it when these sources are less productive.
- **Remote and Off-Grid Areas:** It can provide reliable power in remote or off-grid areas where a constant energy supply is essential.
- **Resilience:** Gravity storage can serve as a backup power source during grid outages and emergencies.

THERMAL ENERGY STORAGE

Thermal energy storage (TES) is a key technology for enabling a clean energy future. TES systems can store heat or cold for later use, which can help to balance energy demand and supply, reduce energy costs, and improve energy efficiency. TES systems are used in a variety of applications, including heating and cooling of buildings, industrial processes, and power generation.

There are three main types of TES systems: sensible heat storage, latent heat storage, and thermochemical storage. Sensible heat storage systems store heat energy by raising the temperature of a material. Latent heat storage systems store heat energy by melting a solid material. Thermochemical storage systems store heat energy by using chemical reactions.

TES systems play an important role in the integration of renewable energy sources into the grid. For example, TES systems can be used to store solar energy during the day and release it at night, when demand is higher.

TES systems can also be used to store wind energy when the wind is blowing and release it when the wind is not blowing. TES systems are still under development, but they have the potential to revolutionize the way we generate and use energy. TES systems can help us to reduce our reliance on fossil fuels, improve energy efficiency, and create a more sustainable energy future.

i. SENSIBLE HEAT STORAGE

Overview

Sensible heat storage is the simplest and most widely used form of thermal energy storage. It involves storing energy by raising or lowering the temperature of a material without any change in its physical state. The amount of heat stored depends on the mass of the material, its specific heat capacity, and the temperature change.

$$Q = m^{*}c_p\Delta T$$

Where:

Q = heat stored (J)

m = mass of the material (kg)

c_p = specific heat capacity (J/kg·K)

ΔT = temperature change (K)

This method is widely used because it is simple, cost-effective, and uses readily available materials such as water, rocks, sand, and molten salts. Although it has lower energy density compared to other TES types, it remains dominant due to its reliability and ease of implementation.

a) Liquid-Based Sensible Heat Storage

Liquid-based systems use fluids such as water, thermal oils, or molten salts as storage media. These systems are highly efficient because liquids can circulate, allowing rapid heat transfer through convection.

Water is commonly used for low-temperature applications such as domestic heating and cooling. For high-temperature applications like concentrated solar power plants, molten salts are used due to their thermal stability and ability to store heat at temperatures above 500°C.

$$Q = m*c_p(T_{out} - T_{in})$$

Where:

m = mass flow rate (kg/s)

c_p = specific heat capacity (J/kg·K)

T_{out}, T_{in} = outlet and inlet temperatures (K)

These systems are widely used because of their high efficiency, ease of operation, and scalability. They are commonly found in solar thermal plants, industrial heating systems, and district heating networks.

b) Solid-Based Sensible Heat Storage

Solid-based sensible heat storage systems use materials such as rocks, sand, concrete, bricks, or ceramics to store thermal energy. These materials are chosen because they are inexpensive, widely available, and capable of withstanding high temperatures. Unlike liquid systems, solids do not flow, so a separate heat transfer fluid (such as air or oil) is required to carry heat into and out of the storage medium.

In most designs, the solid material is arranged as a packed bed, where small particles or blocks are stacked together with spaces between them. A hot fluid flows through these spaces, transferring heat to the solid material during charging. During discharge, a cooler fluid is passed through the bed, extracting the stored heat.

The temperature distribution within the solid is governed by heat diffusion:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T$$

Where:

T = temperature (K)

t = time (s)

α = thermal diffusivity (m^2/s)

In practical systems, heat does not spread evenly. Instead, a temperature front (called a thermocline) moves through the material. This behavior affects how efficiently heat can be stored and retrieved.

From a practical perspective, solid-based systems are attractive because:

- Materials like sand and rocks are extremely cheap
- They can operate at very high temperatures (>1000°C)
- They are durable and have long lifespans

These systems are increasingly being used for:

- Industrial waste heat recovery
- Renewable energy storage
- Long-duration energy storage

However, they also have limitations:

- Heat transfer is slower compared to liquids
- Large volumes are required
- Designing efficient airflow is challenging

Despite these challenges, solid-based storage is gaining attention as a low-cost solution for large-scale energy storage.

c) Electric Thermal Energy Storage

Electric Thermal Energy Storage (ETES) systems convert electrical energy into heat and store it in high-temperature solid materials such as ceramics or graphite. These systems are especially useful for storing excess renewable electricity (from solar or wind) and using it later when demand increases.

The process is based on resistive (Joule) heating, where electrical energy is directly converted into heat with very high efficiency. The stored heat can then be used for industrial processes, steam generation, or converted back into electricity.

ETES is considered a cost-effective solution for large-scale and long-duration energy storage, particularly where heat is the final requirement. However, reconversion of heat to electricity involves efficiency losses due to thermodynamic limits.

$$P_{in} = Q_{stored} + \text{losses}$$

Where:

P_{in} = electrical input power (W)

Q_{stored} = stored thermal energy rate (W)

During charging, electricity is passed through heating elements, generating heat through Joule heating. This heat is then stored in the solid medium. The conversion of electricity to heat is nearly 100% efficient.

During discharge, the stored heat can be used in several ways:

- Direct industrial heating
- Steam generation
- Conversion back to electricity using turbines or thermophotovoltaic systems

From a real-world perspective, ETES is particularly important because:

- It allows excess renewable electricity (solar/wind) to be stored
- It reduces curtailment of renewable energy
- It provides a lowcost alternative to batteries for long-duration storage

Recent developments show that thermal storage can be significantly cheaper than battery storage, making it attractive for industrial applications.

However, when converting heat back into electricity, efficiency drops due to thermodynamic limits. Despite this, ETES remains highly valuable for applications where heat is directly required.

d) Underground Thermal Energy Storage (UTES)

Underground Thermal Energy Storage (UTES) systems store thermal energy in natural geological formations such as soil, rock, aquifers, or boreholes. These systems are particularly useful for large-scale and seasonal storage.

$$Q = \rho V c_p \Delta T$$

Where:

ρ = density (kg/m^3)

V = volume (m^3)

c_p = specific heat capacity

ΔT = temperature change (K)

UTES systems work by circulating a heat transfer fluid through pipes embedded underground. Heat is transferred to the surrounding ground during charging and extracted during discharging.

There are several types:

- Borehole Thermal Energy Storage
- Aquifer Thermal Energy Storage
- Pit Thermal Energy Storage

From a practical perspective:

- Heat can be stored in summer and used in winter
- The ground acts as a natural insulation layer

- Large volumes allow massive energy storage

These systems are commonly used in:

- District heating systems
- Large buildings and campuses
- Smart city infrastructure

However, UTES systems depend heavily on geological conditions. Factors such as soil type, groundwater flow, and thermal conductivity significantly affect performance.

ii. LATENT HEAT STORAGE

Latent heat storage (LHS) is a method of thermal energy storage in which energy is stored during a phase change of a material, most commonly between solid and liquid states. Unlike sensible heat storage, where temperature continuously increases with energy input, latent heat storage allows energy to be absorbed or released at nearly constant temperature. This occurs because the supplied energy is used to change the internal molecular structure rather than increasing kinetic energy.

$$Q = mL + mc_p\Delta T$$

Where:

Q = total heat stored (J)

m = mass (kg)

L = latent heat of phase change (J/kg)

c_p = specific heat (J/kg·K)

ΔT = temperature change (K)

During the phase change process, heat is absorbed (endothermic process) when a material melts and released (exothermic process) when it solidifies. The key advantage of this mechanism is that a large amount of energy can be stored within a small temperature range, making it highly efficient for applications requiring temperature regulation.

Latent heat storage systems have significantly higher energy density than sensible heat storage, often 2 to 10 times higher, allowing for smaller and more compact storage systems.

Another important characteristic is the near-isothermal nature of storage. Since the temperature remains nearly constant during phase change, these systems are ideal for applications such as:

- Building thermal comfort
- Solar thermal energy storage
- Air conditioning and refrigeration
- Electronics cooling

However, the performance of latent heat storage systems depends heavily on the properties of the phase change material (PCM). Ideal PCMs should have:

- High latent heat capacity
- Suitable phase change temperature
- High thermal conductivity
- Chemical and thermal stability
- Low cost and availability

Despite their advantages, latent heat systems face challenges such as low thermal conductivity, supercooling, phase segregation, and material degradation over repeated cycles.

a) Phase Change Material (PCM) Systems

Phase Change Material (PCM) systems store thermal energy during phase transitions, typically from solid to liquid. During this process, energy is absorbed or released at nearly constant temperature, making these systems highly efficient for temperature control applications.

PCM systems are widely used in buildings, refrigeration, and electronics cooling due to their high energy density and ability to maintain stable temperatures. However, their performance depends on material properties such as melting point, thermal conductivity, and stability.

To improve heat transfer, design enhancements like fins or encapsulation are often used. Challenges include low thermal conductivity, supercooling, and material degradation.

$$Q = m^*c_p(T_m - T_i) + mL + m^*c_p(T_f - T_m)$$

Where:

T_i = initial temperature

T_m = melting temperature

T_f = final temperature

L = latent heat of phase change (J/kg)

Working Principle

- Sensible Heating (Before Phase Change): The temperature of the material increases until it reaches the melting point.
- Latent Heat Storage (Phase Change): At the melting temperature, the material absorbs heat without temperature rise. This energy is stored in molecular bonds as latent heat.

- Sensible Heating (After Phase Change): Once fully melted, additional heat raises the temperature again.

During cooling, the reverse process occurs, and the stored heat is released.

Types of PCM

PCMs are broadly classified into:

- Organic PCMs (paraffins, fatty acids)
  - Stable and non-corrosive
  - Low thermal conductivity
- Inorganic PCMs (salt hydrates, metals)
  - Higher energy density
  - Can suffer from phase separation
- Eutectic mixtures
  - Combination of materials with tailored melting points

Practical Design Considerations

PCM systems are not just about the material; they require:

- Heat exchangers for effective heat transfer
- Encapsulation (micro or macro) to prevent leakage
- Proper container design to handle volume changes

Heat transfer is a major challenge because most PCMs have low thermal conductivity. To overcome this, enhancements such as fins, metal matrices, or nanoparticles are used.

Real-World Applications

PCM systems are widely used in:

- Buildings (thermal walls, ceilings)

- Solar water heating systems
- Refrigeration and cold storage
- Thermal management of electronics

For example, in buildings, PCMs absorb excess heat during the day and release it at night, reducing energy consumption.

Limitations

- Low heat transfer rate
- Supercooling effects
- Phase segregation
- Limited lifecycle

Despite these challenges, PCM systems remain one of the most promising latent heat storage technologies.

b) Ice Thermal Energy Storage

Ice Thermal Energy Storage (ITES) uses water as a phase change material to store cooling energy in the form of ice. It takes advantage of the high latent heat of fusion of water, allowing large energy storage at a constant temperature of 0°C.

These systems are mainly used to shift electricity usage from peak to off-peak hours by producing ice at night and using it for cooling during the day. ITES is widely applied in commercial buildings, airports, and district cooling systems.

While it reduces energy costs and peak demand, it requires refrigeration systems and is limited to cooling applications.

$$H_2O(l) \leftrightarrow H_2O(s)$$

Where:

$H_2O(l)$ = liquid water

$H_2O(s)$ = ice

The system relies on the high latent heat of fusion of water (~334 kJ/kg), which allows large amounts of energy to be stored at a constant temperature (0°C).

