ENERGY STORAGE SYSTEMS(ESS)

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Interns

Kerala State Electricity Regulatory Commission

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Kerala

Energy Storage Systems: The Future of Clean Energy

“Energy can neither be created nor be destroyed”
- Law of Thermodynamics.

Energy Storage Systems (ESS) are instrumental in advancing our journey towards a greener and more sustainable energy environment. These systems are purpose-built for the storage of electrical energy, providing a wide range of versatile applications for later utilisation.

Energy Storage Systems (ESS) serve as a crucial component in the pursuit of a cleaner and more sustainable energy landscape. They fulfil a range of vital functions, with one of their primary roles being grid balancing. ESS are adept at storing excess energy during periods of low demand and releasing it when demand peaks, thus upholding the grid's stability and reliability. This capability proves essential in accommodating the intermittency of renewable energy sources such as solar and wind power. ESS effectively enables the seamless integration of renewable energy into the grid by providing a consistent and dependable energy supply, making renewable sources more cost-effective and reliable. This integration, in turn, plays a pivotal role in reducing our dependence on fossil fuels and curbing greenhouse gas emissions. Another significant advantage of ESS is peak shaving. By curbing peak electricity demand, these systems help alleviate the strain on the grid, reducing the need for constructing new power plants and ultimately leading to lower energy costs for consumers. Additionally, ESS serves as a dependable backup power source during outages, ensuring the uninterrupted operation of critical systems. This aspect is indispensable for safeguarding businesses, residences, and essential infrastructure against the disruptions caused by power failures.

In conclusion, Energy Storage Systems (ESS) play a central role in our transition to a sustainable energy future by addressing grid stability, facilitating renewable energy integration, managing peak loads, and meeting backup power requirements, all while contributing to the reduction of our environmental footprint. This flyer showcases various technologies in energy storage systems that are being implemented and researched in different parts of the world.

CONTENTS

I. CHEMICAL BATTERIES

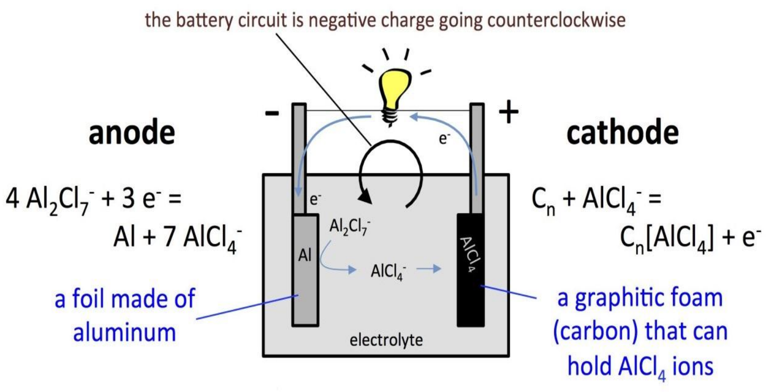
Chemical batteries store chemical energy and convert it to electrical energy using electrochemical reactions. They are made up of two electrodes and an electrolyte. When connected to a circuit, electrons flow from the anode to the cathode, providing an electric current.

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 rechargeable batteries that use aluminium ions as the charge carriers. They are a relatively new and promising technology that has the potential to offer several advantages over traditional lithium-ion batteries. AIBs have the potential to offer a number of advantages over existing battery technologies, including High energy density, Low cost, Safety.

Working Principle:

AIBs work by using the aluminium metal to form an aluminium ion (Al^{3+}) at the anode. The Al^{3+} ions then travel through the electrolyte to the cathode, where they are intercalated into the cathode material. This intercalation process releases electrons, which flow through the external circuit to power devices.

When the battery is discharged, the reverse process occurs. The Al^{3+} ions deintercalate from the cathode and travel back to the anode, where they form aluminium metal. This process consumes electrons from the external circuit, charging the battery.

Chemical Reaction

$4Al + 3O_2 + 6H_2O \rightarrow 4Al(OH)_3 + 2.71\ V$

Research Universities/Institutions/Companies

Asia: Tsinghua University, Peking University, Tokyo Institute of Technology, National University of Singapore (NUS), Nanyang Technological University (NTU), Chinese Academy of Sciences (CAS) China, Seoul National University, South Korea, Japan Advanced Institute of Science and Technology (JAIST), Indian Institute of Technology (IIT) Delhi,, Tsukuba University, Japan, Samsung Advanced Institute of Technology (SAIT), South Korea, University of Tokyo, Kyoto University, Seoul National University, South Korea.

North America: Stanford University, University of California, Berkeley, Massachusetts Institute of Technology (MIT), University of Texas at Austin, Lawrence Berkeley National Laboratory, Argonne National Laboratory, Rutgers, The State University of New Jersey, Caltech (California Institute of Technology), University of Maryland, University of Colorado.

South America: University of São Paulo, Federal University of Rio de Janeiro.

Europe: University of Oxford, University of Cambridge, Imperial College London, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, Karlsruhe Institute of Technology (KIT), Germany, Technische Universität München (TUM), Germany, University College London (UCL), United Kingdom, Technical University of Denmark (DTU), Institut National de l'Énergie Solaire (INES), France, Chalmers University of Technology, Sweden, University of Freiburg, Germany, French National Centre for Scientific Research (CNRS), France, Fraunhofer Institute for Solar Energy Systems (ISE), Germany.

Africa: University of Cape Town, University of Nairobi, Stellenbosch University.

Oceania: University of Melbourne, University of Sydney, University of New South Wales, Altech Chemicals (Australia), American Battery Technology, Log 9 Materials

(India), Graphene Manufacturing Group (Australia), Phinergy (Israel), Altris (sweden), China Aerospace Science and Industry Corporation, Faradion Limited (UK).

Research Companies: Saturnose (India), Aluminum Power (China), Graphene Manufacturing Group (Australia), 24M Technologies, Sila Technologies, Form Energy, InoBat Auto, Slovakia, Altris, Germany, Alectris, UK.

Largest acquired capacity

The largest capacity AIB that has been installed is a 1 MW/1 MWh battery that was installed by Altris (China) in 2022. This battery is used to store energy from a solar power plant.

Specific Capacity

The theoretical specific energy density of aluminum-ion batteries is 1060 Wh/kg.

Cost of making

National Renewable Energy Laboratory (NREL) found that the price to make an aluminum-ion battery could be as low as Rs. 8330.93 per kilowatt-hour (kWh).

Space to implement

Cylindrical 0.1-0.2 (m^3)

Prismatic 0.2-0.4 (m^3)

Pouch 0.1-0.3 (m^3)

Solid-state 0.05-0.1 (m^3)

Positives and Challenges

The positives of aluminium-ion batteries include:

- Low Cost.
- Fast Charging.
- Long Cycle Life.
- Low Environmental Impact.
- Safety: Aluminum-ion batteries may have improved safety characteristics due to the stable nature of Aluminium and the absence of highly reactive materials.
- Operational Stability under high-temperature conditions.
- Can be designed to have a wide range of energy densities and power outputs.

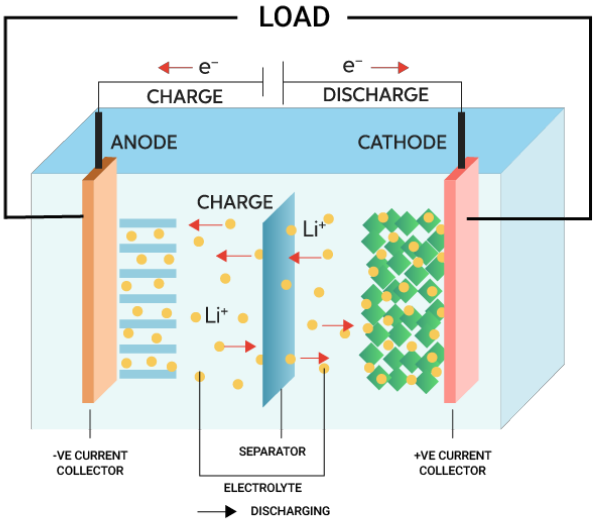
The challenges of aluminium-ion batteries include:

- Lower Energy Density.
- Finding suitable cathode materials for aluminium-ion batteries.
- The Voltage range is low.
- Electrolyte compatibility for reactive Aluminium.
- Low cost manufacturing is to be developed.

Aluminium-ion batteries are currently under development, and they carry the promise of substantial progress in battery technology. If we can overcome the challenges linked to achieving high-performance batteries, aluminium-ion batteries have the potential to revolutionise several sectors, including electric vehicles, grid energy storage, and portable electronics.

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 and release electrical energy, making them widely used in electronics and electric vehicles.

Chemical reaction

Charging: $LiC_6 + CoO_2 \rightarrow C_6 + LiCoO_2$

Discharging: $C_6 + LiCoO_2 \rightarrow LiC_6 + CoO_2$

Research Universities/Institutions/Companies

America: University of California, Berkeley, Stanford University, Massachusetts Institute of Technology (MIT), University of Michigan, University of Texas at Austin, Argonne National Laboratory, National Renewable Energy Laboratory (NREL), Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, Tesla, Panasonic, Solid Power, QuantumScape.

Europe: Fraunhofer Institute for Chemical Technology (ICT), Helmholtz-Zentrum Berlin für Materialien und Energie (HZB).

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 (CECRI), Council of Scientific and Industrial Research (CSIR), Defence Research and Development Organisation (DRDO), Indian Institute of Science (IISc), Indian Institute of Technology Bombay (IITB), Indian Institute of Technology Delhi (IITD), Indian Institute of Technology Kharagpur (IITKGP), Indian Institute of Technology Madras (IITM), International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI), National Chemical Laboratory (NCL), Centre for Materials for Electronics Technology (C-MET), IIT Madras Research Park (IITMRP), Indian Institute of Technology Bombay's Centre for Energy and Environment (IITB CEE), Amara Raja Batteries, Ather Energy, Exide Industries, Hero Electric, Log9 Materials, Ola Electric, Reliance Industries, SES, Tata Chemicals.

Largest acquired capacity

The largest acquired capacity for a lithium-ion battery is 3.9 GWh (gigawatt-hours), which was purchased by Tesla in 2021 from Panasonic. This battery pack will be used in Tesla's Megapack energy storage system, which is designed to store large amounts of energy from renewable sources such as solar and wind power.

Specific capacity

150 and 260 Wh/kg.

Cost of making

Rs. 12746.32 per kilowatt-hour (kWh).

Space to implement

- Electric vehicle battery pack: A typical electric vehicle battery pack requires a space of about 1-2 cubic meters.
- Residential energy storage system battery pack: A typical residential energy storage system battery pack requires a space of about 0.5-1 cubic meters.
- Commercial energy storage system battery pack: A commercial energy storage system battery pack can require a space of several hundred cubic meters or more.

Positives and challenges

Positives:

- **High energy density:** Lithium-ion batteries can store more energy per unit mass than other types of batteries, such as lead-acid batteries. This makes them ideal for applications where weight is a concern, such as electric vehicles and portable electronics.

- **Long lifespan:** Lithium-ion batteries have a long lifespan, typically in the hundreds to thousands of recharge cycles. This means that they can be used for many years before they need to be replaced.
- **Low self-discharge rate:** Lithium-ion batteries have a very low self-discharge rate, meaning that they can hold their charge for a long period of time without being used.
- **Fast charging:** Lithium-ion batteries can be charged relatively quickly, compared to other types of batteries.
- **Wide operating temperature range:** Lithium-ion batteries can operate in a wide range of temperatures, from below freezing to over 100 degrees Celsius.

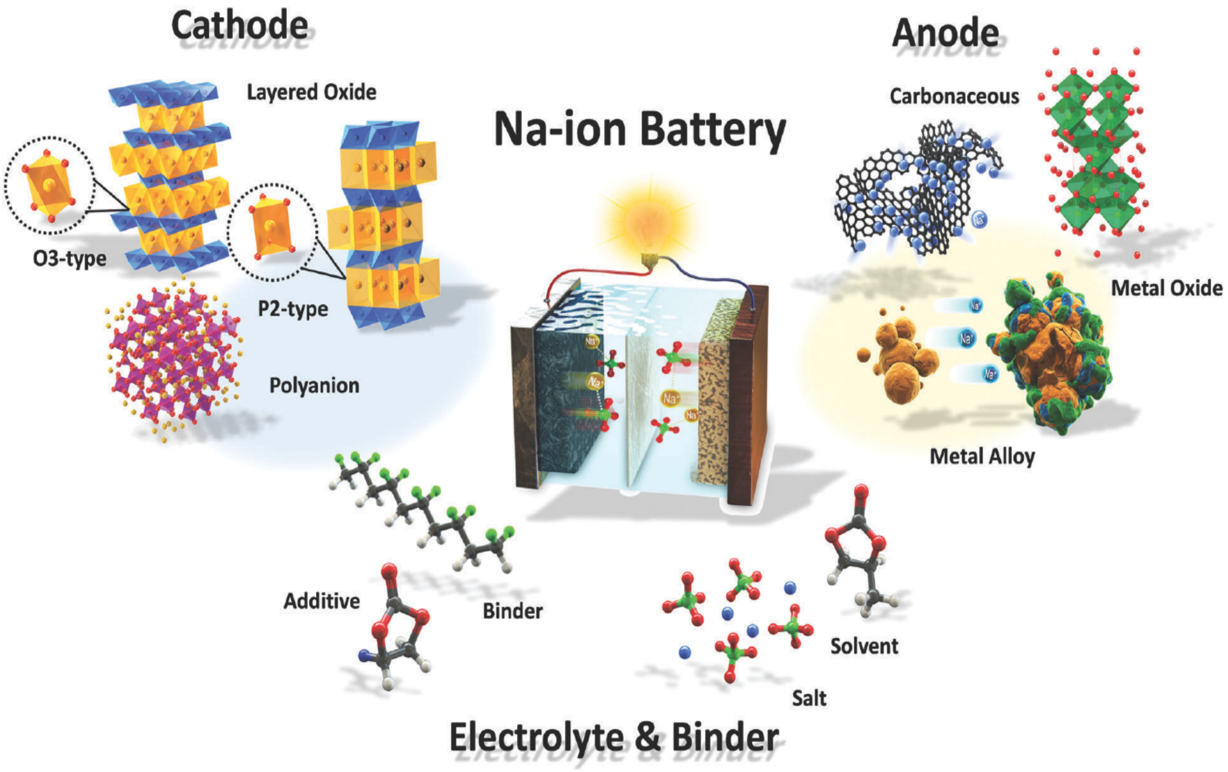
Challenges:

- **Cost:** Lithium-ion batteries are still relatively expensive to produce, although the cost has decreased significantly in recent years.
- **Safety:** Lithium-ion batteries can be flammable if they are damaged or overheated. This is why it is important to use lithium-ion batteries that are equipped with a battery management system (BMS) to protect them from damage and overheating.
- **Limited resources:** The raw materials used to make lithium-ion batteries, such as lithium, cobalt, and nickel, are limited resources. This means that there is a potential for supply shortages and price increases in the future.
- **Disposal:** Lithium-ion batteries contain hazardous materials, so they need to be disposed of properly. This can be challenging, especially for large battery packs.

iii. SODIUM-ION BATTERY

Overview

Sodium-ion (Na-ion) batteries, a much more abundant and cheaper alternative to the standard Lithium-ion, are on the verge of commercialisation. Though there's enough Lithium in the world to support global electrification targets, tightening demand and supply chain constraints point at the urgent need for an alternative. The cost of a Na-ion battery cell is expected to be around Rs. 3332.37- 6664.74/kWh compared to an average of Rs. 9997.12/kWh for a Li-ion cell. Na-ion batteries are safer (operating temperature range, stability), and have faster charging times and longer cycle lives.