Working Principle

Charging (Freezing Stage)

- Water is cooled using a refrigeration system
- Heat is removed, and ice is formed
- Energy is stored as latent heat

Storage Stage

- Ice is maintained in insulated tanks
- Minimal energy loss occurs

Discharging (Melting Stage)

- Warm fluid passes over ice
- Ice melts, absorbing heat and providing cooling

System Configurations

- Ice-on-coil systems
- Encapsulated ice storage
- Slurry ice systems

Application

- Commercial buildings
- Airports
- Data centres
- District cooling systems

Advantages

- High energy density
- Reduces peak electricity demand
- Smaller chiller size required

Challenges

- Requires refrigeration system

- Limited to cooling applications
- Heat exchanger design complexity

Real-World Insight

ITES is one of the few TES systems that is already widely commercialized because it directly reduces electricity bills and peak demand charges.

iii. THERMO CHEMICAL ENERGY STORAGE

Thermochemical Energy Storage (TCS) stores energy through reversible chemical reactions. During charging, heat drives an endothermic reaction, and during discharge, the reverse reaction releases heat.

A key advantage of TCS is that energy can be stored without thermal losses, as it is stored in chemical form. These systems also offer very high energy density and are suitable for long-term and seasonal storage.

However, they are complex to design and require careful control of reaction conditions and materials.

$$AB + \text{Heat} \leftrightarrow A + B$$

Where:

AB = reactant compound

A, B = reaction products

During the charging phase, heat is supplied to drive an endothermic reaction, breaking chemical bonds. The products are stored separately. During discharge, the reverse reaction occurs, releasing heat.

A major advantage of TCS is that energy can be stored without thermal losses, since the products can be kept at ambient temperature.

TCS systems offer:

- Very high energy density
- Long-term (seasonal) storage capability

- Minimal heat loss over time

They are particularly suitable for:

- Solar thermal power plants
- Industrial heat storage
- Long-duration energy storage

a) Calcium Hydroxide System

This system is based on the reversible reaction between calcium hydroxide and calcium oxide. Heat is stored during the dehydration of calcium hydroxide and released during the hydration of calcium oxide.

It operates at moderate temperatures (400–600°C) and uses low-cost, widely available materials. The separation of products allows storage without heat loss.

Challenges include slow reaction rates and material degradation over repeated cycles.

$$Ca(OH)_2 \leftrightarrow CaO + H_2O$$

Where:

$Ca(OH)_2$ = calcium hydroxide

CaO = calcium oxide

H_2O = water vapor

This system operates based on a reversible dehydration–hydration reaction.

Working Principle

Charging (Dehydration): $Ca(OH)_2 \rightarrow CaO+H2O$

- Heat is supplied (400–600°C)
- Water vapor is released
- Energy is stored in chemical bonds

Storage:

- CaO and water vapor are stored separately

- No thermal losses occur

Discharging (Hydration): $CaO + H_2O \rightarrow Ca(OH)_2$ + Heat

- Water vapor recombines with CaO
- Heat is released

Practical Insights

- Materials are cheap and widely available
- System operates at moderate temperatures
- Suitable for solar and industrial heat storage

Challenges

- Slow reaction kinetics
- Material degradation after cycles
- Reactor design complexity

Real-World Potential

This system is being studied for:

- Solar thermal storage
- Industrial heat recovery
- Decarbonization technologies

b) Calcium Carbonate System

The calcium carbonate system is another important thermochemical storage technology that operates at higher temperatures compared to the calcium hydroxide system. It is based on the reversible calcination and carbonation reaction between calcium carbonate, calcium oxide, and carbon dioxide.

This system is particularly relevant for high-temperature applications such as concentrated solar power plants and industrial processes. During the charging phase, calcium carbonate is heated to high temperatures (700–900°C), causing it to decompose into calcium oxide and carbon dioxide. This process absorbs a significant amount of energy, which is stored chemically.

The ability to store CO_2 separately makes this system highly versatile. During discharge, carbon dioxide is recombined with calcium oxide, releasing heat through an exothermic reaction. This feature also opens opportunities for integration with carbon capture and storage (CCS) technologies, making it environmentally beneficial.

The calcium carbonate system offers very high energy density and uses materials that are already widely used in industries such as cement and lime production. This makes it easier to scale and integrate into existing infrastructure.

$$CaCO_3 \leftrightarrow CaO + CO_2$$

Where:

$CaCO_3$ = calcium carbonate

CaO = calcium oxide

CO_2 = carbon dioxide

This system is based on the reversible calcination–carbonation reaction and operates at higher temperatures.

Working Principle

Charging (Calcination): $CaCO_3 \rightarrow CaO + CO_2$

- Heat is absorbed (~700–900°C)
- CO_2 gas is released

Storage:

- CaO and CO_2 stored separately
- No energy loss

Discharging (Carbonation): $CaO + CO_2 \rightarrow CaCO_3 + \text{Heat}$

Practical Importance

- Very high energy density
- Relevant to cement and lime industries
- Can integrate with carbon capture systems

Real-World Perspective

This system is particularly attractive because:

- It uses materials already used in industry
- It can reduce CO_2 emissions
- It supports circular energy systems

Challenges

- Handling and storage of CO_2
- High temperature requirements
- Reactor durability

c) Sorption Systems

The key principle behind sorption systems is the reversible interaction between the sorbent and the sorbate. During the charging phase, heat is applied to remove the working fluid from the sorbent, storing energy in the process. During discharge, the working fluid is reabsorbed or adsorbed, releasing heat.

One of the most significant advantages of sorption systems is their ability to store energy with minimal losses over long periods. Since the working fluid and sorbent can be stored separately, there is no continuous heat loss, making these systems ideal for seasonal storage.

$$Q = m \cdot \Delta H_{ads}$$

Where: H_{ads} = enthalpy of adsorption

Sorption systems store energy through adsorption or absorption processes involving a working fluid and a sorbent material.

Working Principle

- Heat input removes moisture (charging)
- Moisture reabsorption releases heat (discharging)

Applications

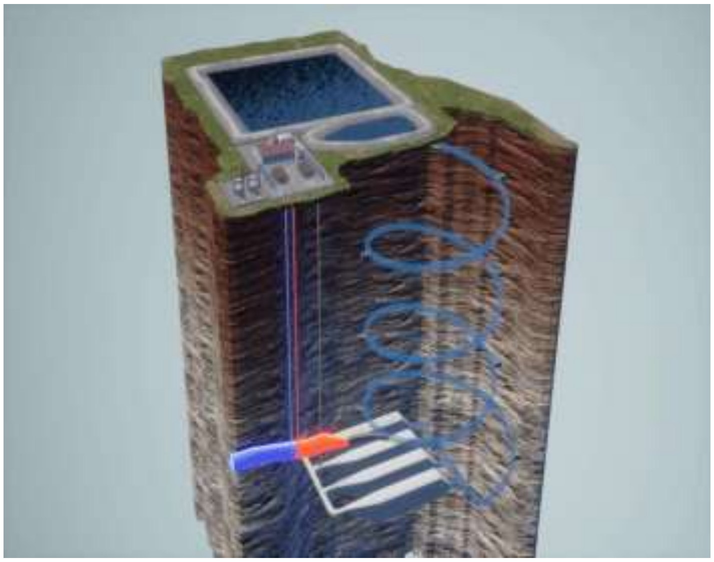
- Building heating and cooling
- Seasonal storage
- Solar energy systems

Key Advantage

Extremely low energy loss over

COMPRESSED AIR ENERGY STORAGE SYSTEM

Compressed air energy storage (CAES) is a way to store energy for later use by compressing air and storing it in underground caverns, salt domes, or aquifers. When the energy is needed, the compressed air is released and expanded through a turbine to generate electricity.



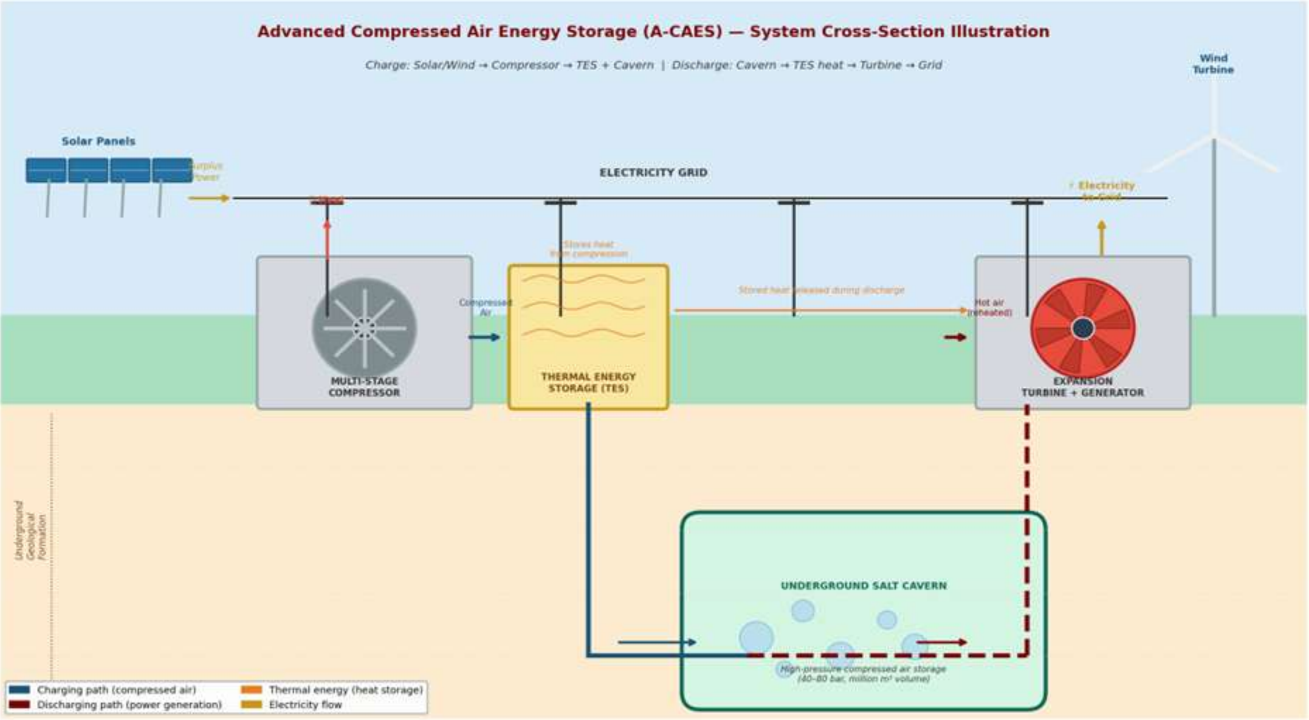
CAES systems are one of the most mature energy storage technologies available, and they have been in commercial operation for decades. CAES systems are well-suited for large-scale energy storage applications, and they can provide reliable and affordable electricity for peak demand and grid balancing.

CAES systems are also well-suited for integration with renewable energy sources. For example, CAES systems can be used to store excess solar and wind energy when the sun is not shining and the wind is not blowing. CAES systems can then be used to generate electricity when demand is high and renewable energy sources are not available.

CAES systems are playing an increasingly important role in the global energy mix. As the world transitions to a clean energy future, CAES systems will provide the reliable and affordable energy storage that is needed to integrate renewable energy sources into the grid.

i. ADVANCED COMPRESSED AIR ENERGY STORAGE (A-CAES)

Overview



Advanced Compressed Air Energy Storage (A-CAES) eliminates the fundamental flaw of first-generation CAES — the need to burn supplementary natural gas to reheat expanding air. Instead, A-CAES captures and stores the heat generated during compression in a dedicated Thermal Energy Storage (TES) unit. This stored heat is returned to the air during the discharge phase, making A-CAES a fully fuel-free, zero-emission energy storage solution with round-trip efficiencies of 65–72%.

Working Principle

A-CAES operates in two phases: charging (energy storage) and discharging (power generation) with one transformative innovation: thermal energy is captured during compression and stored separately, then reunited with the compressed air only at the point of generation, eliminating any need for fossil fuel reheating.

Charging Phase (Storing energy)

- Surplus renewable electricity (solar or wind) drives a multi-stage air compressor.
- Compression generates significant heat (300–600°C). This heat is extracted by a heat exchanger and stored in the Thermal Energy Storage (TES) unit packed with rocks, molten salt, or pressurised water.
- The now-cooled, high-pressure air is pumped into the underground geological formation at 40–80 bar pressure equivalent to 40–80 times atmospheric pressure.
- The system holds the compressed air and the stored heat separately until power is needed. The underground cavern acts as the energy reservoir.

Discharging Phase (Storing energy)

- On demand, the cavern valves open and high-pressure air flows to the surface.
- Before entering the turbine, the air passes through the TES unit and picks up the stored heat arriving at the turbine hot, pressurised, and energetic. No fossil gas is burned at any stage.
- The hot, high-pressure air expands through multi-stage expansion turbines, driving a generator that delivers electricity to the grid.
- The now low-pressure, cooled air exits to the atmosphere harmlessly. The cycle is complete and can repeat immediately.

Underground Storage — The Geological Heart of A-CAES

The underground cavern is the defining physical component that gives A-CAES its bulk storage capability and long operational life. Unlike batteries where storage is limited by electrode chemistry, the storage capacity of A-CAES scales with cavern volume — which can be millions of cubic metres.

Types of Underground Storage for CAES

Compressed Air Energy Storage (CAES) systems rely on suitable underground formations to store compressed air safely and efficiently. Different types of geological structures are used based on availability, cost, and technical feasibility.

•**Salt Caverns (Most Preferred):** Salt caverns are the most widely used and preferred option for CAES. They are naturally airtight and chemically inert, which prevents leakage and contamination. These caverns can be easily created using solution mining techniques and are capable of withstanding high pressures without fracturing, making them highly reliable for long-term storage.

•**Depleted Gas or Oil Fields:** These are previously used reservoirs that have already proven their ability to store gases under pressure. They offer large storage volumes and existing infrastructure advantages. However, since they are porous in nature, there is a risk of air leakage, and continuous monitoring is required to ensure safe operation.

•**Hard Rock Caverns (Mined Tunnels):** Hard rock caverns are artificially constructed underground storage spaces created by mining. They can be developed in locations where salt formations are not available, offering flexibility in site selection. However, construction costs are higher due to excavation and engineering requirements.

•**Porous Aquifers:** Aquifers are underground water-bearing rock formations that can potentially be used for air storage. However, their use is less common due to challenges associated with water displacement, pressure control, and system complexity.

Researching Universities/Institutions/Companies

Advanced Adiabatic Compressed Air Energy Storage (A-CAES) is gaining increasing global attention as a promising long-duration energy storage technology. Its development is being actively supported by leading research institutions, universities, utilities, and private companies across various regions. These organizations are contributing to advancements in system efficiency, thermal energy storage integration, underground cavern engineering, and commercial-scale deployment. China currently leads in large-scale implementation, while North America and Europe are progressing through technology development and major utility-scale projects. Australia has emerged as an active market for new installations, and India is in the early stages of research, feasibility assessment, and policy planning for future adoption.

- **China** is one of the global leaders in A-CAES development, supported by the Institute of Engineering Thermophysics (IET) under the Chinese Academy of Sciences, which has played a pioneering role in the technology. Other major contributors include Zhongchu Guoneng (ZCGN), Huaneng Group, Tsinghua University, and Jiangsu University, all of which are involved in research, engineering, and commercial deployment.

- In **North America**, Hydrostor Inc. (Canada/USA) is a leading commercial developer of A-CAES systems, with large-scale projects under development in California. Other important contributors include Apex CAES, the National Renewable Energy Laboratory (NREL), Lawrence Berkeley National Laboratory, and utility companies such as PG&E.

- **Europe** is also advancing in this field through companies such as Corre Energy (Netherlands), Eneco, and Storelectric (UK). Academic and technical institutions including the University of Birmingham, ETH Zurich, and the German Aerospace Center (DLR) are carrying out important research and system development. Industrial support is also provided by Siemens Energy.

- **Australia** has shown growing momentum in A-CAES deployment with Hydrostor’s Angas A-CAES project in South Australia already operational. The Broken Hill A-CAES project with a planned capacity of 200 MW has also received environmental clearance in 2025.

- In **India**, institutions such as IIT Bombay, IIT Delhi, IIT Madras, and IISc Bengaluru have the potential to contribute significantly to future A-CAES research and development. Public sector organizations such as NTPC, CSIR, and SECI can play an important role in feasibility studies, geological surveys, pilot projects, and future commercial implementation. With increasing renewable energy capacity and suitable geological conditions, India presents strong long-term potential for A-CAES adoption.

Largest capacity acquired

The largest capacity compressed air energy storage (CAES) facility in the world is the Huai'an Salt Cavern CAES plant in China, fully commissioned in 2026. It has a total energy capacity of 2,400 megawatt-hours (MWh) and can generate up to 600 megawatts (MW) of electricity for four hours at full load with a round-trip efficiency of 71%.

Specific capacity

0.2–0.5 kWh/m³

Space needed to implement

Estimated space needed:

- 250 MW / 1 GWh — 1 million cubic meters of space.
- 500 MW / 2 GWh — 2 million cubic meters of space.
- 1.5 GW / 6 GWh — 6 million cubic meters of space.

Cost of storing energy

According to updated global studies (including NREL and IEA 2025-26 data), the Levelized Cost of Storage (LCOS) for CAES is estimated to be between ₹2,100 and ₹4,200 per megawatt-hour (MWh). This positions CAES as one of the most cost-effective technologies for long-duration storage exceeding 8 hours.

Applications and Significance

Compressed Air Energy Storage (CAES) has multiple applications in modern power systems and is increasingly valued for its ability to provide long-duration, utility-scale energy storage.

• **Renewable Energy Firming (38%):** CAES stores excess solar and wind energy during periods of high generation and releases it during evening or peak demand hours. This helps address the “duck curve” problem commonly seen in renewable-rich grids and improves the reliability of power systems such as those with growing solar penetration.

- **Peak Shaving and Energy Arbitrage (25%):** CAES can charge using low-cost electricity during off-peak hours and discharge during periods of high demand when electricity prices are higher. This reduces overall electricity costs for utilities and consumers while improving grid economics.

- **Grid Balancing and Frequency Regulation (17%):** CAES supports grid stability by absorbing surplus electricity or injecting stored power when renewable output fluctuates. It helps maintain frequency balance and can operate alongside faster-response technologies such as supercapacitors and batteries.

- **Backup Power and Black-Start Capability (10%):** CAES can provide emergency backup power during outages. It also offers black-start capability, meaning it can help restore power to a completely shut-down grid without relying on external electricity supply. This is particularly valuable after cyclones, storms, or other natural disasters.

- **Transmission Deferral (6%):** By installing CAES near demand centres or grid congestion points, utilities can defer or avoid expensive transmission and distribution upgrades. This helps reduce capital expenditure while improving local grid reliability.

- **Seasonal and Ultra-Long Duration Storage (4%):** CAES can store energy for several days or even weeks, making it suitable for bridging seasonal mismatches between renewable generation and demand. This capability is especially important for future energy systems and is difficult to achieve economically using conventional battery technologies.

Positives and Challenges

The positives of A-CAES include: Large-scale projects like the Silver City Energy Storage System (1.6 GWh) in Australia and the Huai'an project (2.4 GWh) in China are proving the commercial viability of emission-free storage. These initiatives provide prolonged duration (4–24+ hours) and extreme durability (50+ years). By utilizing Advanced Adiabatic (A-CAES) technology, these plants eliminate fossil fuel use, significantly enhancing power supply reliability and contributing to national clean energy goals.

The Challenges of A-CAES include: One of the main challenges is associated with geological dependency, as high-capacity systems typically require specific underground formations like salt caverns. Additionally, while efficiency has reached 70%+, engineering and thermal modeling for high-temperature heat exchange remain complex, requiring high up-front capital investment compared to shorter-duration battery alternatives.

VII. SUPER CAPACITANCE BASED ENERGY STORAGE

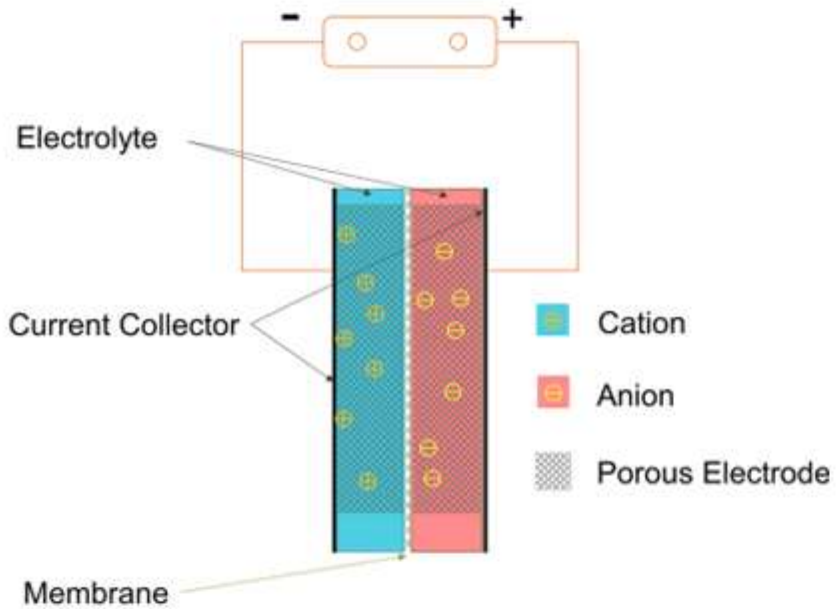
Supercapacitance-based energy storage (SCES) is a promising technology for a variety of applications due to its high power density, fast charge/discharge rates, and long cycle life. Supercapacitors are energy storage devices that bridge the gap between electrolytic capacitors and rechargeable batteries. They can store more energy per unit volume or mass than electrolytic capacitors, can accept and deliver charge much faster than batteries, and tolerate many more charge and discharge cycles than rechargeable batteries.

SCES systems are typically composed of two electrodes immersed in an electrolyte. When the system is charged, ions from the electrolyte accumulate on the surface of the electrodes, forming an electric double layer. This electric double layer stores the energy in the system. When the system is discharged, the ions from the electrolyte flow back into the electrolyte, releasing the energy. The future of SCES is very bright. As the cost of SCES systems continues to decline and their performance improves, SCES is expected to play an increasingly important role in the global energy mix.