Working Principle

A sodium-ion battery consists of a sodium metal negative electrode, a positive electrode, and an electrolyte. During discharge, sodium ions are oxidised at the negative electrode and reduced at the positive electrode. The electrolyte transports the sodium ions between the electrodes. The most common positive electrode materials for sodium-ion batteries are transition metal oxides and sulphides. These materials have high conductivity and can accommodate a large number of sodium ions.The electrolyte in a sodium-ion battery can be either aqueous or non-aqueous. Aqueous electrolytes are less expensive, but they are also more corrosive. Non-aqueous electrolytes are more stable, but they are also more expensive.

Chemical Reaction

$Na + xC \leftrightarrow Na_xC^6$

Researching Universities/Institutions/Companies

India : Indian Institute of Technology Bombay (IITB), Indian Institute of Technology Kharagpur (IITKGP), Indian Institute of Technology Madras (IITM), Indian Institute of Technology Delhi (IITD), National Chemical Laboratory (NCL), Centre for Materials for Electronics Technology (C-MET), Faradion Limited (Bought by Reliance Industries), AGM Batteries Ltd, NGK Insulators Ltd, HiNa Battery Technology Co. Ltd.

Europe: University of Münster (Germany), University of Oxford (United Kingdom), University of Cambridge (United Kingdom), University of Warwick (United Kingdom), Helmholtz-Zentrum Berlin für Materialien und Energie (Germany), Fraunhofer Institute for Solar Energy Systems (Germany), CNRS (France), CEA

(France), University of Groningen (Netherlands), Delft University of Technology (Netherlands), Chalmers University of Technology (Sweden), Uppsala University (Sweden).

Asia: City University of Hong Kong (Hong Kong), Hong Kong Polytechnic University (Hong Kong), University of Science and Technology of China (China), Tsinghua University (China), Peking University (China), Shanghai Jiao Tong University (China), Nanyang Technological University (Singapore), National University of Singapore (Singapore), Seoul National University (South Korea), POSTECH (South Korea), University of Tokyo (Japan), Kyoto University (Japan), University of New South Wales (UNSW), University of Melbourne, Monash University, RMIT University, Deakin University.

America: University of São Paulo (Brazil), Pontifical Catholic University of Rio de Janeiro (Brazil), University of Campinas (Brazil), University of Buenos Aires (Argentina), University of Chile (Chile).

Largest Capacity Acquired

As of 2023, the largest sodium-ion battery has a capacity of 160 Wh/kg and was developed by CATL. The largest installed sodium-ion battery project is in China and has a capacity of 38.4 MW / 250 MWh.

Cost of making

Cost- Rs. 3332.37 - 6664.74/kWh

Specific capacity

100 Wh/kg to 160 Wh/kg

Positives and Challenges

- Low cost-The cost of Na-ion batteries is expected to be significantly lower than that of Li-ion batteries. This is around Rs. 3332.37 - 6664.74/kWh for a Na-ion cell compared to an average of Rs. 9997.12/kWh for a Li-ion cell.
- Abundant raw materials-Sodium-ion batteries also offer advantages in terms of sustainability, compared to Li-ion batteries. The large abundance of sodium opens the door for more diverse sourcing. At the same time, some configurations can open the door to reducing the need for critical materials, such as copper (given their aluminium current collector), nickel and cobalt. While layered metal oxide Na-ion batteries (the most predominant type), such as the one developed by Faradion, use nickel and cobalt, some Prussian white and some polyanion types do not use any of these materials.
- Safe and environment friendly- In terms of safety, sodium-ion batteries have shown promising results, having wider operating temperature ranges and a more stable anode-electrolyte mixture than Li-ion batteries, and the possibility of being safely transported and fully discharged.
- In terms of performance, sodium-ion batteries have excellent capacity retention even in freezing temperatures, fast charging times (80% SOC in 15 minutes) and longer cycle lives (80% capacity retention after 4,000-5,000 cycles) than lithium batteries.
- One of the main limitations of these batteries is their energy density, as lower energy densities also mean bulkier and heavier batteries. The latest announcements from some battery manufacturers mention energy densities of 160 Wh/kg for these batteries, also mentioning 200 Wh/kg as their next milestone. While these numbers are comparable to some

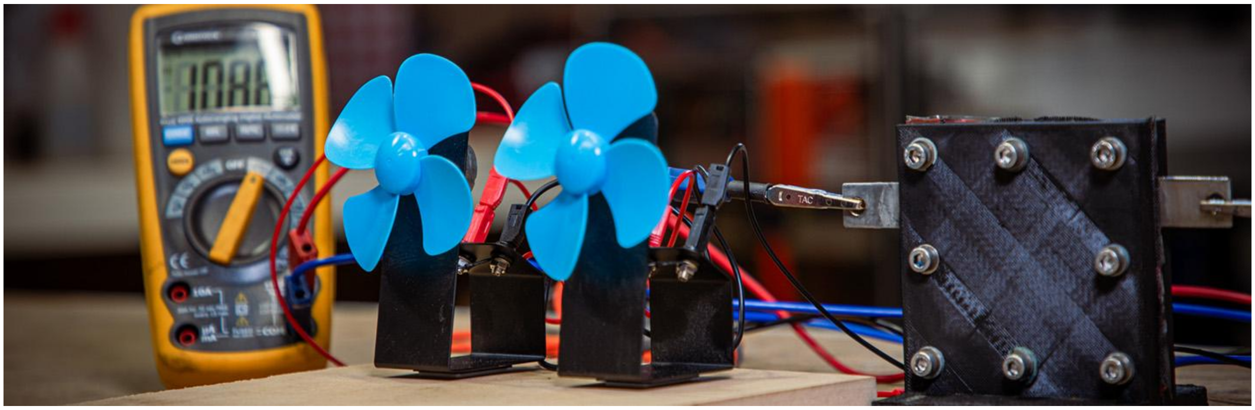
lower-end Li-ion batteries, they are still behind other commercially available Li-ion chemistries, e.g. Tesla batteries in the range of 250 Wh/kg.

Sodium-ion batteries hold promise as a viable alternative to lithium-ion batteries in various applications. These batteries offer advantages such as the abundance of sodium resources, potentially lower cost, and a reduced environmental impact. However, they are still undergoing research and development to address key challenges, including energy density, cycle life, and overall performance.

As technology advances, sodium-ion batteries could find applications in grid energy storage, electric vehicles, and portable electronics, contributing to more sustainable and accessible energy solutions. The future of sodium-ion batteries depends on continued innovation and investment in research to overcome their current limitations and realise their full potential in the ever-evolving field of energy storage.

iv. PROTON BATTERY

Overview

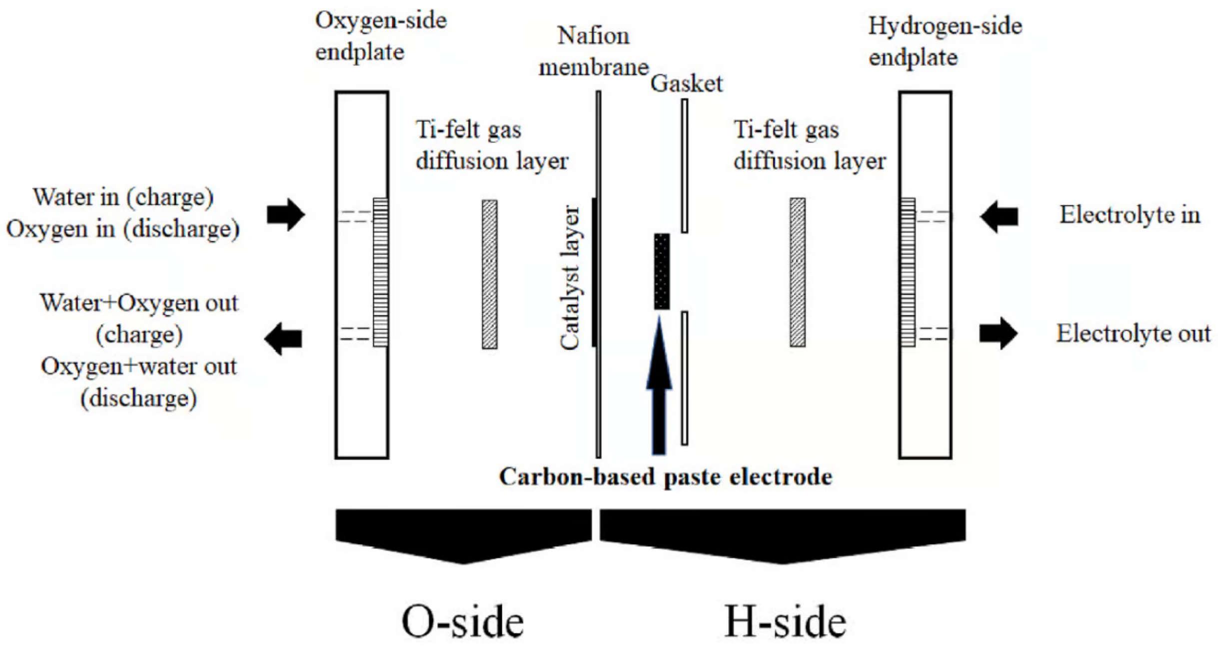


Proton batteries are a class of rechargeable batteries in which protons (H+) serve as charge carriers. Protons are the smallest and lightest ions, which makes them ideal for high-performance batteries. Proton batteries are also non-toxic and environmentally friendly.

Working principle

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.



Inner schematic of the proton battery

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

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

Largest Acquired Capacity

The largest capacity proton battery in the world right now is the 100MW/100MWh proton battery energy storage system (BESS) developed by Form Energy. This means that it can deliver 100 MW of power for 1 hour.

Cost of Energy storage

One study by the National Renewable Energy Laboratory (NREL) found that the cost of storing energy in a proton battery could be as low as $10 per kilowatt-hour (kWh). This is significantly lower than the current cost of storing energy in a lithium-ion battery, which is typically around Rs. 16661.86 per kWh.Another study by the RMIT University in Australia found that the cost of storing energy in a proton battery could be even lower, at around Rs. 416.55 per kWh.

Specific Capacity

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

Space needed 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.

Researching Universities/Institutions/Companies

India: Indian Institute of Technology Madras (IIT Madras), Indian Institute of Science (IISc), Indian Institute of Technology Bombay (IIT Bombay), Indian Institute of Technology Delhi (IIT Delhi), National Institute of Technology Tiruchirappalli (NIT Tiruchirappalli), National Institute of Technology Karnataka (NIT Karnataka), Central Electrochemical Research Institute (CECRI), Indira Gandhi Centre for Atomic Research (IGCAR), Bhabha Atomic Research Centre (BARC).

America: California Institute of Technology (Caltech), University of California, Berkeley, University of California, Los Angeles (UCLA), University of Michigan, Stanford University, University of Texas at Austin.

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

Asia: University of Tokyo, Kyoto University, City University of Hong Kong, Hong Kong Polytechnic University, University of Science and Technology of China, Peking University.University of New South Wales (UNSW), University of São Paulo, South America.

Positives and Challenges

The positives of proton batteries are:

- High energy density.
- Non-toxic and environmentally friendly.
- Fast charging and discharging.
- Long cycle life.

The challenges of proton batteries include:

- High cost.
- Difficult to develop high-performance electrolytes.
- Not yet commercially available.

These innovative batteries have the potential to significantly impact various sectors, including energy storage, electric vehicles, consumer electronics, space exploration, medical devices, and grid support. They offer the prospect of higher energy density, faster charging times, and a more sustainable approach to energy storage.

v. SOLID-STATE BATTERY

Overview

Solid-state batteries are a type of battery that uses a solid electrolyte instead of a liquid electrolyte. This makes them safer, more durable, and potentially more energy-dense than traditional liquid-based batteries.