SCES is a promising technology with the potential to revolutionize the way we generate and use energy. SCES systems can help us to reduce our reliance on fossil fuels, improve energy efficiency, and create a more sustainable energy future.

i. SUPERCAPACITORS

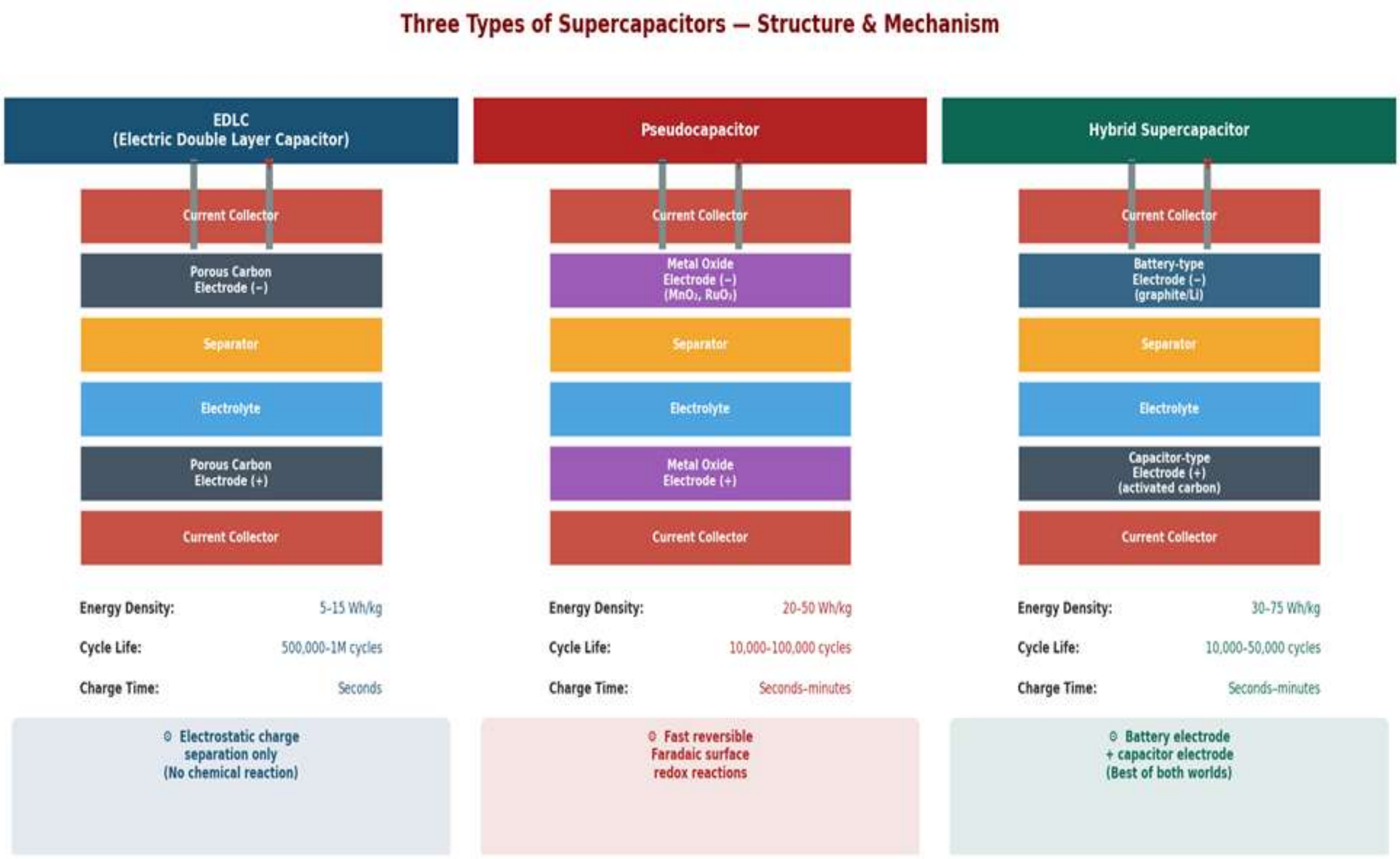
Overview



A supercapacitor also called an ultracapacitor is an energy storage device that stores electrical charge on the surface of its electrodes. Unlike a battery, which stores energy through chemical reactions deep inside its materials, a supercapacitor stores charge physically, at the surface. This is why supercapacitors charge and discharge in seconds, last for a million cycles, and never wear out chemically.

The key to a supercapacitor's performance is the electrode material usually activated carbon, which has an extraordinarily high surface area. One gram of activated carbon has a surface area of up to 3,000 square metres roughly the size of half a football field, packed into a space the size of a sugar cube. This enormous surface area is what allows the supercapacitor to store so much more charge than a conventional capacitor.

The three types of supercapacitors



Supercapacitors are not a single technology. They come in three distinct types, each storing energy in a slightly different way, offering a different balance of energy, power, and longevity.

Storage Mechanism

Supercapacitors store energy using different mechanisms based on their internal structure and electrode materials. These types are classified according to how charge is stored and transferred within the device.

- **EDLC (Electric Double-Layer Capacitor):** EDLCs store energy through physical charge separation at the interface between the electrode and electrolyte. No chemical reaction occurs during operation, which allows for extremely fast charging and discharging, as well as a very long cycle life.

- **Pseudocapacitor:** Pseudocapacitors store energy through fast and reversible surface-level chemical (redox) reactions on the electrode material. This mechanism provides higher energy storage compared to EDLCs, but involves partial chemical processes.

- **Hybrid Supercapacitor:** Hybrid supercapacitors combine one battery-type electrode with one capacitor-type electrode. This design allows them to achieve a balance between high energy density and high power density, offering improved overall performance compared to individual types.

Electric Double Layer Capacitors (EDLC)

The most commercially mature supercapacitor. An EDLC works by attracting ions from a liquid electrolyte onto the surface of two high-surface-area carbon electrodes. When voltage is applied, positive ions collect on one electrode and negative ions on the other, forming an extremely thin electric 'double layer' — just a few nanometres thick. This layer stores energy like a stretched spring. When the device is connected to a load, the ions return to the electrolyte, releasing the stored energy as electric current. Since no chemical reaction ever takes place, the process is completely reversible — the device never degrades, which is why EDLCs can last over a million charge-discharge cycles.

Key Specifications of EDLC

- **Energy Density:** Supercapacitors typically have an energy density in the range of 5 to 15 Wh/kg, which is lower than batteries but sufficient for short-duration energy storage applications.

- **Power Density:** They offer very high power density, generally between 1,000 and 10,000 W/kg, which is about 10 to 100 times higher than lithium-ion batteries, enabling rapid energy delivery.

- **Cycle Life:** Supercapacitors have an extremely long cycle life, ranging from 500,000 to over 1,000,000 cycles, making them almost maintenance-free over long periods.

- **Charge Time:** They can be charged within seconds, unlike batteries that typically require hours, making them suitable for applications requiring quick energy bursts.

- **Round-trip Efficiency:** Supercapacitors have very high efficiency, around 95% to 98%, meaning minimal energy is lost during charging and discharging.

- **Operating Temperature:** They can operate effectively over a wide temperature range of −40°C to +70°C, making them suitable for extreme environmental conditions.

- **Electrode Material:** Common electrode materials include activated carbon, which can have a surface area up to 3,000 m^2/g, as well as advanced materials like graphene and carbon nanotubes to enhance performance.

- **Electrolyte:** Supercapacitors use either organic electrolytes such as acetonitrile or ionic liquids, which allow operation at higher voltages.

- **Self-discharge Rate:** They exhibit a relatively high self-discharge rate of about 20% to 40% per day, meaning stored energy gradually reduces if not used.

- **Typical Cell Voltage:** A typical supercapacitor cell operates at around 2.5 V to 2.7 V, and multiple cells are connected in series for higher voltage applications.

Working

An Electric Double-Layer Capacitor (EDLC) operates through a purely physical process of charge storage without involving any chemical reactions. When the EDLC is connected to a power source, an electric field is established between its two electrodes. The electrolyte inside the capacitor contains mobile positive and negative ions, which begin to migrate under the influence of this electric field. Positive ions move toward the negatively charged electrode, while negative ions move toward the positively charged electrode.

As these ions accumulate at the surface of the electrodes, they form an extremely thin layer, only a few nanometres thick, known as the electric double layer. Energy is stored in this region in the form of an electrostatic field, similar to energy stored in a compressed spring. Since no chemical bonds are formed or broken during this process, the system remains highly stable and efficient.

When the EDLC is connected to a load such as a motor, sensor, or electrical grid, the stored energy is released as the ions move back into the electrolyte, generating an electric current. This discharge process occurs very rapidly, often within seconds. After discharge, the electrodes and electrolyte remain unchanged, allowing the capacitor to be recharged and used repeatedly. This reversible and non-degrading mechanism enables EDLCs to achieve extremely high cycle life, often exceeding hundreds of thousands to millions of cycles.

Key Advantage of EDLC

The single biggest advantage of an EDLC is its cycle life. A lithium-ion battery lasts 500–5,000 cycles before its capacity drops significantly. An EDLC lasts over a million cycles with no measurable degradation. At one full charge-discharge per day, that is 2,700 years of operation. Even at 100 cycles per day (as in intensive grid applications), that is 27 years of maintenance-free service. This is why EDLCs are preferred for applications involving thousands of daily cycles like regenerative braking in metro trains or grid frequency regulation.

Application of EDLC

- **Grid frequency regulation** responds in under 1 millisecond when grid frequency deviates, stabilising the power system before slower systems react
- **Regenerative braking** in metro trains, trams, and electric buses captures braking energy in seconds and reuses it for the next acceleration
- **UPS (Uninterruptible Power Supply)** for data centres and hospitals bridges the gap between power failure and backup generator startup
- **Wind turbine pitch control** adjusts blade angle instantly during sudden wind gusts to protect the turbine

- **Industrial crane energy recovery** stores energy when a load is lowered and returns it when the load is raised

Pseudocapacitors

A pseudocapacitor looks similar to an EDLC from the outside, but its electrode material is different typically a metal oxide like manganese dioxide (MnO_2) or ruthenium oxide (RuO_2), or a conducting polymer. When voltage is applied, these materials undergo fast, reversible chemical reactions on their surface not deep inside the material like a battery, but only at the outermost atomic layer. Because the reaction stays on the surface, it is much faster than a battery reaction and causes far less degradation over time. This allows pseudocapacitors to store 3–5 times more energy than an EDLC while still charging in seconds. The trade-off is a shorter cycle life than an EDLC typically 10,000–100,000 cycles, which is still far greater than any battery.

Key Specifications of Pseudocapacitors

Pseudocapacitors are an advanced type of supercapacitor that combine fast charge-discharge capability with higher energy storage through surface-level chemical reactions.

- **Energy Density:** Pseudocapacitors offer an energy density in the range of 20 to 50 Wh/kg, which is approximately 3 to 5 times higher than EDLCs, making them more suitable for applications requiring greater energy storage.

- **Power Density:** They provide high power density, typically between 500 and 5,000 W/kg, which is still significantly higher than conventional batteries, enabling rapid energy delivery.

- **Cycle Life:** The cycle life of pseudocapacitors ranges from 10,000 to 100,000 cycles, which is lower than EDLCs but still much higher than most battery technologies.

- **Charge Time:** They can be charged quickly, usually within seconds to a few minutes, maintaining the fast-response advantage of supercapacitors.

• **Round-trip Efficiency:** Pseudocapacitors have a high efficiency of around **85% to 95%**, ensuring minimal energy loss during operation.

• **Electrode Material:** Common electrode materials include **manganese dioxide (MnO_2)**, **ruthenium oxide (RuO_2)**, and conducting polymers such as **polyaniline** and **polypyrrole**, which enable fast redox reactions.

• **Key Advantage:** The main advantage of pseudocapacitors is their higher energy density compared to EDLCs, while still maintaining fast charging and discharging capabilities.

• **Key Limitation:** Some electrode materials, especially ruthenium oxide, are expensive, and certain materials may experience reduced stability over long-term cycling.

Applications of pseudocapacitors

- Portable electronics needing more energy than an EDLC but faster response than a battery
- Medical devices implantable sensors and cardiac defibrillators where both energy and speed matter
- Hybrid vehicle energy recovery in moderate-duty cycles
- Research and development of next-generation high-energy supercapacitor devices

Hybrid Supercapacitors

A hybrid supercapacitor uses two different types of electrodes: one electrode works like a battery (stores a large amount of energy through reversible chemical reactions), and the other works like an EDLC supercapacitor (stores charge physically for fast delivery). The battery electrode gives the device much higher energy density than a conventional EDLC. The capacitor electrode gives it much higher power and longer life than a conventional battery. The result is a device that sits comfortably between batteries and supercapacitors on the Ragone plot — offering energy densities of 30–75 Wh/kg with charge times of seconds to a few minutes. This is the fastest-growing type of supercapacitor, projected at a CAGR of 17.62% through 2031.