Working principle

The solid electrolyte in a solid-state battery is typically made of a ceramic material, such as garnet or sulphide. This material is chosen because it is stable and does not conduct electricity, which helps to prevent short circuits and fires. The electrodes in a solid-state battery are also made of different materials than those used in traditional lithium-ion batteries. The anode is typically made of a metal, such as lithium or silicon, and the cathode is typically made of a transition metal oxide, such as cobalt oxide or nickel oxide.

Chemical Reaction

Li metal + $LiCoO_2$ --> $Li_{1-x}CoO_2$ + $Li_{1+x}PF_6^-$

Researching Universities/Institutions/Companies

Oceania: Indian Institute of Science (IISc), Bangalore, Indian Institute of Technology Bombay (IITB), Mumbai, Indian Institute of Technology Roorkee (IITR), Roorkee, Indian Institute of Technology Kanpur (IITK), Kanpur, Indian Institute of Technology Kharagpur (IITKGP), Kharagpur, Indian Institute of Technology Delhi (IITD), Delhi, Indian Institute of Technology Hyderabad (IITH), Hyderabad, Indian Institute of Technology Madras (IITM), Chennai, Indian Institute of Technology Guwahati (IITG), Guwahati, Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR), Bangalore, Centre for Energy and Environmental Technology (CEET), Indian Institute of Petroleum (IIP), Dehradun, International Centre for Automotive Technology (ICAT), Manesar, China - Tsinghua University, Peking University, Chinese Academy of Sciences. Japan - Kyoto University, Tokyo University, Toyota Central R&D Laboratories. South Korea - Seoul National University, Pohang University of Science and Technology, Samsung Advanced Institute of Technology (SAIT), University of Melbourne, Monash University, University of Queensland.

America: United States - Stanford University,University of California, Berkeley, University of Michigan, Massachusetts Institute of Technology (MIT), Argonne National Laboratory. Canada - University of Waterloo, Dalhousie University, McGill University, Brazil - University of São Paulo, Federal University of Rio de Janeiro, University of Campinas.

Europe: United Kingdom - University of Oxford, University of Cambridge, Imperial College London. Germany - Karlsruhe Institute of Technology, Technical University of Munich, Helmholtz-Zentrum Berlin für Materialien und Energie (HZB). France - National Centre for Scientific Research (CNRS), University of Bordeaux, Grenoble Institute of Technology.

Largest Capacity Acquired

The largest capacity solid-state battery that QuantumScape has publicly announced has a capacity of 20 MW/20 MWh. QuantumScape is currently working on developing solid-state batteries for electric vehicles. The company expects to start mass production of these batteries in 2024.

Cost of making

The cost of making solid-state batteries is still under development, but it is estimated to be around Rs. 6664.74 - Rs. 7497.84 per kilowatt-hour (kWh).

Specific Capacity

In 2023, researchers at the University of Texas at Austin developed a solid-state battery with a specific energy density of 711 Wh/kg.

Positives and Challenges

In addition to being safer and more energy-dense than traditional lithium-ion batteries, solid-state batteries also have other advantages. These include:

- They can be operated at higher temperatures, which makes them more suitable for use in hot environments.
- They have a longer lifespan than traditional lithium-ion batteries.
- They are less likely to degrade over time.

Despite their positives, solid-state batteries still face some challenges. These include:

- The high cost of production.

- The difficulty of developing a solid electrolyte that is both stable and conductive.
- The lack of a standardised manufacturing process.

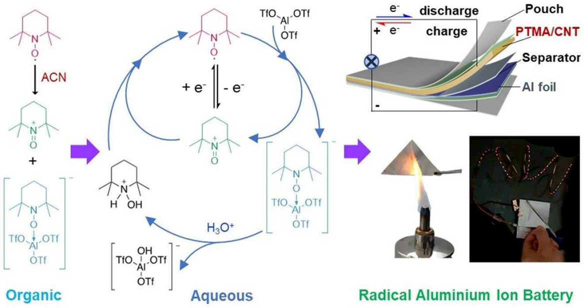
Overall, solid-state batteries represent a promising new technology that has the potential to revolutionise the battery industry. By offering higher energy density, improved safety, and faster charging times, these batteries could play a crucial role in driving the adoption of cleaner and more efficient energy storage solutions.

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.

Researching Universities/Institutions/Companies

India: Indian Institute of Technology Bombay (IITB), Mumbai, Indian Institute of Technology Madras (IITM), Chennai, Indian Institute of Science (IISc), Bangalore, Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR), Bangalore, Centre for Energy and Environmental Technology (CEET), Indian Institute of Petroleum (IIP), Dehradun.

North America: USA - University of Illinois at Urbana-Champaign, Stanford University, University of California, Berkeley, University of Maryland, College Park, Northwestern University.

South America: Brazil - University of São Paulo

Europe: UK - University of Oxford, University of Cambridge, Imperial College London. Germany - Karlsruhe Institute of Technology, Technical University of Munich. France - National Centre for Scientific Research (CNRS), Grenoble Institute of Technology.

Asia: China - Tsinghua University, Peking University, Chinese Academy of Sciences. Japan - Kyoto University, Tokyo University. South Korea - Seoul National University, Pohang University of Science and Technology.

Australia: University of Melbourne, Monash University, University of Queensland.

Largest Capacity Acquired

The largest capacity aluminium-radical battery in the world is currently being developed by Form Energy. This battery has a capacity of 100 MW / 1000 MWh. This means that it can store enough energy to power 100,000 homes for 10 hours.

Form Energy's battery is still under development, but it is expected to be commercially available in 2025. Once it is commercialised, it is likely to have a major impact on the energy storage market.

Specific Capacity

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

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.

Positives and Challenges

Positives of aluminium-radical batteries:

- High energy density: Aluminium-radical batteries have the potential to store much more energy per unit volume than current lithium-ion batteries. This makes them ideal for applications where space and weight are at a premium, such as electric vehicles and grid-scale energy storage.
- Low cost: Aluminium is a relatively abundant and inexpensive metal, making aluminium-radical batteries potentially much cheaper to produce than lithium-ion batteries.
- Safety: Aluminium-radical batteries are non-flammable and non-combustible, making them safer than lithium-ion batteries, which can catch fire if damaged.
- Long lifespan: Aluminium-radical batteries are expected to have a much longer lifespan than lithium-ion batteries, with some estimates suggesting that they could last for up to 20 years.

Challenges of aluminium-radical batteries:

- New technology: Aluminium-radical batteries are still in the early stages of development, and there are still many technical challenges that need to be overcome before they can be commercialised.
- Low power density: Aluminium-radical batteries have a lower power density than lithium-ion batteries, meaning that they cannot discharge energy as quickly. This makes them less suitable for applications where high power output is required, such as electric power tools and sports cars.
- Electrode degradation: Aluminium-radical batteries are susceptible to electrode degradation, which can reduce their capacity over time. This is an area of active research, and scientists are working on developing new materials and chemistries to mitigate this problem.

Overall, aluminium-radical batteries have the potential to revolutionise the energy storage market. They offer a number of advantages over traditional lithium-ion batteries, such as higher energy density, lower cost, and improved safety. However, they are still in the early stages of development, and there are a number of technical challenges that need to be overcome before they can be commercialised.

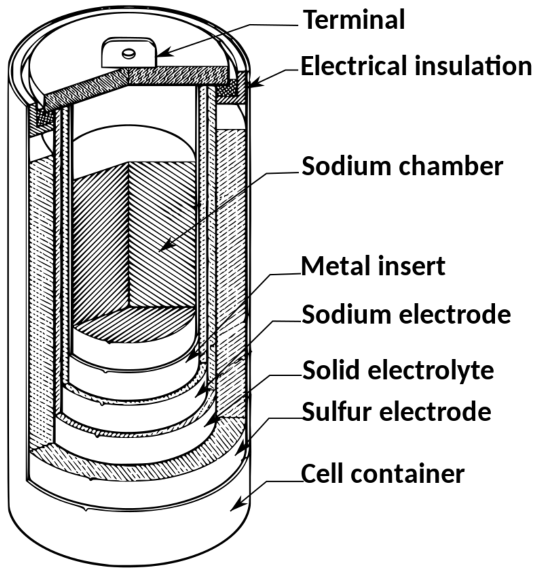
It is important to note that the research on aluminium-radical batteries is rapidly evolving, and new developments are being made all the time. As the technology continues to mature, it is likely that we will see significant improvements in performance and cost.

vii. SODIUM-SULPHUR BATTERY

Overview

Sodium-sulphur (NaS) batteries are a type of electrochemical battery that uses molten sodium and sulphur as the electrodes. They have a high energy density (100-160 Wh/kg) and a long cycle life (>3,000 cycles). However, they operate at a high temperature (300-350°C), which limits their use in portable applications. NaS batteries are used in large-scale energy storage applications, such as grid stabilisation and renewable energy integration.

Working principle



The negative electrode is made of molten sodium, and the positive electrode is made of molten sulphur. The electrolyte is a solid ceramic material, such as beta-alumina, that allows sodium ions to pass through but blocks electrons. When the battery is charged, sodium ions move from the negative electrode to the positive electrode, and sulphur atoms move from the positive electrode to the negative electrode. When the battery is discharged, the reverse reaction occurs.

Chemical reaction

2Na + 4S → Na2S4

Researching Universities/Institutions

India: Indian Institute of Technology Madras (IIT Madras), Indian Institute of Technology Bombay (IIT Bombay), Indian Institute of Technology Delhi (IIT Delhi), Indian Institute of Science Bangalore (IISc Bangalore), Indian Institute of Technology Kharagpur (IIT Kharagpur), National Institute of Technology Karnataka (NITK Surathkal), National Institute of Technology Warangal (NIT Warangal), Central Electrochemical Research Institute (CECRI), Anna University, Jawaharlal Nehru Technological University Hyderabad (JNTU Hyderabad), SRM Institute of Science and Technology, Vellore Institute of Technology, Amity University.

Asia: China - Tsinghua University, Peking University, Shanghai Jiao Tong University, Southern University of Science and Technology. Japan - Kyoto University, Tokyo University, Osaka University, Nagoya University. Korea - Seoul National University, Pohang University of Science and Technology, Ulsan National Institute of Science and Technology. National University of Singapore, Hong Kong Polytechnic University, Taiwan Tech University.

North America: United States - Stanford University, Massachusetts Institute of Technology, University of California, Berkeley, University of Texas at Austin. Canada - University of Toronto, McGill University, Dalhousie University.

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South America: Brazil - University of São Paulo, Federal University of Rio de Janeiro, Federal University of Santa Catarina. Argentina - University of Buenos Aires, National University of La Plata, National University of Córdoba.

Africa: South Africa - University of Cape Town, Stellenbosch University, University of Johannesburg. Kenya - University of Nairobi, Egypt - Cairo University, Alexandria University.

Research Companies

HiNa Battery Technology Co., China, Natron Energy, US, NGK Insulators, Japan, Form Energy, Natron Energy, Ambri, InoBat Auto, Slovakia, Altris, Germany, Alectris, UK.

Largest Capacity Acquired

The largest acquired capacity for sodium sulphur battery is 200MW/300MWh. This battery was developed by NGK Insulators and is being used in a grid-scale energy storage project in Japan.

Cost of making

The cost of a sodium-sulfur battery is estimated to be around Rs. 24992.79 - 41654.65 per kilowatt-hour (kWh).

Specific Capacity

The specific capacity of a typical NaS battery is around 400-600 mAh/g. This is about twice the specific capacity of a typical lithium-ion battery. Generally, NaS batteries have a specific capacity in the range of 150-160 mAh/g (milliampere-hours per gram) for the sulphur electrode.

Space for implementation

A 100 kWh sodium-sulphur battery would typically require a space of about 5 cubic meters.

Positives and Challenges

Positives of sodium-sulphur batteries:

- **High energy density**: Sodium-sulphur batteries have one of the highest energy densities of any battery technology, meaning they can store more energy in a smaller volume and weight. This makes them ideal for applications such as electric vehicles and grid-scale energy storage.
- **Low cost**: Sodium-sulphur batteries are relatively inexpensive to produce, due to the abundance and low cost of sodium and sulfur. This makes them a more cost-effective option for some applications than other battery technologies, such as lithium-ion batteries.
- **Long lifespan**: Sodium-sulphur batteries have a long lifespan, with some estimates suggesting that they could last for up to 20 years. This makes them a good investment for applications where durability is important.
- **Improved safety**: Sodium-sulphur batteries are non-flammable and non-combustible, making them safer than lithium-ion batteries, which can catch fire if damaged.

Challenges of sodium-sulphur batteries:

- **High operating temperature:** Sodium-sulphur batteries operate at high temperatures, typically around 300-350 degrees Celsius. This requires them to be well-insulated and cooled to prevent overheating and safety hazards.

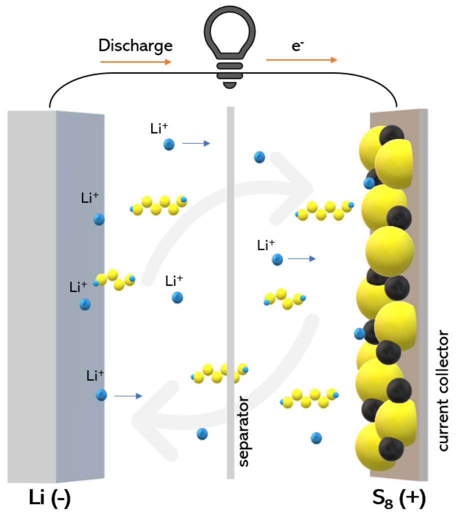
- **Complexity:** Sodium-sulphur batteries are more complex to manufacture than other battery technologies, such as lithium-ion batteries. This contributes to their higher cost.
- **Low power density:** Sodium-sulphur batteries have a lower power density than lithium-ion batteries, meaning they cannot discharge energy as quickly. This makes them less suitable for applications where high power output is required, such as electric power tools and sports cars.
- **Electrode degradation:** Sodium-sulphur batteries are susceptible to electrode degradation, which can reduce their capacity over time. This is an area of active research, and scientists are working on developing new materials and chemistries to mitigate this problem.

Overall, sodium-sulphur batteries have a number of advantages over other battery technologies, such as high energy density, low cost, and long lifespan. However, they also have some disadvantages, such as high operating temperature, low power density, and electrode degradation.

As the technology continues to mature and these disadvantages are addressed, sodium-sulphur batteries are expected to play an increasingly important role in the energy storage market.

viii. LITHIUM-SULPHUR BATTERY

Overview



Lithium-sulphur (Li-S) batteries are a type of rechargeable battery that uses lithium metal as the negative electrode and sulphur as the positive electrode. They have a high theoretical **energy density (2,500 Wh/kg)**, which is about five times that of lithium-ion batteries. However, they have a relatively short cycle life (<500 cycles) and suffer from the shuttle effect, which is the migration of lithium polysulfides from the positive electrode to the negative electrode. Despite these challenges, Li-S batteries are considered to be a promising technology for next-generation energy storage applications, such as electric vehicles and grid storage.

Working principle

The negative electrode is made of lithium metal, and the positive electrode is made of sulphur. The electrolyte is a liquid organic solvent that contains lithium ions. When the battery is charged, lithium ions move from the negative electrode to the positive electrode, and sulphur atoms are oxidised to form sulphur ions. When the battery is discharged, the reverse reaction occurs.

Chemical Reaction

$S_8 + 16Li \rightarrow 8Li_2S$

$8Li_2S \rightarrow S_8 + 16Li$

Researching Universities/Institutions/Companies

India: Indian Institute of Technology Madras (IIT Madras), Indian Institute of Technology Bombay (IIT Bombay), Indian Institute of Technology Delhi (IIT Delhi), Indian Institute of Science Bangalore (IISc Bangalore), Indian Institute of Technology Kharagpur (IIT Kharagpur), National Institute of Technology Karnataka (NITK Surathkal), National Institute of Technology Warangal (NIT Warangal), Central Electrochemical Research Institute (CECRI), Anna University, Jawaharlal Nehru Technological University Hyderabad (JNTU Hyderabad), SRM Institute of Science and Technology, Vellore Institute of Technology.

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Africa: South Africa - University of Cape Town, Stellenbosch University, University of Johannesburg. Kenya - University of Nairobi. Egypt - Cairo University, Alexandria University.

Largest Capacity Acquired

The largest capacity acquired by a lithium-sulphur battery in the world is 15 MW / 60 MWh. This battery was installed in Yantai, China in 2022. It is used to store energy from renewable sources, such as solar and wind power, and then discharge it onto the grid when needed.

Cost of making

According to a 2022 report by BloombergNEF, the cost of lithium sulfur batteries is expected to fall to Rs. 8330.93 per kilowatt-hour (kWh) by 2025, and to Rs. 4998.56 per kWh by 2030.

Specific Capacity

A theoretical specific energy capacity of 2600 Wh/kg.

Largest acquired Capacity

The largest acquired capacity of lithium-sulfur batteries in 2022 was 500 MWh, acquired by Oxis Energy and SES.

Positives and Challenges

Lithium-sulphur (Li-S) batteries are a promising new technology for energy storage. They offer a number of advantages over traditional lithium-ion batteries, including:

- Higher energy density: Li-S batteries have the potential to store twice as much energy as lithium-ion batteries in the same volume and weight. This makes them ideal for applications where space and weight are at a premium, such as electric vehicles and grid-scale energy storage.
- Lower cost: Sulphur is a much more abundant and less expensive material than lithium, which could lead to significantly lower costs for Li-S batteries.
- Improved safety: Li-S batteries are non-flammable and non-explosive, making them safer than lithium-ion batteries, which can catch fire if damaged.However, Li-S batteries are still in the early stages of development, and there are a number of challenges that need to be overcome before they can be commercialised.

These challenges include:

- Cycle life: Li-S batteries currently have a shorter cycle life than lithium-ion batteries, meaning they can only be charged and discharged a limited number of times before they start to degrade.

- Polysulfide shuttle: During the charging and discharging process, lithium polysulfides can dissolve and diffuse through the electrolyte, reducing the battery's capacity and performance.
- Lithium metal anode: The lithium metal anode used in Li-S batteries is highly reactive and can form dendrites, which can pierce the separator and cause a short circuit.

Researchers are working on addressing these challenges, and there has been significant progress in recent years. For example, new materials and electrolytes have been developed to improve the cycle life and reduce the polysulfide shuttle effect. Additionally, new methods have been developed to stabilise the lithium metal anode. As these challenges are overcome, Li-S batteries are expected to play a major role in the future of energy storage.

ix. LEAD-ACID BATTERY

Overview

The lead acid battery is the most used secondary battery in the world. The most common is the SLI battery used for motor vehicles for engine Starting, vehicle Lighting and engine Ignition, however it has many other applications (such as communications devices, emergency lighting systems and power tools) due to its cheapness and good performance.

It was first developed in 1860 by Raymond Gaston Planté. Strips of lead foil with coarse cloth in between were rolled into a spiral and immersed in a 10% solution of sulphuric acid. The cell was further developed by initially coating the lead with oxides, then by forming plates of lead oxide by coating an oxide paste onto grids. The electrodes were also changed to a tubular design.

Working principle

Lead-acid batteries work by a chemical reaction between lead and lead dioxide. The electrodes of the battery are made of lead, and the electrolyte is a solution of sulfuric acid. When the battery is discharging, the lead and lead dioxide react with the sulfuric acid to form lead sulphate. This reaction releases electrons, which flow through the circuit to power the device. When the battery is charging, the reverse reaction occurs. The lead sulphate is converted back into lead and lead dioxide, and the sulfuric acid is regenerated. The lead acid battery uses lead as the anode and lead dioxide as the cathode, with an acid electrolyte.

Chemical Reaction

The following half-cell reactions take place inside the cell during discharge:

At the anode: $Pb + HSO_4^- \rightarrow PbSO_4 + H^+ + 2e^-$

At the cathode: $PbO_2 + 3H^+ + HSO_4^- + 2e^- \rightarrow PbSO_4 + 2H_2O$

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

Researching University/Company

India: Indian Institute of Technology Kharagpur (IIT Kharagpur), Indian Institute of Technology Madras (IIT Madras), Indian Institute of Technology Bombay (IIT Bombay), Indian Institute of Technology Delhi (IIT Delhi), National Institute of Technology Tiruchirappalli (NITT), Indian Institute of Science Bangalore (IISc Bangalore), Central Electrochemical Research Institute (CECRI), Anna University, Jawaharlal Nehru Technological University Hyderabad (JNTU Hyderabad), SRM Institute of Science and Technology, Vellore Institute of Technology, Amity University.

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Africa: South Africa - University of Cape Town, Stellenbosch University, University of Johannesburg. Kenya - University of Nairobi. Egypt - Cairo University, Alexandria University.

Largest Capacity Acquired

The largest capacity acquired by a lead-acid battery in the world is 350 MW / 1400 MWh. This battery was installed in Hornsdale Power Reserve, South Australia in 2017. It is used to store energy from renewable sources, such as solar and wind power, and then discharge it onto the grid when needed.

Specific capacity

35-40(Wh/kg)

Cost of making

Rs. 8330 to 24990 Rs per kWh.

Space needed to Implement

A standard automotive lead-acid battery, such as the type used in most cars, typically measures around 9-15 inches in length, 6-7 inches in width, and 9-10 inches in height.

Positives and Challenges

Positives of lead-acid batteries:

- Low cost: Lead-acid batteries are the least expensive type of rechargeable battery.
- High availability: Lead-acid batteries are widely available from a variety of manufacturers.
- Mature technology: Lead-acid batteries have been around for over 160 years and are well-understood.
- High surge current capability: Lead-acid batteries can deliver high currents in short bursts, making them ideal for starting engines and other applications that require a lot of power quickly.
- Wide range of operating temperatures: Lead-acid batteries can operate in a wide range of temperatures, from below freezing to over 100 degrees Fahrenheit.
- Recyclable: Lead-acid batteries are highly recyclable.

Challenges of lead-acid batteries:

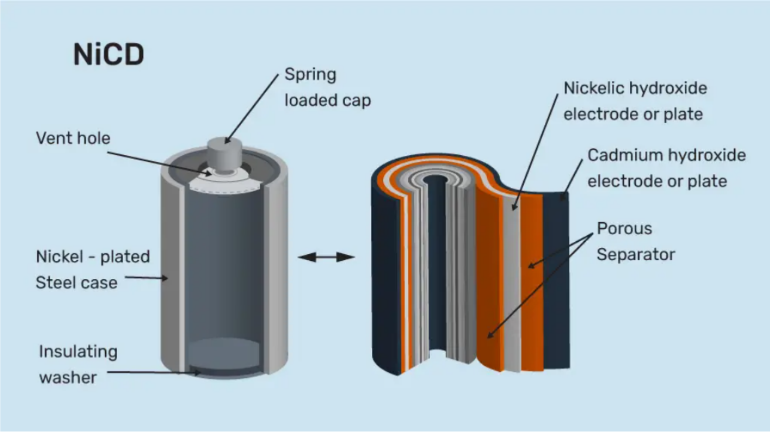
- Low energy density: Lead-acid batteries have a lower energy density than other battery technologies, such as lithium-ion batteries. This means that lead-acid batteries are heavier and larger for the same amount of energy storage.

- Shallow discharge: Lead-acid batteries should not be discharged below 50% of their capacity on a regular basis. This is because deep discharging can damage the battery and shorten its lifespan.
- Limited cycle life: Lead-acid batteries have a limited cycle life, meaning they can only be charged and discharged a limited number of times before they start to degrade.
- Self-discharge: Lead-acid batteries self-discharge at a rate of about 3-5% per month. This means that they need to be recharged regularly, even if they are not being used.
- Environmental concerns: Lead is a toxic metal, and lead-acid batteries contain sulfuric acid, which is corrosive. This means that lead-acid batteries need to be disposed of properly to prevent environmental contamination.

Despite their challenges, lead-acid batteries are still widely used in a variety of applications due to their low cost and wide availability. However, as the cost of other battery technologies, such as lithium-ion batteries, continues to decline, lead-acid batteries are likely to be used less frequently in the future.

x. NICKEL-CADMIUM BATTERY

Overview



Nickel-cadmium batteries (NiCd) are a type of rechargeable battery. They are known for their high energy density, long lifespan, and ability to withstand deep discharges. NiCd batteries are used in a variety of applications, including portable electronics, power tools, and emergency lighting. Specific energy is around 50-60 Wh per Kg.

Working principle

Nickel-cadmium batteries work by a chemical reaction between nickel oxide hydroxide and cadmium. The electrodes of the battery are made of nickel and cadmium, and the electrolyte is a solution of potassium hydroxide. When the battery is discharging, the nickel oxide hydroxide and cadmium react with the potassium hydroxide to form nickel hydroxide and cadmium hydroxide. This reaction releases electrons, which flow through the circuit to power the device.

When the battery is charging, the reverse reaction occurs. The nickel hydroxide and cadmium hydroxide are converted back into nickel oxide hydroxide and cadmium, and the potassium hydroxide is regenerated.

Chemical Reaction

$Cd(s) + NiO2(s) + 2H2O(l) \rightarrow Cd(OH)2(s) + Ni(OH)2(s)$

Researching Universities/Institutions/Companies

India: Indian Institute of Technology Madras (IIT Madras), Indian Institute of Technology Bombay (IIT Bombay), Indian Institute of Technology Delhi (IIT Delhi), National Institute of Technology Karnataka (NITK Surathkal), Central Electrochemical Research Institute (CECRI), Anna University, Jawaharlal Nehru Technological University Hyderabad (JNTU Hyderabad), SRM Institute of Science and Technology,Vellore Institute of Technology, Amity University, University of Mysore, University of Hyderabad.

Asia: China - Tsinghua University, Peking University, Shanghai Jiao Tong University. Japan - Kyoto University, Tokyo University, Osaka University. Korea - Seoul National University, Pohang University of Science and Technology, Ulsan National Institute of Science and Technology. Others - National University of Singapore, Hong Kong Polytechnic University, Taiwan Tech University.

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Africa: South Africa - University of Cape Town, Stellenbosch University, University of Johannesburg. Kenya - University of Nairobi. Egypt - Cairo University, Alexandria University.

Largest Capacity Acquired

The largest capacity acquired using nickel-cadmium batteries in the world is 440 MW / 1760 MWh. This capacity is distributed across a number of installations, including:

- 50 MW / 200 MWh : Kashiwazaki-Kariwa Nuclear Power Plant, Japan
- 100 MW / 400 MWh : Kagawa Prefecture, Japan
- 20 MW / 80 MWh : Ibaraki Prefecture, Japan
- 50 MW / 200 MWh : Hokkaido Electric Power Company, Japan
- 200 MW / 800 MWh : Fukushima Electric Power Company, Japan

These installations use nickel-cadmium batteries to store energy from renewable sources, such as solar and wind power, and then discharge it onto the grid when needed.

Cost of making

The cost of producing 1 kWh using a nickel-cadmium battery is estimated to be between Rs. 62.38 and Rs 103.97

Specific Capacity

The specific capacity of a nickel-cadmium (NiCd) battery typically ranges from about 30 to 80 watt-hours per kilogram (Wh/kg).