Key Specifications of Hybrid Supercapacitors

Hybrid supercapacitors combine the features of both batteries and conventional capacitors, offering a balance between high energy density and high power performance.

- **Energy Density:** Hybrid supercapacitors provide an energy density in the range of 30 to 75 Wh/kg, which approaches the lower range of lithium-ion batteries and is significantly higher than conventional EDLCs.

- **Power Density:** They deliver high power density, typically between 500 and 5,000 W/kg, allowing rapid energy transfer while still outperforming most battery systems in power delivery.

- **Cycle Life:** The cycle life ranges from 10,000 to 50,000 cycles, which is substantially higher than lithium-ion batteries that typically offer 500 to 5,000 cycles.

- **Charge Time:** These devices can be charged within seconds to a few minutes, maintaining the fast-charging advantage of supercapacitors.

- **Negative Electrode:** The negative electrode is battery-type, commonly made of materials such as graphite, lithium titanate ($Li_4Ti_5O_{12}$), or hard carbon, which helps increase energy storage capacity.

- **Positive Electrode:** The positive electrode is capacitor-type, usually composed of activated carbon, similar to EDLCs, enabling fast charge-discharge behavior.

- **Key Advantage:** The major advantage of hybrid supercapacitors is their ability to offer higher energy density than EDLCs while maintaining faster response than conventional batteries, making them suitable for a wide range of applications.

- **Market Growth:** Hybrid supercapacitors represent the fastest-growing segment in the supercapacitor market, with an expected growth rate of around 17.62% CAGR through 2031, driven by increasing demand in electric vehicles and energy storage systems.

- **Commercial Example:** Recent commercial developments include the Ioxus Hybrid Capacitor Series, launched in April 2025, highlighting ongoing advancements and industry adoption of hybrid supercapacitor technology.

Why Hybrid Supercapacitors are the future

The limitation of conventional EDLCs has always been low energy density — they can deliver power in a flash but run out quickly. Hybrid supercapacitors solve this by incorporating a battery-type electrode that holds much more energy, while the capacitor-type electrode ensures the power can still be delivered rapidly. As electrode materials improve — especially graphene, MXene, and lithium titanate — hybrid supercapacitors are approaching energy densities that begin to overlap with the lower range of lithium-ion batteries. Within the next 5–10 years, hybrid supercapacitors are expected to replace batteries entirely in many short-to-medium duration applications, as they offer comparable energy with far longer service life and faster response.

Applications of Hybrid Supercapacitors

- Electric vehicles — higher energy density allows longer distance assist during acceleration and more complete braking energy recovery
- AI data centre UPS — millisecond response with enough energy to bridge a 30–90 second power interruption until diesel generators start
- 48V mild-hybrid vehicle systems — EU Euro 7 regulation (effective 2025) requires these in all new European vehicles
- Electric aircraft and drones — weight-sensitive applications where energy density improvements are critical
- Grid-scale fast storage — hybrid supercapacitors are now being evaluated as replacements for short-duration Li-ion grid storage

Researching Universities/Institutions/Companies

The global development of advanced energy storage technologies, including supercapacitors and related high-power storage systems, is being supported by leading universities, research institutions, and industrial companies across multiple regions. These organizations are contributing to innovation in materials science, grid storage, electric mobility, fast-charging systems, and commercial manufacturing.

- **Asia:** Asia is one of the strongest centres for research and manufacturing in advanced energy storage. Major contributors include the National University of Singapore (NUS), Nanyang Technological University (NTU), Tsinghua University, Peking University, and the Chinese Academy of Sciences (CAS). Other important institutions include Shanghai Jiao Tong University, KAIST, Seoul National University, DGIST, Kyungpook National University, UNIST, Tokyo Institute of Technology, University of Tokyo, Osaka University, Tohoku University, IIT Madras, and Nagaland University.

- **Americas:** The Americas host several globally recognized institutions engaged in battery and capacitor innovation. Leading universities include the Massachusetts Institute of Technology (MIT), Stanford University, UCLA, University of Texas at Austin, University of South Carolina (CIBI), Georgia Tech, UC Berkeley, and Northwestern University. Major national laboratories such as Argonne National Laboratory, Lawrence Berkeley National Laboratory, National Renewable Energy Laboratory (NREL), and Pacific Northwest National Laboratory (PNNL) are also actively involved. Commercial contributors include Maxwell Technologies (Tesla) and Hydrostor (Canada/USA).

- **Europe:** Europe is an important region for advanced storage systems and industrial applications. Key organizations include Skeleton Technologies (Estonia/Germany), one of Europe's leading manufacturers, along with Allotrope Energy (UK), Fraunhofer ISE & IEE (Germany), AVL (Austria), Imperial College London, EPFL Lausanne, Technical University of Munich (TUM), University of Cambridge, ETH Zurich, Delft University of Technology, and Chalmers University of Technology.

- **Industry Leaders:** Major commercial leaders in advanced energy storage include Skeleton Technologies, Maxwell Technologies (Tesla), Panasonic, Murata Manufacturing, Eaton, Siemens, Kilowatt Labs, CAP-XX (Australia), Ioxus (USA), LS Materials (South Korea) known for its CellDule technology, Nippon Chemi-Con (Japan), SPEL Technologies (India), KYOCERA AVX, and Hydrostor in the CAES sector.

Largest Capacity Acquired

In a landmark study, researchers at the University of Texas at El Paso (UTEP) and the Medical University of Bialystok, Poland, reported the highest capacitance ever recorded in a supercapacitor, using a material with a carbon "nano-onion" core structure that creates multiple pores allowing for greater energy storage. The findings were published in *Scientific Reports* by Nature Portfolio. On the commercial/system scale, China's Huaneng Luoyuan Power Plant commissioned what is reported as the world's largest capacity supercapacitor energy storage system — a 5 MW unit operating in a hybrid mode alongside a 15 MW lithium battery, improving grid frequency regulation response time by more than 14 times.

Specific Capacity

Researchers from the Korea Institute of Science and Technology (KIST) and Seoul National University developed composite fiber supercapacitors using single-walled carbon nanotubes and polyaniline (PANI), achieving a specific capacitance of 1,714 F/g, an energy density of 418 Wh/kg, and a power density of 1,150 W/cm^3. The device retained nearly 100% of its original capacity after 100,000 charge/discharge cycles. This is a dramatic improvement over the 575 Wh/kg figure cited in older reports, and reflects the rapid progress in carbon nanotube and polymer-based electrode materials.

Space for Implementation

Supercapacitors are also relatively compact and lightweight, making them well-suited for space-constrained applications. For example, supercapacitors are being used in electric vehicles to provide peak power for acceleration and regenerative braking. They are also being used in aerospace applications to provide backup power for critical systems.

Cost of making

The cost landscape has shifted considerably. A typical supercapacitor system storing 15 seconds of electricity now carries a capital cost of around $10,000/kWh of energy, but only $40/kW of power making them highly competitive with lithium-ion batteries and flywheels for short-duration, high-frequency applications like voltage regulation. Graphene-enhanced supercapacitors are emerging as cost-reduction drivers, offering 15–20% higher energy density at comparable prices to traditional models, while manufacturing hubs in Asia particularly China dominate production with over 60% market share, leveraging economies of scale. In rupee terms, this broadly translates to roughly ₹830–₹16,600+ per Wh depending on type and scale, a wide range that reflects the diversity of applications from small consumer cells to MW-scale grid systems.

Applications across industries

Supercapacitors are widely used in modern electrical and electronic systems due to their high power density, rapid charging capability, and long operational life.

- **Electric and Hybrid Vehicles**: Supercapacitors are used for regenerative braking energy capture, peak power assistance during acceleration, start-stop systems, and 48V mild-hybrid vehicle architecture. They help improve fuel efficiency and reduce battery stress. Recent developments include advanced hybrid supercapacitor systems for high-performance automotive applications.

- **AI and Data Centres:** Supercapacitors provide millisecond-level Uninterruptible Power Supply (UPS) support for GPU clusters, servers, and AI computing infrastructure. Even short power interruptions can disrupt critical processing, making supercapacitors valuable for instant backup power. Hybrid UPS systems are increasingly being deployed in data centres worldwide.

- **Grid Frequency Regulation**: Supercapacitors can inject power almost instantly, often within less than one second, to stabilise grid frequency after sudden disturbances such as generator trips or renewable fluctuations. Their response speed is much faster than conventional batteries, allowing them to act as a bridge until slower backup systems respond.

- **Public Transport**: Electric buses, trams, and metro systems use supercapacitors for rapid charging at stations or bus stops, sometimes within 30 seconds. This reduces battery size requirements, lowers vehicle weight, and improves operational efficiency. Such systems are widely adopted in countries like China, Japan, and parts of Europe.

- **Renewable Energy Smoothing**: Supercapacitors absorb short-duration fluctuations in solar and wind output, helping maintain grid power quality and voltage stability. They are often used together with batteries or CAES systems to provide layered energy storage support.

- **Industrial Automation**: Supercapacitors are used in cranes, forklifts, elevators, and heavy machinery for energy recovery and peak power buffering. For example, cranes can recover energy during load lowering operations, reducing electricity consumption and lowering peak demand charges.

- **Consumer Electronics and Wearables**: Miniature and flexible supercapacitors are used in IoT sensors, wearable devices, health monitors, and compact electronics. They offer fast charging, long cycle life, and reliable performance for low-power portable systems.

- **Aerospace and Defence**: Supercapacitors are used for backup power in aircraft avionics, emergency systems, and pulse power applications. They are also suitable for aerospace environments because they can operate across a wide temperature range and withstand harsh conditions.

Challenges

Supercapacitors continue to face challenges around energy density limits, manufacturing costs, materials scalability, electrode design, electrolyte formulation, and the difficulty of scaling up fabrication techniques for industrial use. A shortage of precursor materials for synthetic graphene in mid-2025 caused a 12% price spike in high-end supercapacitor cells, revealing that the supply chain is not yet robust enough to handle the projected 20% CAGR in demand. However, progress is accelerating: hybrid supercapacitors combining the rapid charge/discharge capability of supercapacitors with the substantial energy storage of batteries achieved an ultra-high specific capacitance of 2,390 F/g in recent studies, along with excellent cycle stability. The global supercapacitors market is projected to grow from $3.29 billion in 2026 to $12.39 billion by 2034, at a CAGR of 18.1%.

VIII. MAGNETIC ENERGY STORAGE

Magnetic energy storage (MES) is a technology that stores energy in a magnetic field. This magnetic field can be generated by an electric current flowing through a coil of wire. MES systems are highly efficient and can store large amounts of energy for long periods of time.