Positives and Challenges

Positives of nickel-cadmium (NiCd) batteries:

- High energy density: NiCd batteries have a higher energy density than lead-acid batteries, meaning they can store more energy in the same volume and weight. This makes them ideal for applications where space and weight are at a premium, such as electric vehicles and portable power tools.

- Long lifespan: NiCd batteries have a long lifespan, with some batteries lasting up to 20 years. This makes them a cost-effective option for applications where frequent battery replacement is required.
- Wide operating temperature range: NiCd batteries can operate in a wide range of temperatures, from below freezing to over 100 degrees Fahrenheit. This makes them well-suited for applications in harsh environments.
- Low self-discharge rate: NiCd batteries have a low self-discharge rate, meaning they can hold their charge for a long period of time, even when not in use. This makes them ideal for applications where standby power is required.

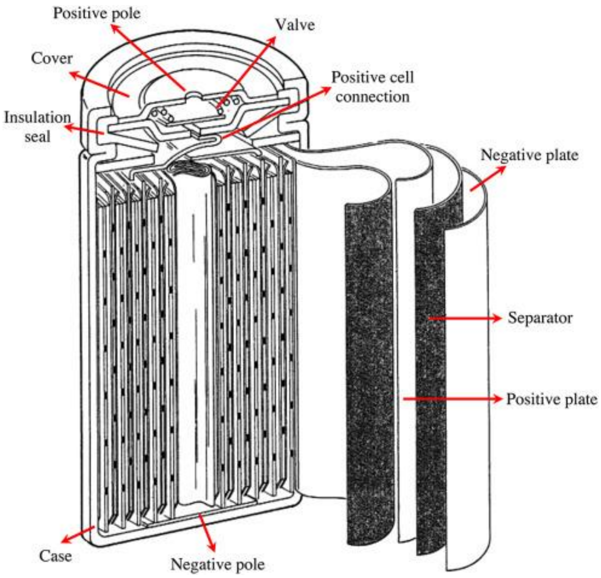
Challenges of NiCd batteries:

- High cost: NiCd batteries are more expensive than lead-acid batteries and lithium-ion batteries. This is due to the cost of the raw materials used in NiCd batteries, such as nickel and cadmium.
- Environmental concerns: Nickel and cadmium are both toxic metals, and NiCd batteries contain cadmium hydroxide, which is a known carcinogen. This means that NiCd batteries need to be disposed of properly to prevent environmental contamination.
- Memory effect: NiCd batteries can develop a memory effect, which occurs when the battery is repeatedly discharged to the same level. This can reduce the overall capacity of the battery.

Overall, NiCd batteries have a number of advantages over other battery technologies, including high energy density, long lifespan, wide operating temperature range, and low self-discharge rate. However, NiCd batteries are also more expensive and environmentally hazardous than other battery technologies. Despite these challenges, NiCd batteries are still widely used in a variety of applications, including electric vehicles, portable power tools, medical devices, and industrial equipment. NiCd batteries are also used in grid-scale energy storage systems to store energy from renewable sources, such as solar and wind power.

xi. NICKEL-METAL HYDRIDE BATTERY

Overview



Nickel-metal hydride batteries are a type of rechargeable battery. They are a development of the nickel-cadmium battery, and they offer several advantages over nickel-cadmium batteries, including longer life, lower self-discharge rate, and less toxicity.

Working principle

A Nickel-Metal Hydride (NiMH) battery system is an energy storage system based on electrochemical charge/discharge reactions that occur between a positive electrode (cathode) that contains nickel oxide-hydroxide as the active material and a negative electrode (anode) that is composed of a hydrogen-absorbing alloy. The electrodes are separated by a permeable membrane which allows for electron and ionic flow between them and is immersed in an electrolyte that is made up of aqueous potassium hydroxide that undergoes no significant changes during operation

Chemical Reaction

$NiO2(s) + H2O(l) + MH(s) \rightarrow Ni(OH)2(s) + MOH(s)$

Researching University/Company

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

Delhi), Indian Institute of Science (IISc), National Institute of Technology Karnataka (NITK), National Institute of Technology Rourkela (NIT Rourkela).

Africa: Stellenbosch University (South Africa), University of Pretoria (South Africa), University of Cape Town (South Africa).

Asia: Tsinghua University (China), Peking University (China), University of Tokyo (Japan), Kyoto University (Japan), Seoul National University (South Korea), Indian Institute of Technology Bombay (India), Indian Institute of Technology Delhi (India), National University of Singapore (Singapore).

Australia: University of Melbourne (Australia), University of Sydney (Australia), Queensland University of Technology (Australia).

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).

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), University of Waterloo (Canada), McGill University (Canada).

South America: University of São Paulo (Brazil), State University of Campinas (Brazil), University of Buenos Aires (Argentina).

Largest Capacity Acquired

The largest capacity acquired using Nickel-Metal Hydride (NiMH) Battery in the world is 440 MW/990 MWh. It is located in Japan and is operated by Kansai Electric Power Company.

The cost to produce 1 kWh using a nickel-metal hydride (NiMH) battery is around Rs. 8322.35-Rs. 14980.23. This is based on a study by the US Department of Energy (DOE) in 2019. The study found that the cost of NiMH batteries had fallen significantly in recent years, from around Rs. 41611.75 - Rs.45772.93 per kWh in 2013 to around Rs. 8322.35-Rs. 14980.23 per kWh in 2019.

Specific Capacity

75 – 80 Wh/kg

Cost of making

The cost of manufacturing a NiMH battery is estimated to be between Rs. 4165.47 and Rs. 8330.93 per kilowatt-hour (kWh).

Positives and Challenges

Positives of Nickel-Metal Hydride Batteries

- High energy density: NiMH batteries have a high energy density, meaning that they can store a lot of energy in a relatively small and lightweight package. This makes them ideal for applications where space and weight are at a premium, such as electric vehicles and portable electronics.
- Low self-discharge rate: NiMH batteries have a low self-discharge rate, meaning that they can hold their charge for a long time when not in use. This makes them a good choice for applications where batteries may not be used regularly, such as emergency flashlights and remote controls.
- Long cycle life: NiMH batteries have a long cycle life, meaning that they can be recharged many times before they need to be replaced. This makes them a cost-effective choice for applications where batteries are used frequently, such as power tools and cordless phones.

- Wide operating temperature range: NiMH batteries can operate in a wide range of temperatures, from below freezing to above boiling. This makes them suitable for use in a variety of climates and environments.
- Environmentally friendly: NiMH batteries are environmentally friendly because they do not contain any toxic materials. They can also be recycled, which helps to reduce waste.

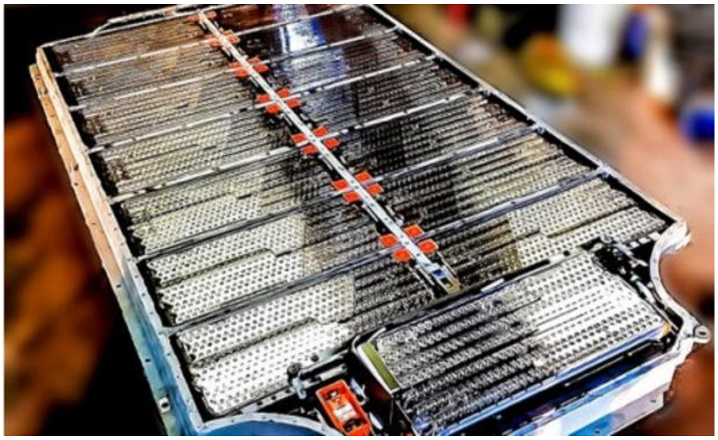
Challenges of Nickel-Metal Hydride Batteries

- Cost: NiMH batteries are more expensive than alkaline batteries, but they are less expensive than lithium-ion batteries.
- Memory effect: NiMH batteries can develop a memory effect, which means that they lose their capacity if they are not fully discharged before being recharged. However, the memory effect in NiMH batteries is much less pronounced than in nickel-cadmium batteries.
- High self-heating rate: NiMH batteries can heat up significantly when they are charged or discharged at high rates. This can reduce the battery's lifespan and safety.

Overall, nickel-metal hydride batteries are a versatile and reliable battery technology with a wide range of applications. They offer a good balance of energy density, cycle life, and cost.

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 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

$LiFePO_4 + LiC_6 \rightarrow Li_2FePO_4 + C_6$

$Li_2FePO_4 + C_6 \rightarrow LiFePO_4 + LiC_6$

Researching Universities/Company

Africa : Stellenbosch University (South Africa),Stellenbosch University, University of Cape Town (South Africa), University of Cape Town, University of Pretoria (South Africa), University of Pretoria.

Asia: Tsinghua University (China), Peking University (China), University of Tokyo (Japan), Kyoto University (Japan), Seoul National University (South Korea), Indian Institute of Technology Bombay (India), Indian Institute of Technology Delhi (India), National University of Singapore (Singapore).

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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).

South America: University of São Paulo (Brazil), State University of Campinas (Brazil), University of Buenos Aires (Argentina).

Largest Capacity Acquired

The largest capacity acquired using a cobalt-free lithium-ion battery in the world is 200 MW / 800 MWh. This is the capacity of the battery energy storage system (BESS) that was installed in Dalian, China in 2023 by the Chinese company Rongke Power.

Cost for making

The cost required to produce 1 kWh using a cobalt-free lithium-ion battery is estimated to be between Rs. 8330.93 and Rs. 9997.12 per kWh as of August 2023.

Specific Capacity

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

Positives and Challenges

Positives of Cobalt-Free Lithium-Ion Batteries

- Lower cost: Cobalt-free lithium-ion batteries are less expensive to produce than cobalt-containing lithium-ion batteries. This is because cobalt is a relatively expensive metal, and cobalt-free lithium-ion batteries do not require any cobalt.
- More environmentally friendly: Cobalt-free lithium-ion batteries are more environmentally friendly than cobalt-containing lithium-ion batteries. This is because the mining and processing of cobalt can have negative environmental impacts, such as water pollution and deforestation.
- Safer: Cobalt-free lithium-ion batteries are safer than cobalt-containing lithium-ion batteries. This is because cobalt-free lithium-ion batteries are less prone to thermal runaway, which is a condition in which the battery overheats and catches fire.
- Higher energy density: Cobalt-free lithium-ion batteries have a higher energy density than cobalt-containing lithium-ion batteries. This means that cobalt-free lithium-ion batteries can store more energy in a smaller and lighter package.

Challenges of Cobalt-Free Lithium-Ion Batteries

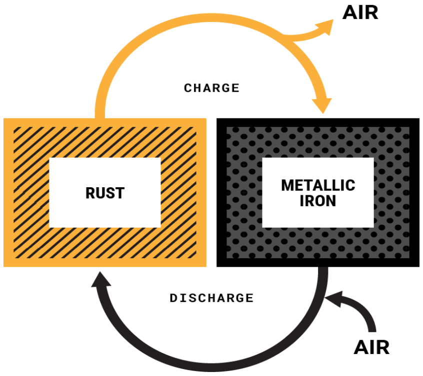
- Lower cycle life: Cobalt-free lithium-ion batteries have a lower cycle life than cobalt-containing lithium-ion batteries. This means that cobalt-free lithium-ion batteries can be recharged fewer times before they need to be replaced.
- Higher internal resistance: Cobalt-free lithium-ion batteries have a higher internal resistance than cobalt-containing lithium-ion batteries. This means that cobalt-free lithium-ion batteries have a lower power output and a lower efficiency.
- Less mature technology: Cobalt-free lithium-ion battery technology is less mature than cobalt-containing lithium-ion battery technology. This means that there are fewer cobalt-free lithium-ion batteries on the market, and they are more expensive to produce.

Overall, cobalt-free lithium-ion batteries have a number of advantages over cobalt-containing lithium-ion batteries, including lower cost, more environmental friendliness, and safety. However, cobalt-free lithium-ion batteries also have a number of challenges, including lower cycle life, higher internal resistance, and less mature technology.

Despite these challenges, cobalt-free lithium-ion batteries are a promising new technology with the potential to revolutionise the energy storage industry. Researchers are working to address the challenges of cobalt-free lithium-ion batteries, and the technology is expected to improve significantly in the coming years.

xiii. IRON-AIR BATTERY

Overview



Iron-air batteries are a type of metal-air battery that uses iron as the anode and oxygen from the air as the cathode. They have a very high energy density, making them a promising candidate for grid-scale energy storage. However, they also have a slow charging rate and a shorter lifespan than some other battery technologies.

Working principle

Iron-air batteries work by the principle of reversible rusting. When the battery is discharging, the iron anode reacts with oxygen from the air to form iron oxide. This reaction releases electrons, which flow through the external circuit to power a load. When the battery is charging, the iron oxide is reduced back to iron, and the electrons flow back through the external circuit.

The electrolyte in an iron-air battery is usually an alkaline solution, such as potassium hydroxide. The electrolyte helps to conduct the ions between the anode and cathode, and it also helps to prevent the iron oxide from forming a solid layer on the anode, which would block the flow of electrons.

Researching Universities/Institutions/Companies

America: University of Massachusetts Amherst, Rice University, University of California, Los Angeles (UCLA), University of Michigan, Argonne National Laboratory, Lawrence Berkeley National Laboratory, National Renewable Energy Laboratory (NREL), ESS Inc., Form Energy, EnergyOR Technologies, ESS Tech, Inc., EnZinc, Zinc8 Energy Solutions.

Europe: University of Cambridge.

Asia: Form Energy.

Largest Capacity Acquired

The largest capacity iron-air battery that has been installed to date is a 100 kWh battery system in China. The battery is made up of iron-air cells and is used to store energy from a solar power plant.

Cost of making

The estimated cost of manufacturing an iron air battery is currently around Rs. 16661.86 per kilowatt-hour (kWh).