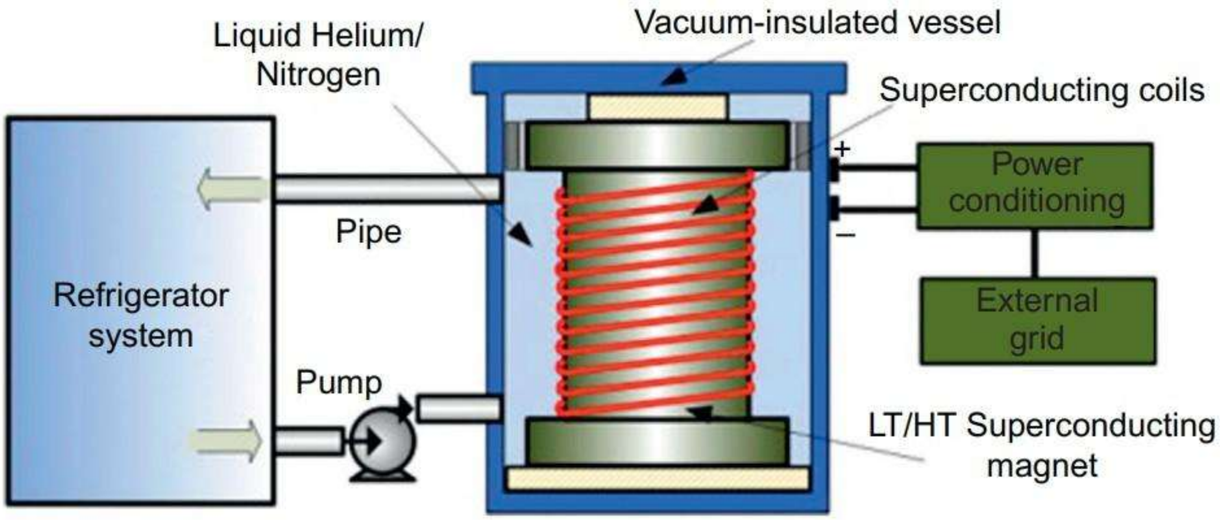
There are two main types of MES systems: superconducting magnetic energy storage (SMES) and inductive magnetic energy storage (IMES).

SMES systems use superconducting coils to store energy. Superconducting coils have zero electrical resistance, which means that they can store energy for long periods of time without any losses.

SMES systems are very efficient, but they are also very expensive. IMES systems use inductive coils to store energy. Inductive coils have some electrical resistance, which means that they lose some energy over time. However, IMES systems are less expensive than SMES systems.

i. SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES)

Overview



Superconducting Magnetic Energy Storage (SMES) is an advanced energy storage technology in which electrical energy is stored in the magnetic field generated by a direct current flowing through a superconducting coil. This coil is maintained at cryogenic temperatures to achieve superconductivity, thereby eliminating electrical resistance sand allowing energy to be stored with extremely high efficiency. Unlike conventional storage systems such as batteries or pumped hydro torage, SMES is designed primarily for high-power, short-duration applications, making it particularly suitable for power quality improvement and grid stability. Due to its near-instantaneous response time and minimal energy loss, SMES has emerged as a critical technology in modern power systems, especially with the increasing penetration of renewable energy sources.

Working principle

SMES is a unique energy storage technology that utilises the flow of electric current to generate a magnetic field, which serves as the storage medium. This current circulates continuously until it's required for discharge. The working principle of Superconducting Magnetic Energy Storage (SMES) is based on the unique properties of superconductors, which exhibit zero electrical resistance and can maintain persistent currents without energy loss.

The operation of SMES is based on the principle of electromagnetic energy storage, where energy is stored in the magnetic field created by a current circulating through a superconducting coil. The stored energy is mathematically expressed as:

$$E= \frac{1}{2} LI^2$$

where E represents the stored energy, L is the inductance of the coil, and I is the current flowing through it. Because the coil is superconducting, the current can persist without decay, allowing the system to maintain stored energy with negligible losses. The system typically consists of a superconducting magnet, a power conditioning system for interfacing with the grid, and a cryogenic refrigeration unit to maintain the required low temperatures. This configuration enables SMES systems to deliver or absorb power within milliseconds, making them highly effective for stabilizing power fluctuations.

Largest capacity acquired

The capacity of Superconducting Magnetic Energy Storage (SMES) systems is fundamentally constrained by factors such as superconducting material limitations, mechanical stresses due to high magnetic fields, cryogenic requirements, and overall system cost. As a result, unlike conventional energy storage technologies, SMES systems are not designed for large-scale energy storage but rather for high-power, short-duration applications. The largest capacities achieved to date are summarized as follows:

- Experimental/Demonstration Systems:

  The largest experimentally demonstrated SMES systems have achieved capacities in the range of 20–30 megajoules (MJ), which corresponds to approximately 5–8 kilowatt-hours (kWh). These systems represent the current upper limit of practical implementation using existing superconducting materials and engineering techniques.

- Commercial / Industrial Systems:

  Most commercially deployed SMES systems operate in the range of 1–10 MJ, primarily for applications such as power quality improvement, voltage stabilization, and protection of sensitive industrial equipment.

- Advanced Research Prototypes:

  Recent research developments have focused on 10 MJ-class high-temperature superconducting (HTS) SMES systems, utilizing materials such as YBCO and REBCO, with improvements in efficiency, compactness, and reduced cryogenic load.

- Theoretical / Conceptual Large-Scale Systems:

  Conceptual designs have proposed megawatt-hour (MWh) to gigawatt-hour (GWh) scale SMES systems, but these would require extremely large superconducting coils (potentially hundreds of meters in diameter), making them currently impractical due to structural, economic, and safety constraints

Specific capacity

The energy density of SMES systems reflects their specialization as high-power storage devices rather than high-energy storage systems. The volumetric energy density can reach values of up to approximately 100 MJ per cubic meter under optimized conditions, while the gravimetric energy density typically ranges between 0.5 and 5 Wh per kilogram, which is significantly lower than that of electrochemical batteries. Despite this limitation, SMES systems provide extremely high power density, enabling them to deliver large amounts of power in very short durations. This characteristic makes them particularly valuable in applications where rapid energy exchange is more important than long-term storage capacity.

Space needed to implement

The spatial requirements of Superconducting Magnetic Energy Storage (SMES) systems are significant due to the need for superconducting c50 to 150oils, cryogenic infrastructure, magnetic shielding, and mechanical support structures designed to withstand high electromagnetic forces. The required space varies substantially depending on system capacity and design configuration, and the following numerical estimates provide a realistic understanding of implementation requirements:

- Small-scale / Industrial SMES (1–10 MJ):

  These systems typically occupy approximately 10 to 50 m^2 of floor area,including the superconducting coil, cryostat, and power electronics, with a total system volume in the range of 5 to 20 m^3.

- Medium-scale SMES (10–30 MJ):

  Experimental and advanced prototype systems require approximately $\mathbf{m^2}$, with system volumes ranging from 20 to 100 m^3, depending on coil geometry and shielding requirements.

- Large-scale Conceptual Systems (MWh-class):

  Proposed large-scale SMES systems would require superconducting coils with diameters in the range of 50 to 200 meters, resulting in land area requirements exceeding 2,000 to 30,000 m^2, including safety clearances and auxiliary infrastructure.

- Gigawatt-hour (GWh) Scale Theoretical Systems:

  Extreme theoretical designs indicate that a 5 GWh SMES system would require a coil of approximately 800 meters in diameter, with total land requirements potentially exceeding 500,000 m^2, making such systems impractical with current technology.

- Magnetic Field Safety Clearance:

  Additional spacing of 5 to 20 meters around the system is typically required for magnetic field containment and safety, depending on shielding effectiveness.

Cost of energy storage

The cost of Superconducting Magnetic Energy Storage (SMES) systems is significantly higher than conventional energy storage technologies due to the use of superconducting materials, complex cryogenic cooling systems, and robust structural components required to handle high electromagnetic forces. While SMES offers exceptional performance in terms of efficiency and response time, its economic viability is currently limited to specialized high-performance applications.

- Capital Cost (Energy Basis):

  Approximately \$1,000 to \$10,000 per kWh depending on system size, superconducting material, and design complexity.

- Cost per Power Rating:

  Typically in the range of \$300 to \$1,500 per kW, reflecting the high power capability of SMES systems.

- Superconducting Material Cost Contribution:

  Accounts for roughly 30% to 50% of total system cost, especially when using high-temperature superconductors such as YBCO or REBCO.

- Cryogenic System Cost:

  Contributes approximately 20% to 30% of total cost, including refrigeration units and insulation systems.

- Operation and Maintenance Cost:

  Estimated at 2% to 5% of capital cost per year, primarily due to continuous cryogenic operation.

- Cost Comparison:

  SMES is typically 5 to 10 times more expensive per kWh than lithium-ion battery systems, which generally range from \$100 to \$300 per kWh.

Performance Characteristics

Superconducting Magnetic Energy Storage (SMES) systems exhibit exceptional performance compared to conventional energy storage technologies, particularly in terms of efficiency, response time, and power delivery. These characteristics make SMES highly suitable for applications requiring rapid energy exchange and high reliability.

- Round-Trip Efficiency:

  Typically 95% to 98%, among the highest of all energy storage technologies.

- Response Time:

  Extremely fast, in the range of 1 to 10 milliseconds, enabling near-instantaneous power delivery.

- Power Density:

  Very high, typically 10,000 to 100,000 W/kg (10–100 kW/kg) depending on system design.

- Energy Density (Gravimetric):

  Approximately 0.5 to 5 Wh/kg, significantly lower than batteries.

- Energy Density (Volumetric):

  Up to 50 to 100 MJ/m^3 under optimized conditions.

- Cycle Life:

  Practically unlimited (>10^6 cycles) with negligible degradation over time.

- Self-Discharge Loss:

  Extremely low, typically <1% per day, mainly due to auxiliary system losses.

- Charge/Discharge Rate:

  Capable of full charge or discharge within seconds, depending on system capacity.

- Operating Temperature:

  Typically 4 K to 77 K, depending on the type of superconductor used (low-temperature vs high-temperature superconductors).

Researching Universities/Institutions/Companies

The advancement of Superconducting Magnetic Energy Storage (SMES) technology is being driven by a combination of leading universities, national laboratories, and industrial organizations across the globe, each contributing to specific aspects such as superconducting materials, magnet design, cryogenic systems, and grid integration. Alongside these institutional efforts, recent research has accelerated significantly, with a strong focus on improving efficiency, reducing cost, enhancing scalability, and enabling integration with modern energy systems.

- **Massachusetts Institute of Technology** is actively conducting research on high-field superconducting magnets and advanced high-temperature superconducting (HTS) materials, with a focus on improving current density, enhancing coil efficiency, and developing compact SMES systems suitable for next-generation energy grids. Complementing this, ongoing research across institutions is advancing HTS materials such as YBCO and REBCO, which allow SMES systems to operate at higher temperatures and significantly reduce the complexity and cost of cryogenic cooling systems.

- **Los Alamos National Laboratory** has played a foundational role in the early development of SMES technology and continues to work on advanced superconducting systems, particularly focusing on large-scale magnet design, energy storage optimization, and national grid reliability applications. Recent research in coil design is also focusing on optimized geometries such as toroidal and solenoidal configurations to reduce magnetic field leakage, improve structural stability, and enhance overall system performance.

- **Toshiba Corporation** is engaged in the development and demonstration of SMES systems for power grid applications, with ongoing work centered on improving system reliability, integrating SMES with utility networks, and enhancing performance in real-world operational environments. Demonstration projects after 2023 have shown improved SMES performance in applications such as metro rail systems, where SMES is used to capture regenerative braking energy and improve energy efficiency.

- **Hitachi Energy** is focusing on grid modernization technologies, including SMES integration for voltage stabilization and renewable energy support, while also working on advanced power electronics and control systems to improve response time and system efficiency. In parallel, modern control systems incorporating real-time monitoring and intelligent algorithms are being developed to optimize SMES operation within smart grids, enabling faster response, improved stability, and better integration with renewable energy sources.

- **American Superconductor Corporation** is involved in the commercialization of superconducting technologies, including SMES, with particular emphasis on grid stability solutions, superconducting wire development, and scalable energy storage applications. **Siemens Energy** is conducting research on integrating SMES with modern power grids, focusing on hybrid energy systems, grid resilience, and the use of superconducting technologies to enhance energy infrastructure performance. Several institutions and companies are similarly developing hybrid energy storage systems that combine SMES with batteries, supercapacitors, and hydrogen storage technologies, enabling a balance between high power response and long-duration energy storage.