Specific Capacity

The specific energy capacity of iron-air batteries were typically reported in the range of 100 to 200 watt-hours per kilogram (Wh/kg).

Future Prospects

The development of iron-air batteries is still in its early stages, and there are a number of challenges that need to be addressed. Some of the challenges include:

- Improving the charging rate of iron-air batteries.
- Increasing the lifespan of iron-air batteries.
- Reducing the cost of iron-air batteries.

Despite the challenges, there is significant research and development activity in this area, and it is expected that iron-air batteries will become more common in the future.

Here are some of the positives of iron-air batteries:

- High energy density: Iron-air batteries have a very high energy density, which means that they can store a lot of energy in a small volume. This makes them a good candidate for grid-scale energy storage, where space is limited.

- Low cost: Iron is a very abundant and inexpensive material, which makes iron-air batteries a cost-effective option.
- Environmentally friendly: Iron-air batteries do not use any toxic or hazardous materials, making them a more environmental friendly option than some other battery technologies.

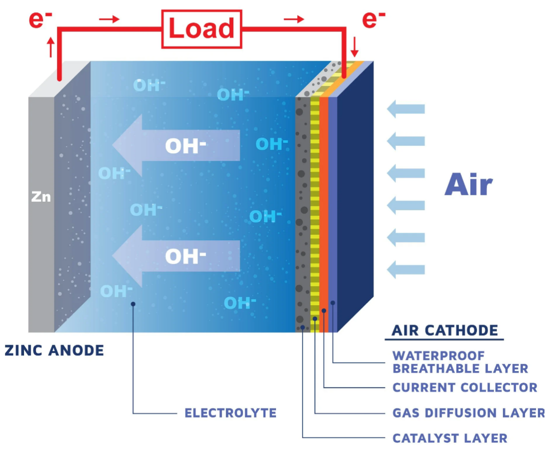
Here are some of the challenges that need to be addressed before iron-air batteries can be widely adopted:

- Slow charging rate: Iron-air batteries have a slow charging rate, which means that they are not suitable for applications where a quick charge is needed.
- Short lifespan: Iron-air batteries have a shorter lifespan than some other battery technologies.
- Research and development: Iron-air batteries are still in the early stages of development, and there is still much research that needs to be done to improve their performance and reduce their cost.

Overall, iron-air batteries have the potential to be a promising technology for grid-scale energy storage. However, there are still a number of challenges that need to be addressed before they can be widely adopted.

xiiv. ZINC-AIR BATTERY

Overview



Zinc-air batteries are a type of metal-air battery that uses zinc as the anode and oxygen from the air as the cathode. They have a very high energy density, making them a promising candidate for grid-scale energy storage and other applications where a lot of energy is needed in a small volume. However, they also have a slow charging rate and a shorter lifespan than some other battery technologies.

Working principle

Zinc-air batteries work by the principle of reversible rusting. When the battery is discharging, the zinc anode reacts with oxygen from the air to form zinc oxide. This reaction releases electrons, which flow through the external circuit to power a load. When the battery is charging, the zinc oxide is reduced back to zinc, and the electrons flow back through the external circuit.

The electrolyte in a zinc-air battery is usually an alkaline solution, such as potassium hydroxide. The electrolyte helps to conduct the ions between the anode and cathode, and it also helps to prevent the zinc oxide from forming a solid layer on the anode, which would block the flow of electrons.

Chemical Equation

$4Fe(s) + 3O2(g) + 6H2O(l) \rightarrow 4Fe(OH)3(s)$

Researching Universities/Institutions/Companies

America: University of Massachusetts Amherst, Rice University, Lawrence Berkeley National Laboratory, Argonne National Laboratory, National Renewable Energy Laboratory (NREL), ESS Inc., Form Energy, EnergyOR Technologies, ESS Tech, Inc, EnZinc.

Asia: Indian Institute of Technology (IIT) Madras, Indian Institute of Technology (IIT) Bombay, Indian Institute of Technology (IIT) Kanpur, Indian Institute of Technology (IIT) Delhi, Central Electrochemical Research Institute (CECRI), Council of Scientific and Industrial Research (CSIR),India , Tata Chemicals, Amara Raja Batteries, Exide Industries, Reliance Industries, ReJoule Electric, University of Sydney, University of New South Wales, Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Tsinghua University, Wuhan University, Osaka University.

Europe: Friedrich Schiller University Jena, Helmholtz Institute Jena, Forschungszentrum Jülich, Germany, University of Nottingham, University of Southampton, Imperial College London, England.

Largest Capacity Acquired

The largest capacity zinc-air battery that has been installed to date is a 100 kWh battery system in China. The battery is made up of zinc-air cells and is used to store energy from a solar power plant.

Specific Capacity

400 to 450 Wh/kg.

Space for implementation

Battery for Hearing aid	0.1 cm³
Battery for Smartphone	10 cm³

Battery for Laptop	50 cm^3
Battery for Electric vehicle	10,000 cm^3

Cost of making

Battery for Hearing aid	Rs. 4.17
Battery for Smartphone	Rs. 83.31
Battery for Laptop	Rs. 416.55
Battery for Electric vehicle	Rs. 8330.93

Future Prospects

The development of zinc-air batteries is still in its early stages, and there are a number of challenges that need to be addressed. Some of the challenges include:

- Improving the charging rate of zinc-air batteries.
- Increasing the lifespan of zinc-air batteries.
- Reducing the cost of zinc-air batteries.

Despite the challenges, there is significant research and development activity in this area, and it is expected that zinc-air batteries will become more common in the future.

Here are some of the potential benefits of zinc-air batteries:

- High energy density: Zinc-air batteries have a very high energy density, which means that they can store a lot of energy in a small volume. This makes them a good candidate for grid-scale energy storage, where space is limited.
- Low cost: Zinc is a very abundant and inexpensive material, which makes zinc-air batteries a cost-effective option.
- Environmentally friendly: Zinc-air batteries do not use any toxic or hazardous materials, making them a more environmentally friendly option than some other battery technologies.

Here are some of the challenges that need to be addressed before zinc-air batteries can be widely adopted:

- Slow charging rate: Zinc-air batteries have a slow charging rate, which means that they are not suitable for applications where a quick charge is needed.
- Short lifespan: Zinc-air batteries have a shorter lifespan than some other battery technologies.
- Research and development: Zinc-air batteries are still in the early stages of development, and there is still much research that needs to be done to improve their performance and reduce their cost.

II. Advanced Chemical Energy Storage

Advanced chemical energy storage (ACES) refers to a new generation of chemical batteries that are more efficient, durable, and environmentally friendly than traditional batteries. ACES batteries are still under development, but they have the potential to revolutionize the way we store and use energy.

One of the key advantages of ACES batteries is their high energy density. This means that they can store more energy in a smaller volume, making them ideal for use in portable and space-constrained applications. ACES batteries are also more durable than traditional batteries, meaning that they can withstand more charge/discharge cycles before they need to be replaced.

Another important advantage of ACES batteries is their safety. Traditional batteries can be flammable and hazardous to the environment, but ACES batteries are designed to be much safer. This makes them ideal for use in a wider range of applications, including homes and businesses.

ACES batteries have the potential to transform the way we generate, store, and use energy. They could help us to reduce our reliance on fossil fuels and transition to a more sustainable energy future.

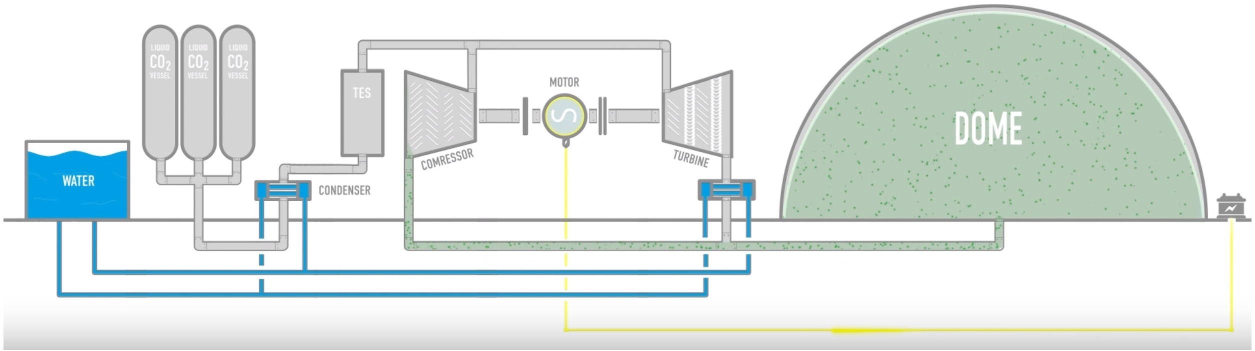
i. CO_2 BATTERY

Overview

The CO2 battery is a long-duration energy storage system that uses carbon dioxide (CO2) as its working fluid. It is a closed-loop system, meaning that the CO2 is never released into the atmosphere. The CO2 battery can store energy for up to 10 hours, making it a good candidate for applications such as solar and wind power smoothing, peak shaving, and backup power.

Working principle

The battery works by compressing CO_2 at normal temperature and pressure, storing the heat produced. Later, the heat is released, turning CO_2 into liquid. To generate power, the liquid CO_2 is heated back into gas, powering a turbine. The system is sealed, using steel, CO_2, and water, avoiding rare materials like cobalt or lithium. This technology is versatile and can be produced and used globally.



Researching University/Company

Energy Dome (Italy), University of Surrey (UK), Massachusetts Institute of Technology (MIT), Pohang University of Science and Technology (POSTECH) (South Korea).

Largest Capacity Acquired

The largest CO2 battery to date is a 20 MW/200MWh system that was installed by Energy Dome in Sardinia, Italy in 2023. This system is capable of storing enough energy to power 20,000 homes for 10 hours.

Specific capacity

313.76 to 614.65 watt-hours per kilogram (Wh/kg)

Cost of making

Cost is around Rs. 4165.47 - 4998.56 per MWh

Positives

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

- It is relatively inexpensive to build and operate.
- It is made from readily available materials, such as CO2, steel, and water.
- It is non-toxic and environmentally friendly.

The future of CO_2 batteries

CO2 batteries are a promising new technology for long-duration energy storage. They are still under development, but they have the potential to play a significant role in the future of renewable energy.

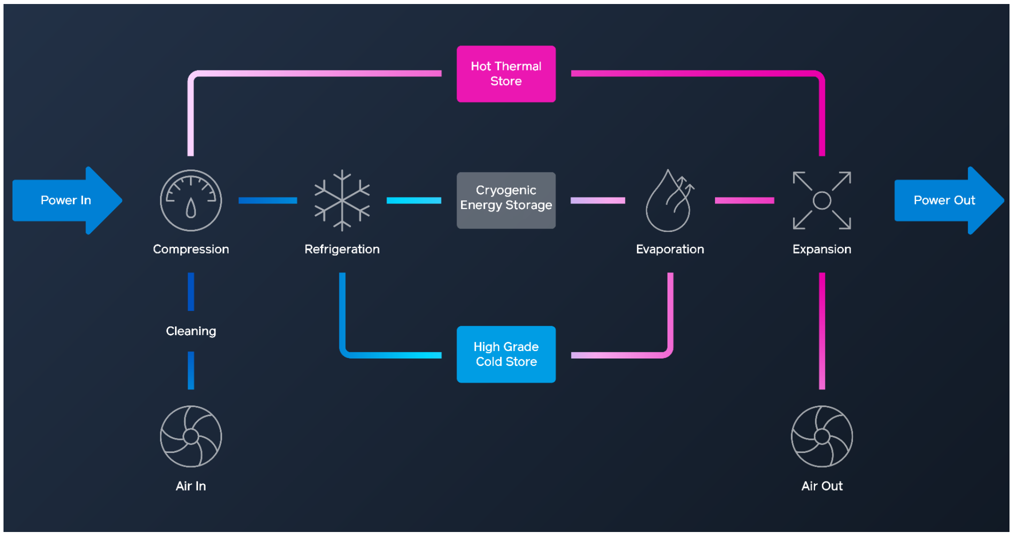
Here are some of the challenges that need to be addressed before CO2 batteries can be widely deployed:

- The efficiency of the CO2 battery can be improved.
- The cost of the CO2 battery needs to be further reduced.
- The technology needs to be scaled up to larger sizes.

Despite these challenges, CO2 batteries have the potential to be a major breakthrough in energy storage. They could help to make renewable energy more reliable and affordable, and they could play a role in decarbonizing the global economy.

ii. HIGHVIEW POWER CRYO-BATTERY

Overview



Highview introduced its CRYOBattery technology through a pilot facility in Slough, subsequently advancing it at a demonstration plant in Pilsworth, Greater Manchester, UK. This plant has been operational since 2018, marking the world's first successful demonstration of cryogenic energy storage technology on a grid scale. It received £8 million funding from the UK government. In October 2019, HighView Power revealed that a 200MW facility could potentially attain a levelized storage cost of Rs. 11663.30/MWh.

Working principle

Formerly referred to as liquid air energy storage, Highview's technology utilises liquid air for storage purposes. This approach involves utilising surplus or off-peak energy to cleanse, compress, and chill air down to -196°C. The liquefied air is subsequently stored within well-insulated tanks at lower pressure. When energy is required, the liquid air is retrieved from the tanks, subjected to high pressure through pumping, rewarmed, and then expanded. This process generates high-pressure gas, which powers turbines for energy generation.

Largest capacity acquired

50 MW/250 MWh system located in Greater Manchester, England.

Specific capacity

Approximately 60-70 Wh/kg

Cost of storing

Rs. 11663.30 per megawatt-hour (MWh) for a 10-hour, 200 MW/2 GWh system.