- **SuperOx** specializes in the production of high-temperature superconducting materials such as REBCO tapes, which are critical for improving the efficiency and reducing the cost of SMES systems, and is actively supporting research in advanced coil fabrication. Researchers are also focusing on reducing AC losses in superconducting coils, which is critical for improving efficiency and thermal stability under dynamic operating conditions.

- **Hyosung Heavy Industries** is working on power system applications of SMES, including grid stabilization and industrial power quality solutions, while also exploring large-scale deployment opportunities in emerging energy markets. Integration of SMES into DC grids and microgrid systems is being explored in parallel to support next-generation power systems, with particular emphasis on maintaining voltage stability and ensuring uninterrupted power supply.

- **Research institutions across Europe**, particularly in France and Germany, are focusing on high-field superconducting magnet development and hybrid energy storage systems, contributing to advancements in coil design, thermal stability, and integration with renewable energy systems. Advances in cryogenic engineering, including the development of compact and closed-cycle cryocoolers, are also improving system efficiency and reliability while reducing operational costs associated with maintaining superconducting conditions.

- **Research organizations in China** are making significant progress in scaling high-temperature superconducting coils and developing cost-effective SMES systems, with a strong emphasis on large-scale grid integration and domestic energy infrastructure development, further reinforcing the global momentum behind SMES as a viable next-generation energy storage solution.

Positives and Challenges:

Positives:

- High energy density: SMES systems have one of the highest energy densities among energy storage technologies, making them suitable for applications requiring compact energy storage.
- High efficiency: Minimal energy loss due to the absence of electrical resistance in superconducting materials.
- Rapid response time: SMES systems can charge and discharge energy very quickly, making them suitable for grid stabilisation and emergency power applications.
- Long cycle life: Superconducting materials can withstand many charge-discharge cycles without significant degradation.

Challenges:

Superconducting Magnetic Energy Storage (SMES) systems, despite their superior performance characteristics, face several technical challenges that currently limit their large-scale adoption and commercialization. These challenges arise from material limitations, system complexity, and economic constraints.

- High Cost of Superconducting Materials:

  The use of high-temperature superconductors such as YBCO and REBCO significantly increases system cost, as these materials are expensive to manufacture and require specialized fabrication techniques.

- Cryogenic Cooling Requirements:

  SMES systems require continuous operation at very low temperatures (typically 4 K to 77 K), necessitating complex and energy-intensive cryogenic refrigeration systems that increase both capital and operational costs.

- Low Energy Density:

  Compared to batteries, SMES systems have very low energy density (0.5–5 Wh/kg), making them unsuitable for large-scale energy storage applications where compactness is required.

- Mechanical Stress and Structural Integrity:

  The high currents and strong magnetic fields generate substantial Lorentz forces within the coil, requiring robust mechanical structures that add weight, cost, and design complexity.

- Quench Protection Issues:

  A sudden loss of superconductivity (quenching) can lead to rapid energy dissipation and potential system damage, requiring advanced protection systems and monitoring mechanisms.

- Magnetic Field Containment:

  Strong external magnetic fields necessitate shielding and safety clearance zones, increasing the overall system footprint and limiting installation flexibility.

- AC Losses in Superconductors:

  Under dynamic operating conditions, alternating current losses can occur in superconducting materials, affecting efficiency and thermal stability.

- Complex Integration with Power Systems:

  Integration with modern grids requires advanced power electronics and control systems, which increases system complexity and cost.

Future Prospects

The future of Superconducting Magnetic Energy Storage (SMES) technology is promising, particularly with ongoing advancements in materials science, cryogenic engineering, and power system integration. Continued research and innovation are expected to address current limitations and expand the applicability of SMES systems in modern energy infrastructure.

The development of more cost-effective high-temperature superconductors is expected to significantly reduce the overall cost of SMES systems while allowing operation at higher temperatures, thereby simplifying cooling requirements and improving system efficiency. In addition, advancements in cryogenic technology, including compact and energy-efficient closed-cycle cooling systems, are likely to enhance system reliability and reduce operational costs.

Another major area of future development is the integration of SMES with hybrid energy storage systems, where it can be combined with batteries, supercapacitors, or hydrogen storage technologies to create systems that offer both high power and high energy capacity. Such hybrid configurations are expected to play a crucial role in next-generation smart grids and renewable energy systems.

Furthermore, the increasing penetration of renewable energy sources such as solar and wind is driving the demand for fast-response energy storage solutions, positioning SMES as a key technology for grid stabilization, frequency regulation, and voltage control. Advances in digital control systems, including real-time monitoring and intelligent energy management, are also expected to improve the performance and adaptability of SMES systems.

In the long term, breakthroughs in superconducting materials, particularly the potential discovery of room-temperature superconductors, could revolutionize SMES technology by eliminating the need for cryogenic cooling altogether, thereby drastically reducing costs and enabling large-scale deployment. As research continues and technological barriers are overcome, SMES is expected to evolve from a niche, high-performance solution into a more widely adopted component of modern energy systems.

IX. HYDROGEN BASED ENERGY STORAGE

Hydrogen-based energy storage (HBES) is a promising technology for enabling a clean energy future. HBES systems can store hydrogen produced from renewable energy sources, such as solar and wind, for later use. This can help to balance energy demand and supply, reduce our reliance on fossil fuels, and decarbonize the global economy.

HBES systems work by using electrolysis to split water molecules into hydrogen and oxygen. The hydrogen can then be stored in a variety of ways, including as a compressed gas, liquid hydrogen, or in metal hydrides. When the hydrogen is needed, it can be converted back to electricity using a fuel cell or burned in a combustion engine.

HBES systems have a number of advantages over other energy storage technologies, such as batteries. Hydrogen has a much higher energy density than batteries, meaning that a smaller volume of hydrogen can store more energy. Additionally, HBES systems can store energy for longer periods of time than batteries. This makes HBES systems ideal for seasonal energy storage and backup power generation.

However, HBES systems also have some disadvantages. Hydrogen is a flammable gas, so it must be stored and handled carefully. Additionally, the production of hydrogen from renewable energy sources is currently more expensive than the production of electricity from renewable energy sources.

Despite these challenges, HBES is a rapidly developing technology. The cost of producing hydrogen from renewable energy sources is falling, and the efficiency of HBES systems is improving. As a result, HBES is becoming increasingly competitive with other energy storage technologies.

i. HYDROGEN ENERGY STORAGE SYSTEM

Overview

A hydrogen energy storage system (HESS) is a system that stores hydrogen, which can be used as a fuel or energy carrier. Hydrogen can be stored in a variety of ways, including compressed gas, liquid hydrogen, and metal hydrides. HESSs are used in a variety of applications, including Storing renewable energy, such as solar and wind power, Balancing the grid, Providing backup power and Fueling vehicles

Working principle

Hydrogen energy storage operates through a multi-stage process involving energy conversion, storage, and reconversion. Electrical energy, typically from renewable sources, is used in electrolyzers to split water into hydrogen and oxygen. The hydrogen is then stored in various forms, including compressed gas, liquid hydrogen, or solid-state storage materials such as metal hydrides. When energy is required, hydrogen is converted back into electricity using fuel cells or combustion-based systems. The entire cycle forms a “power-to-hydrogen-to-power” (P2H2P) system, enabling flexible energy management across different time scales.

The working principle of a HESS depends on the type of hydrogen storage technology used. For example, a compressed gas HESS stores hydrogen in a high-pressure tank. When energy is needed, the hydrogen is released from the tank and converted into electricity by a fuel cell.

A liquid hydrogen HESS stores hydrogen in a cryogenic tank at very low temperatures. When energy is needed, the hydrogen is vaporized and converted into electricity by a fuel cell.

A metal hydride HESS stores hydrogen in a metal alloy. When energy is needed, the hydrogen is released from the metal alloy and converted into electricity by a fuel cell.

Research Institutions, Universities, Industrial Contributors & Recent Developments

Hydrogen energy storage research has expanded significantly after 2023, with strong collaboration between academia, industry, and government agencies. Alongside these institutional contributions, the field of Hydrogen-Based Energy Storage (HBES) has experienced rapid technological and industrial advancement, driven by global decarbonization goals, policy support, and large-scale investments.

- **The National Renewable Energy Laboratory** conducts advanced research on hydrogen production, system integration, and techno-economic optimization for grid-scale deployment. This work directly supports the broader transition from pilot-scale to gigawatt-scale electrolyzer installations, which has significantly accelerated — particularly in Europe, China, and the Middle East — enabling cost reductions through economies of scale and improved manufacturing processes.
- **The Fraunhofer Society** focuses on industrial hydrogen systems, sector coupling, and integration with renewable energy sources. Complementing this, large-scale projects globally are integrating hydrogen production with offshore wind and solar farms, reducing renewable energy curtailment by significant margins and improving overall grid stability.
- **The International Energy Agency** develops global hydrogen roadmaps, policy frameworks, and large-scale deployment strategies. This institutional guidance has reinforced the momentum behind global policy and investment growth, with

governments worldwide launching national hydrogen strategies, providing financial incentives, subsidies, and regulatory frameworks to accelerate hydrogen adoption.

- **The Chinese Academy of Sciences** leads research on underground hydrogen storage, offshore hydrogen production, and advanced materials. This research has contributed to extensive validation of underground hydrogen storage in salt caverns, depleted gas reservoirs, and aquifers, confirming storage capacities in the GWh to TWh range — a major breakthrough in addressing long-duration energy storage challenges.
- **The Indian Institute of Technology BHU** is developing green hydrogen technologies, including biomass-based hydrogen production and industrial applications. In parallel, research into advanced storage materials such as metal hydrides, chemical hydrides, and Liquid Organic Hydrogen Carriers (LOHCs) has improved safety, storage density, and transport flexibility across the broader research community.
- **Siemens Energy** is developing gigawatt-scale electrolyzers and hydrogen infrastructure for industrial and grid-scale use. This aligns with broader advancements in electrolysis technologies, where emerging approaches such as Anion Exchange Membrane (AEM) and Solid Oxide Electrolysis (SOEC) are improving efficiency and reducing dependence on expensive noble metals. SOEC systems operating at high temperatures have demonstrated efficiencies exceeding 80%, especially when integrated with industrial waste heat.
- **Air Liquide** leads hydrogen liquefaction, storage, and global distribution technologies. Its contributions are central to the rapid development of hydrogen pipelines, refueling stations, liquefaction plants, and export terminals underway globally, enabling the creation of integrated hydrogen supply chains and international trade networks.
- **Plug Power** is advancing hydrogen fuel cell systems and integrated hydrogen energy ecosystems. These efforts are supported by the growing adoption of AI and machine learning across the industry for site selection, system optimization, predictive maintenance, and operational control, which is enhancing system efficiency and reducing operational risks at scale.
- **ITM Power** is developing large-scale electrolyzers for green hydrogen production, contributing to cost reduction achievements that have seen hydrogen production

costs in some pilot projects approach $1–2 per kg under optimal conditions. Demonstrations of hydrogen blending of up to 20–25% in natural gas networks have further validated the potential for a gradual transition to hydrogen-based energy systems without requiring complete infrastructure replacement, reinforcing hydrogen's role as a practical and scalable solution in the global clean energy transition.

Largest Capacity Acquired

Hydrogen-based storage systems have demonstrated significantly larger capacities than most other energy storage technologies due to their scalability and compatibility with existing infrastructure.

- Underground Salt Cavern Storage: Operational hydrogen storage facilities have achieved capacities exceeding 100 GWh, making them among the largest energy storage systems globally.
- Industrial-Scale Projects (Europe & USA): Recent hydrogen hubs and storage projects are achieving capacities in the range of 100–600 GWh, particularly with the reuse of natural gas storage caverns.
- Utility-Scale Hydrogen Systems: Demonstrated systems typically operate in the range of 10–50 GWh, supporting grid balancing and renewable integration.
- Emerging Mega-Projects (Post-2023): Several global projects are targeting TWh-scale storage, especially for seasonal energy storage and national energy security.