Space for Implementation

A 5 MW/50 MWh system will require approximately 1,000 square meters of space, while a 50 MW/250 MWh system will require approximately 5,000 square meters of space.

Positives

The system boasts a lifespan exceeding 30 years and has the capability to utilise industrial waste heat and cold from various applications. Its scalability and flexibility are noteworthy, and it is not restricted by geographical limitations. The plant is constructed in modular components, facilitating deployment.

III. FLOW BATTERIES

Flow batteries are a type of rechargeable battery in which the electrolyte flows through one or more electrochemical cells from one or more tanks. This allows for the storage and discharge of large amounts of energy, as the capacity of the battery is limited only by the volume of the electrolyte tanks. Flow batteries also have a long cycle life, meaning they can be charged and discharged many times without losing their performance.

Flow batteries are made up of two main components: the electrochemical cell stack and the electrolyte tanks. The cell stack is where the chemical energy of the electrolyte is converted into electrical energy, and vice versa. The electrolyte tanks store the electrolyte, which is made up of two different liquid solutions, called the anolyte and the catholyte.

When the battery is charging, the electrolyte flows through the cell stack and the anolyte and catholyte are mixed together. This causes a chemical reaction to occur, which produces electricity. The electricity is then sent to the load device, such as a home or business.

When the battery is discharging, the electrolyte flows back through the cell stack and the chemical reaction is reversed. This produces electricity, which is then sent to the load device.

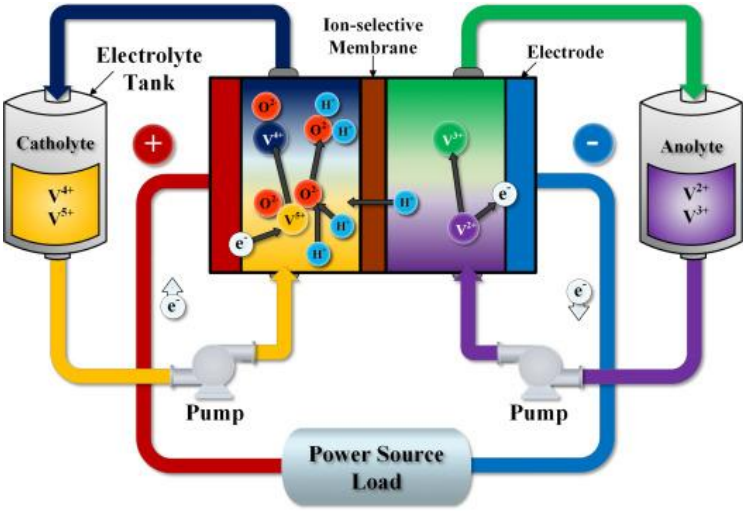
i. VANADIUM REDOX FLOW BATTERY (VRFB)

Overview

VRFBs are a type of electrochemical energy storage device that uses vanadium ions in different oxidation states to store energy. They are known for their long lifespan, low maintenance requirements, and ability to be scalable to large capacities. VRFBs are also relatively environmentally friendly, as they do not use any toxic or hazardous materials.

Working principle

A VRFB consists of two electrochemical cells, each of which contains a vanadium electrolyte solution. The two cells are connected by a membrane that allows vanadium ions to pass through, but prevents electrons from passing through.



During charging, electrons from the power grid are used to oxidise vanadium ions in the positive electrolyte solution. The oxidised vanadium ions then pass through the membrane to the negative electrolyte solution, where they are reduced.

During discharging, the process is reversed. Electrons from the load are used to reduce vanadium ions in the negative electrolyte solution. The reduced vanadium ions then pass through the membrane to the positive electrolyte solution, where they are oxidised.

Chemical Reaction

Positive Electrode: VO2+ + H2O - e- → VO2+ + 2 H+

Negative Electrode: V3+ + e- → V2+

Research Universities/Institutions

Asia: University of Tokyo (Japan), Kyoto University (Japan), Pohang University of Science and Technology (South Korea), Nanyang Technological University (Singapore), Tsinghua University (China), Yonsei University (South Korea), Tongji University (China), IIT Madras, Bombay, Roorkee, IISc, Council of Scientific and Industrial Research - National Chemical Laboratory (CSIR-NCL).

America: Pacific Northwest National Laboratory (PNNL), Argonne National Laboratory,University of California Berkeley, Stanford University, Massachusetts Institute of Technology (MIT).

Europe: CIC energiGUNE (Spain), Cenelest (France), Tekniker (Spain), University of Padua (Italy), Zhaw (Switzerland), Delft University of Technology (TU Delft), Netherlands, Imperial College London, UK, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, University of Sheffield, UK, German Aerospace Center (DLR), Germany.

Research Companies

Asia: VanadiumCorp (Australia), Primus Power (Japan), Sumitomo Electric Industries (Japan), LG Chem (South Korea), BYD (China), Rongke Power (China), Dalian Rongke Power (China), Redflow (Australia with operations in

Asia), ESS Inc., UniEnergy Technologies, Invinity Energy Systems, VRB Energy, Form Energy, CellCube (Germany), InEnergy (Norway), Largo Clean Energy (Canada), Voith (Germany), W.L. Gore & Associates (USA), JenaBatteries (Germany), Kemiwatt (Germany), Pinflow energy storage (Germany), Vanevo (Switzerland), Volterion (Netherlands), VoltStorage, CellCube Energy Storage Systems Inc., Vionx Energy.

Largest Capacity Acquired

The largest vanadium redox flow battery (VRB) installed to date is a 100 MW/400 MWh battery in Dalian, China. It was commissioned in December 2021 and is used to store energy from renewable sources, such as wind and solar.

Cost of energy storing

Cost - Rs. 24992.79 - 49985.58/KWh.

Space for Implementation

Space needed- 1 MW / 4 MWh needs 200 sq.m

Specific Capacity

Specific capacity- 20 to 40 Wh/kg (Li-ion 80-200 Wh/kg)

Applications

VRFBs are also being considered for a variety of applications, such as:

- Grid balancing
- Peak shaving
- Backup power
- Vehicle-to-grid (V2G)
- Microgrids
- Remote power

Positives and Challenges

The positives of VRFBs include:

- Long lifespan (up to 20 years, 20,000 cycles).
- Low maintenance requirements.
- Environmentally friendly.
- Scalability.
- Deep Discharge.
- Low impact on nature.

The challenges of VRFBs include:

- High initial cost.
- Slow charging and discharging rates.
- Sensitive to impurities in the electrolyte.
- Moderate energy density.
- Large space needed.

Overall, VRFBs are a promising technology for energy storage applications. They offer a number of positives over other technologies, such as long lifespan, low maintenance requirements, and environmental friendliness. However, they also have some challenges, such as high initial cost and slow charging and discharging rates.

ii. ZINC - BROMINE FLOW BATTERY

Overview

Zinc-bromine flow battery (ZBFB) is a type of redox flow battery that uses zinc and bromine as the active materials. ZBFBs have a high energy density and a long cycle life, making them a promising technology for large-scale energy storage applications.

Working principle

ZBFBs work by storing energy in two separate electrolyte solutions, one containing zinc ions and the other containing bromine ions. When the battery is charged, an electric current drives the zinc ions and bromine ions to opposite sides of the battery stack. This creates a chemical potential difference between the two electrolytes.When the battery is discharged, the zinc ions and bromine ions flow back together through the battery stack, generating an electric current. The electrolyte solutions are continuously circulated through the battery stack to ensure that there is always a sufficient supply of active materials.

Chemical reaction

$Zn + Br2 \leftrightarrow ZnBr2$

Researching Universities/Institutions/Companies

India: Indian Institute of Technology Bombay (IIT Bombay), Indian Institute of Technology Delhi (IIT Delhi), Indian Institute of Technology Madras (IIT Madras), National Institute of Technology Karnataka (NITK), Jawaharlal Nehru Technological University Hyderabad (JNTU Hyderabad), Anna University

Chennai (AU Chennai), Indian Institute of Science (IISc Bangalore), CSIR-Central Electrochemical Research Institute (CECRI Kolkata), CSIR-National Chemical Laboratory (NCL Pune), CSIR-Solar Energy Centre (SEC Ahmedabad).

Africa: Stellenbosch University (South Africa), University of Pretoria (South Africa), University of Cape Town (South Africa).

Asia: Tsinghua University (China), Peking University (China), University of Tokyo (Japan), Kyoto University (Japan), Seoul National University (South Korea), Indian Institute of Technology Bombay (India), Indian Institute of Technology Delhi (India), National University of Singapore (Singapore).

Australia: University of Melbourne (Australia), University of Sydney (Australia), Queensland University of Technology (Australia).

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).

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), University of Waterloo (Canada), McGill University (Canada).

South America: University of São Paulo (Brazil), State University of Campinas (Brazil), University of Buenos Aires (Argentina).

Largest Capacity Acquired

The largest capacity zinc-bromine battery currently in operation is the EOS Z3 battery, which has a capacity of 347 MWh and is located at the Angas Downs Wind Farm in South Australia.

Specific capacity

60 and 85 Wh/kg.

Space needed to implement

In general, a ZBB will require approximately 1-2 square feet of space per kWh of storage capacity.

Cost of making

A typical cost range is between Rs. 35656.38 and Rs. 39821.85 per kilowatt-hour (kWh).

Positives and Challenges

Positives:

- High energy density: ZBFBs have a high energy density, meaning that they can store a lot of energy in a relatively small and lightweight package. This makes them ideal for applications where space and weight are at a premium, such as grid-scale energy storage.
- Long cycle life: ZBFBs have a long cycle life, meaning that they can be recharged many times before they need to be replaced. This makes them a cost-effective choice for long-term energy storage applications.
- Non-flammable electrolytes: ZBFBs use non-flammable electrolytes, which makes them safer than other types of batteries, such as lithium-ion batteries.
- Flexible design: ZBFBs can be designed with different power and energy ratings to meet the specific needs of different applications.

Challenges:

- Cost: The cost of producing ZBFBs is still higher than the cost of producing other types of batteries, such as lithium-ion batteries. However, the cost of ZBFBs is expected to continue to fall as the technology improves and production costs are reduced.
- Complexity: ZBFBs are more complex than other types of batteries, such as lithium-ion batteries. This requires more specialised equipment and expertise to manufacture and maintain ZBFBs.
- Zinc dendrite formation: Zinc dendrite formation is a potential problem with ZBFBs. Zinc dendrites are needle-like structures that can form on the zinc electrode during charging. These dendrites can grow and eventually short-circuit the battery, causing it to fail. Researchers are working on ways to prevent zinc dendrite formation in ZBFBs.

IV. 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.

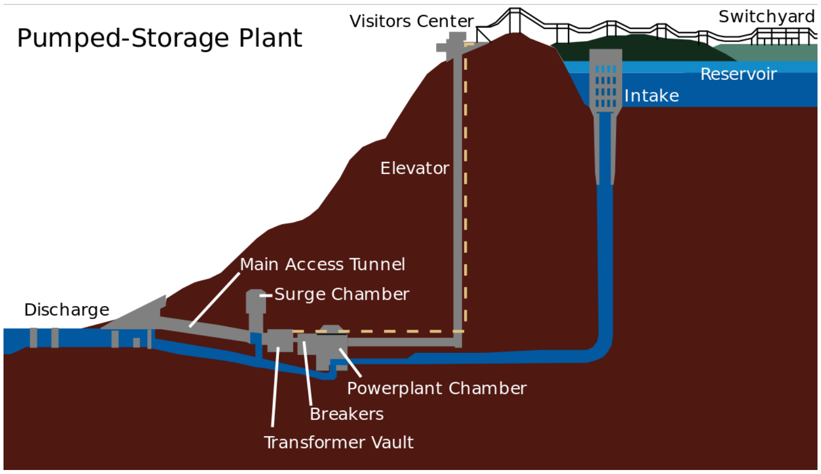
Another type of GES system is a gravity battery. Gravity battery systems use a crane or other lifting device to raise a heavy object to a high elevation. The potential energy stored in the object is then converted to electrical energy when it is lowered back down. Gravity battery systems are still in 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 efficiency of PHS is typically around 80%. This means that for every 100 kWh of electricity that is used to pump the water, 80 kWh of electricity can be generated when the water is released.

Largest Capacity Acquired

The largest pumped hydro storage facility in the world is the Fengning Pumped Storage Power Station in China. It has a capacity of 3600 megawatts (MW) and can store 22400 megawatt-hours (MWh) of energy.

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

the cost of PHS is typically between Rs. 8830.79 and Rs. 16661.86 per kilowatt-hour (kWh) of capacity.

Space needed 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).

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

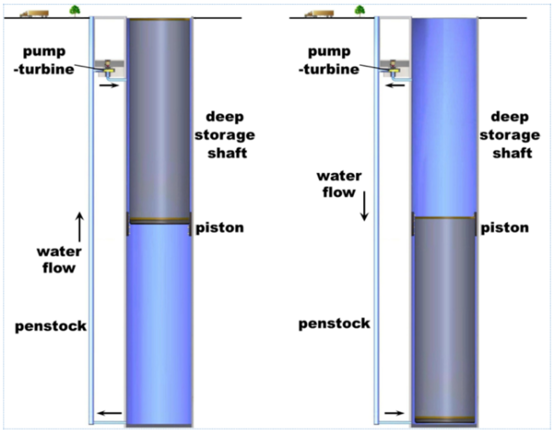
Overview

Gravity-based energy storage systems store energy by lifting a mass to a height. When the mass is released, it falls and its potential energy is converted into 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 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:



GENERATING POWER STORING ENERGY

- **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

Approximately 208115.88 to 291362.23 Rs/ kWh.

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 lifespan and require little maintenance.
- They are relatively inexpensive 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.