Specific capacity

Energy density is a critical parameter in evaluating the feasibility and efficiency of hydrogen-based energy storage systems, as it directly influences storage design, system size, and overall energy transport capability. Hydrogen exhibits one of the highest gravimetric energy densities among all known energy carriers, making it highly attractive for applications requiring lightweight energy storage. However, its low volumetric energy density under ambient conditions necessitates advanced storage techniques such as compression, liquefaction, or material-based storage. The effective energy density of hydrogen systems is therefore highly dependent on the chosen storage method and system configuration.

- Gravimetric Energy Density (Intrinsic Property):

  Hydrogen possesses an energy density of approximately 33 kWh/kg (≈120 MJ/kg), which is nearly 2.5–3 times higher than conventional hydrocarbon fuels and significantly higher than lithium-ion batteries (~0.2–0.3 kWh/kg). This makes hydrogen particularly advantageous for applications where weight is a critical factor, such as transportation and aerospace systems.

- Volumetric Energy Density (Compressed Hydrogen):

  When stored as compressed gas at pressures of 350–700 bar, hydrogen achieves a volumetric energy density of approximately 1–3 kWh/L. Although compression increases storage density, it requires robust high-pressure tanks and introduces additional energy consumption (~10–15% of stored energy).

- Volumetric Energy Density (Liquid Hydrogen):

  In liquid form at −253°C, hydrogen achieves a higher volumetric energy density of approximately 2–3 kWh/L, representing a more compact storage solution. However, liquefaction is energy-intensive, consuming approximately 25–30% of the stored energy, and requires advanced cryogenic insulation to minimize boil-off losses.

- Solid-State and Advanced Storage Methods:

  Emerging storage technologies such as metal hydrides, chemical hydrides, and Liquid Organic Hydrogen Carriers (LOHCs) offer improved volumetric density and safer storage conditions. These systems can achieve effective volumetric densities comparable to or exceeding compressed hydrogen but often involve slower kinetics and additional thermal management requirements.

- System-Level Energy Density:

  When accounting for the entire storage system, including tanks, insulation, and auxiliary components, the effective energy density is reduced significantly.

Practical system-level values typically range from 0.5 to 2 kWh/L, depending on the storage technology and application.

- Energy Conversion Efficiency Impact:

  The overall usable energy density is further influenced by conversion losses during electrolysis and reconversion. With electrolysis efficiencies of 60–80% and fuel cell efficiencies of 40–60%, the effective delivered energy is reduced, resulting in a net round-trip efficiency of 30–50%.

Space Requirements

The spatial requirements of Hydrogen-Based Energy Storage (HBES) systems are a critical design consideration, as they directly influence system feasibility, safety, and scalability. Unlike compact electrochemical storage systems, hydrogen storage requires additional infrastructure for compression, liquefaction, or material-based storage, along with safety buffers due to its flammable nature. The overall space requirement depends strongly on the storage method, pressure conditions, and system capacity, and can vary from relatively compact industrial installations to large-scale underground facilities designed for grid-level energy storage.

- Compressed Hydrogen Storage Systems:

  For industrial-scale applications operating at 350–700 bar, storage systems typically require 50 to 500 m² of surface area, including high-pressure tanks, compressors, and associated piping. The volumetric footprint increases with storage capacity due to the relatively low volumetric energy density of compressed hydrogen. Cylindrical or spherical tank configurations are commonly used, with additional spacing required for safety and maintenance access.

- Liquid Hydrogen Storage Facilities:

  Liquid hydrogen systems require larger infrastructure due to cryogenic storage conditions (−253°C) and insulation requirements. Typical installations occupy approximately 500 to 2000 m², including liquefaction units, storage tanks, and vapor management systems. The tanks are usually double-walled with vacuum insulation, and additional space is required to manage boil-off gas and ensure thermal stability.

- Underground Hydrogen Storage (Salt Caverns and Depleted Reservoirs):

  Large-scale hydrogen storage systems utilize underground geological formations such as salt caverns, which can store GWh-scale energy with relatively minimal surface footprint. The above-ground infrastructure typically requires 1000 to 5000 m^2, while the actual storage volume underground can reach 10^5 to 10^6 m^3 per cavern. This approach is currently considered the most space-efficient solution for large-scale and seasonal energy storage.

- Pipeline and Distribution Infrastructure:

  Hydrogen transport and distribution systems require additional spatial allocation for pipelines, compressors, and transfer stations. Dedicated hydrogen pipelines or repurposed natural gas pipelines may extend over large distances, contributing significantly to overall land use in large-scale deployments.

- Safety Clearance and Zoning Requirements:

  Due to hydrogen's high flammability and low ignition energy, safety regulations mandate clearance zones of approximately 10 to 50 meters around storage and processing units. These zones ensure safe dispersion of potential leaks and reduce the risk of explosion hazards, thereby increasing the total effective land requirement.

- Scalability Considerations:

  While above-ground hydrogen storage scales linearly with capacity (requiring more tanks or larger facilities), underground storage offers high scalability with minimal additional surface area, making it more suitable for national-level energy storage applications.

Cost of energy storage

The economic viability of Hydrogen-Based Energy Storage (HBES) depends on the combined costs of hydrogen production (electrolysis), storage, transportation, and reconversion to electricity. While hydrogen systems currently exhibit higher upfront costs compared to conventional storage technologies, they become increasingly cost-effective for long-duration and large-scale storage, particularly when integrated with renewable energy systems and operating at high utilization factors.

- Levelized Cost of Storage (LCOS):

  Typically \$5–\$50 per kWh for long-duration applications, with costs decreasing as system scale increases and utilization improves.

- Hydrogen Production Cost (Green Hydrogen):

  Approximately \$2–\$6 per kg, depending on electricity price, electrolyzer efficiency, and capacity factor; projections indicate potential reduction to \$1–\$2 per kg by 2030 with large-scale deployment.

- Electrolyzer Capital Cost:

  Alkaline electrolysis: \$500–\$1000 per kW ,PEM electrolysis: \$800–\$1500 per kW Emerging AEM systems: expected < \$700 per kW in near future .\

- Fuel Cell System Cost:

  Approximately \$1000–\$3000 per kW, with significant cost reductions expected through mass manufacturing and catalyst optimization.

- Storage Cost (By Method):

  Compressed gas: \$500–\$1500 per kg H_2 storage capacity

  Liquid hydrogen: \$1000–\$3000 per kg H_2 (including liquefaction infrastructure)

  Salt cavern storage: \$0.8–\$10 per kg H_2 (most cost-effective at scale)

- Operational and Maintenance Cost:

  Typically 2–5% of capital cost per year, including maintenance of electrolyzers, compressors, and storage systems.

- Cost Reduction Trends (Post-2023):

  Driven by gigawatt-scale electrolyzer deployment, improved catalysts (e.g., non-precious metals), and economies of scale in hydrogen infrastructure.

Applications

Hydrogen-Based Energy Storage (HBES) has a wide range of applications across the energy, industrial, and transportation sectors due to its ability to store large quantities of energy over long durations and facilitate sector coupling. Its versatility enables integration with renewable energy systems, industrial processes, and emerging energy carriers, making it a key enabler of a decarbonized energy ecosystem.

- Renewable Energy Integration and Curtailment Reduction:

  HBES plays a critical role in managing the intermittency of renewable energy sources such as solar and wind by converting excess generation into hydrogen. This stored energy can be utilized during periods of low generation, thereby reducing curtailment and improving overall system efficiency. Large-scale deployments have demonstrated the capability to significantly enhance renewable utilization in grid systems.

- Grid Balancing and Long-Duration Energy Storage:

  Hydrogen storage systems are increasingly used for load leveling, peak shaving, and frequency regulation in modern power grids. While their response time is slower than batteries, their ability to store energy for days to months makes them indispensable for long-duration grid stability and seasonal balancing.

- Industrial Decarbonization:

  HBES is being widely adopted in energy-intensive industries such as steel, cement, and chemical production. Hydrogen is used as a clean feedstock and reducing agent, replacing fossil fuels in processes such as direct reduced iron (DRI) production and ammonia synthesis, thereby significantly reducing carbon emissions.

- Transportation Sector (Fuel Cell Mobility):

  Hydrogen is used as a fuel in fuel cell electric vehicles (FCEVs), including cars, buses, trucks, trains, and maritime vessels. Its high gravimetric energy density enables longer driving ranges and faster refueling compared to battery-electric systems, making it particularly suitable for heavy-duty and long-haul transportation.

- Power-to-X Applications:

  Hydrogen serves as an intermediate energy carrier in Power-to-X systems, where it is converted into other fuels such as ammonia, methanol, synthetic hydrocarbons, and aviation fuels. These derivatives enable energy storage, transport, and utilization in sectors where direct electrification is challenging.

- Backup Power and Critical Infrastructure:

  HBES systems provide reliable backup power for critical infrastructure such as data centers, hospitals, telecommunications, and defense systems. Their long storage duration and reliability make them a viable alternative to diesel generators.

- Off-Grid and Remote Energy Systems:

  Hydrogen storage is increasingly used in remote and islanded power systems where grid connectivity is limited. Coupled with renewable energy sources, HBES provides a sustainable and reliable energy solution with minimal environmental impact.

- Hydrogen Blending in Gas Networks:

  Hydrogen can be blended with natural gas (typically up to 20–25%) and transported through existing gas pipelines, enabling gradual integration into current energy infrastructure without major modifications.

Technical Challenges:

Despite rapid advancements, Hydrogen-Based Energy Storage systems face several technical and economic challenges that must be addressed to achieve widespread adoption. These challenges are primarily related to efficiency, safety, material limitations, and infrastructure requirements.

- Low Round-Trip Efficiency:

The overall efficiency of hydrogen storage systems remains relatively low (30–50%) due to multiple energy conversion stages, making it less efficient than battery-based systems for short-duration applications.

- High Capital and Infrastructure Costs:

  The development of hydrogen production, storage, and distribution infrastructure requires substantial investment, including electrolyzers, pipelines, storage facilities, and refueling stations.

- Hydrogen Leakage and Permeation:

  Hydrogen molecules are extremely small, leading to leakage through materials and joints. This not only reduces system efficiency but also raises safety and environmental concerns.

- Material Degradation and Hydrogen Embrittlement:

  Hydrogen can weaken metals and structural materials over time, leading to embrittlement, which affects the durability and safety of storage tanks, pipelines, and system components.

- Storage and Transport Complexity:

  Hydrogen storage requires high-pressure systems, cryogenic conditions, or advanced materials, each with its own technical and economic challenges. Transporting hydrogen over long distances also requires specialized infrastructure.

- Safety Risks and Handling Challenges:

  Hydrogen is highly flammable and has a wide flammability range, necessitating strict safety protocols, advanced monitoring systems, and adequate ventilation and clearance zones.

- Energy Losses During Liquefaction and Compression:

  Significant energy is consumed during hydrogen compression (~10–15%) and liquefaction (~25–30%), reducing overall system efficiency.

- Limited Infrastructure Availability:

Existing energy infrastructure is not fully compatible with hydrogen, and large-scale deployment requires extensive upgrades or new installations.

- Scalability Constraints in Certain Storage Methods:

  While underground storage is highly scalable, above-ground storage methods such as compressed tanks face limitations in terms of cost, safety, and space requirements.

Future Prospects

Despite rapid advancements, Hydrogen-Based Energy Storage systems face several technical and economic challenges that must be addressed to achieve widespread adoption. These challenges are primarily related to efficiency, safety, material limitations, and infrastructure requirements.

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