V. 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.

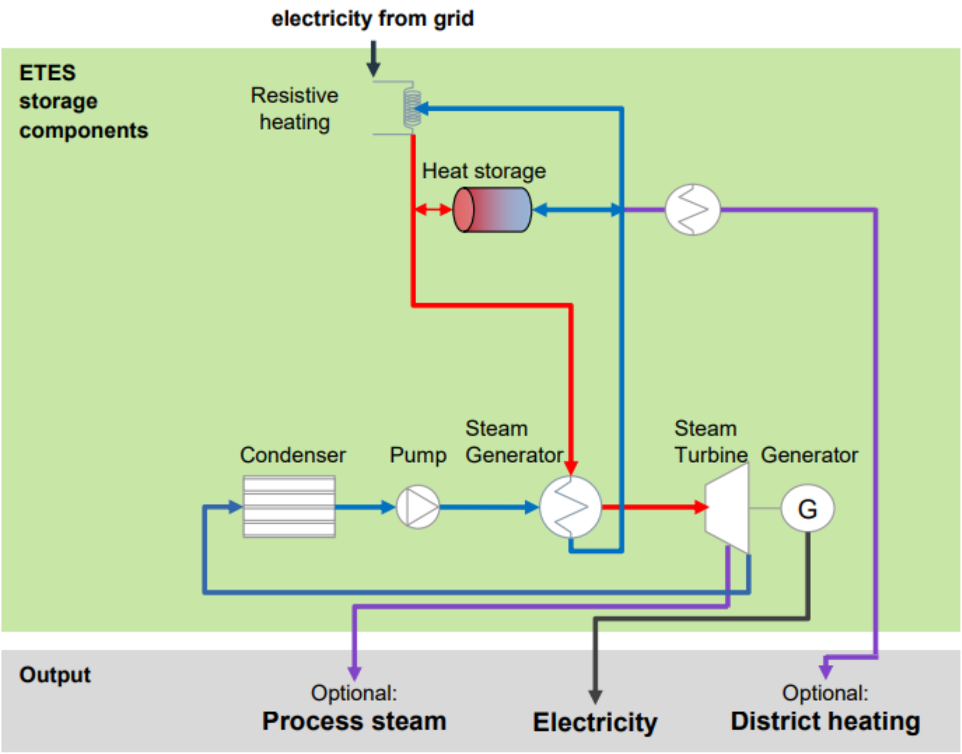
There are three main types of TES systems: sensible heat storage, latent heat storage, and thermochemical storage. Sensible heat storage systems store heat energy by raising the temperature of a material. Latent heat storage systems store heat energy by melting a solid material. Thermochemical storage 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. ELECTRIC THERMAL ENERGY STORAGE (ETES)

Overview



In June 2019, Siemens Gamesa Renewable Energy (SGRE) successfully initiated the operation of its 130MWh Hamburg demonstrator Electric Thermal Energy Storage (ETES) facility. This project is recognized as a significant disruptor in the realm of large-scale (>100MW) and long-duration (several days) energy storage.

Working principle

The working principle of the Demonstrator Plant Electric Thermal Energy Storage (ETES) involves utilising excess electricity to heat a bed of volcanic rocks, raising their temperature. During times of high electricity demand, air is blown through the heated rocks, extracting the stored heat and converting it into electricity using a steam turbine generator. This process provides a flexible and efficient means of storing and releasing energy on demand.

Largest capacity acquired

The largest capacity of electric thermal energy storage (ETES) is currently 87.5 MWh, which is achieved by the demonstration plant at the University of Stuttgart in Germany.

Cost of Energy Storing

Approximately 3561.24 - 5341.86/kWh.

Specific capacity

The specific energy of ETES systems ranges from about 0.2 to 2.0 megawatt-hours per cubic metre (MWh/m³), depending on the type of storage media used. For example, molten salts have a specific energy of about 0.8 MWh/m³, while water has a specific energy of about 0.2 MWh/m³.

Positives and Challenges:

The positives of proton batteries include:

- Cost Effective
- GWh scale
- Modular
- Adaptable

The Challenges of proton batteries include:

- Limited storage capacity.
- Need frequent maintenance.

ETES technology is claimed to utilise 80% off-the-shelf components, maintaining a low-cost level. Particularly in the context of large-scale (>100MW) and long-duration (several days) applications, ETES has the potential to outperform other storage technologies in terms of efficiency and cost-effectiveness. By adopting a brownfield approach, converting existing steam power plants into

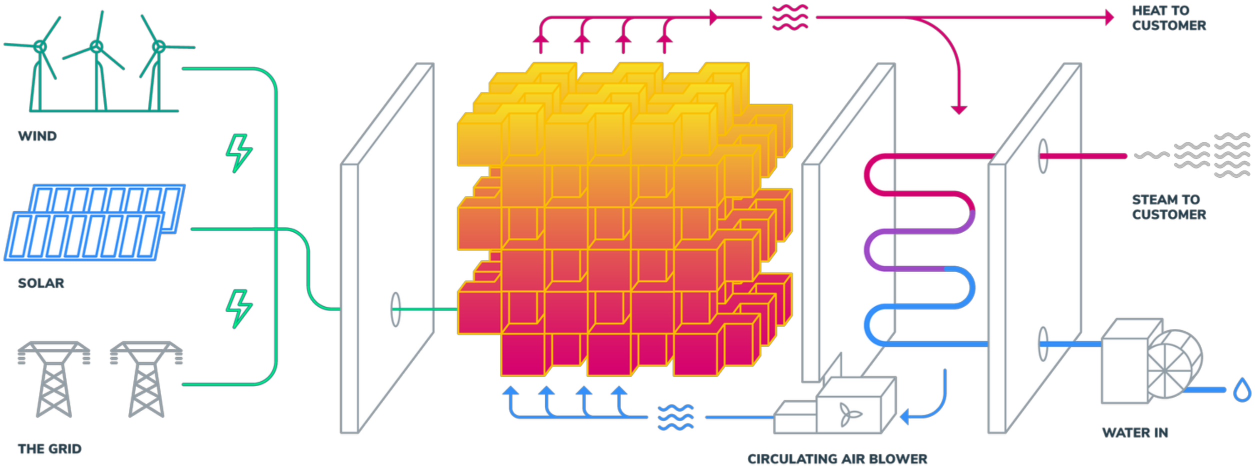
ETES facilities (known as 'ETES:Switch'), and retaining the steam cycle and operational processes, the capacity-specific total cost could be further reduced to around 3562.17 Rs/kWh.

ii. RONDO HEAT BATTERY

Overview

The Rondo Heat Battery is a thermal energy storage system that uses refractory brick to store heat. It is designed to be a drop-in replacement for fossil fuel-fired boilers in industrial processes. The Rondo Heat Battery can store heat for up to 12 hours and deliver it at temperatures up to 1,500 degrees Celsius. It is made of readily available materials and is recyclable at the end of its life.

Working principle



The Rondo Heat Battery uses electric heating elements to heat the refractory brick. The refractory brick used in this is made of oxygen, silicon, and aluminium. These materials are heat-resistant and can withstand temperatures up to 1,800 degrees Celsius. The electric heating elements in this Battery are made of nichrome, a type of alloy that is resistant to corrosion and oxidation. It is insulated with a layer of air or insulation material to prevent heat loss. The heat is stored in the brick by conduction. When heat is needed, the brick is cooled by air or water. The heat is then transferred to the industrial process.

Researching Company

The Rondo Heat Battery is being developed by Rondo Energy, a company based in San Francisco, California. Rondo Energy was founded in 2019 by a team of engineers and scientists with experience in the energy industry.

Largest Capacity Acquired

The largest capacity acquired by the Rondo-Heat battery is 2.4 GWh. This is the capacity of the first factory of Rondo Energy in Thailand. The company plans to expand the factory to reach a capacity of 90 GWh.

Specific capacity

The specific energy of the Rondo Heat Battery is not publicly disclosed, but it is estimated to be in the range of 1.0 to 2.0 MWh/m^3.

Space needed to implement

2 MW/4 MWh - 400 m^2
10 MW/20 MWh - 1,000 m^2
100 MW/200 MWh - 10,000 m^2

Cost of energy storing

Estimate of the cost of storing a Rondo heat battery is 416.18 Rs/kWh.

Other Advantages

The Rondo Heat Battery is a zero-emissions technology, which means it does not produce any harmful pollutants. It is also a modular system, which means it can be scaled to meet the needs of different applications. The Rondo Heat Battery is relatively inexpensive to install and operate.

Future Research

The Rondo Heat Battery is a zero-emissions technology, which means it does not produce any harmful pollutants. It is also a modular system, which means it can be scaled to meet the needs of different applications. The Rondo Heat Battery is relatively inexpensive to install and operate.

iii. SAND ENERGY STORAGE

Overview

A sand battery is a type of thermal energy storage system that uses sand as a heat storage medium. It is a relatively new technology that has the potential to store large amounts of energy at a low cost. Sand batteries work by heating sand to a high temperature, typically around 500 degrees Celsius. The heat is then stored in the sand and can be released later when needed. To release the heat, the sand is cooled and the heat is transferred to a fluid, such as water or air. The fluid can then be used to heat buildings, generate electricity, or provide industrial process heat.

Working principle

A sand battery works by storing heat in sand and releasing it when needed. The sand is heated to a high temperature, typically around 500 degrees Celsius, using electricity from renewable sources such as solar and wind power. The heat is then transferred to a heat storage medium, such as rocks or molten salt. The heat storage medium then stores the heat until it is needed. When heat is needed, the heat storage medium is cooled and the heat is transferred to a working fluid, such as water or air. The working fluid then transfers the heat to the application where it is needed, such as heating a building or generating electricity.

Researching Universities/Institutions/Companies

America: University of California, Berkeley, Stanford University, Massachusetts Institute of Technology (MIT), National Renewable Energy Laboratory (NREL).

Europe: Fraunhofer Institute for Solar Energy Systems, Helmholtz-Zentrum Berlin für Materialien und Energie, DLR - German Aerospace Center.

Asia: Tsinghua University, Chinese Academy of Sciences, Indian Institute of Technology Madras, National Thermal Power Corporation.

Australia: University of South Australia, CSIRO, Energy Resources of Australia.

Largest capacity acquired

The largest capacity acquired for sand energy storage is 1.5 gigawatt-hours (GWh), which was announced in April 2023 by the Australian company Energy Resources of Australia (ERA).

Specific capacity

Between 0.5 and 1 Wh/kg.

Space needed to implement

It will require about 5-10 cubic meters of space per kilowatt-hour (kWh) of storage capacity.

Cost of energy storing

Rs. 4.16 per kilowatt-hour (kWh)

Positives and challenges

Positives:

- Abundant and low-cost material: Sand is a very abundant and low-cost material, making it a promising material for energy storage.
- High heat capacity: Sand has a high heat capacity, meaning that it can store a lot of heat. This makes it well-suited for use in thermal energy storage systems.

- Long lifespan: Sand has a long lifespan, meaning that sand energy storage systems can last for many years.
- Environmentally friendly: Sand is an environmentally friendly material, and sand energy storage systems do not produce any harmful emissions.

Challenges:

- Space requirements: Sand energy storage systems require a significant amount of space.
- Heat transfer: Heat transfer can be challenging in sand energy storage systems. This is because sand is a poor conductor of heat.
- Cost: Sand energy storage systems are still a relatively new technology, and they can be expensive to install.
- Research and development: More research and development is needed to improve the efficiency and cost-effectiveness of sand energy storage systems.

VI. 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.

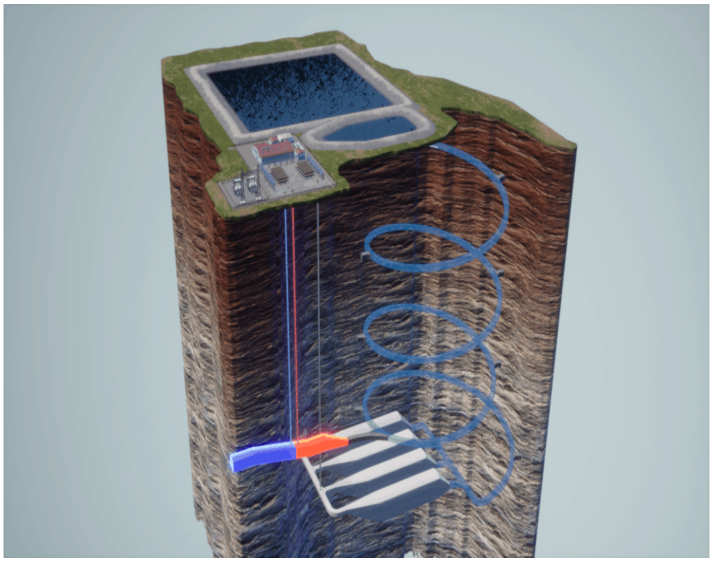
CAES systems are one of the most mature energy storage technologies available, and they have been in commercial operation for decades. CAES systems are well-suited for large-scale energy storage applications, and they can provide reliable and affordable electricity for peak demand and grid balancing.

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) FACILITY

Overview



Hydrostor's Angas Project stands as Australia's pioneer Advanced Compressed Air Energy Storage (A-CAES) facility, showcasing an emissions-free, extended-duration energy storage solution. This innovative technology merges mining methodologies with mechanical systems to create a location-flexible, compressed air-based energy storage system, void of fuel consumption.

Working Principle

A-CAES technology utilises grid electricity to run a compressor, generating heated compressed air. When charging, air displaces water out of the cavern, raising it to a surface reservoir. During discharge, water returns to the cavern, pushing air to the surface under pressure, where it's re-heated and expanded through a turbine to generate on-demand electricity.

Researching Universities/Institutions/Companies

A-CAES systems are still in the early stages of development, but they have the potential to be a major player in the energy storage market. Several A-CAES projects are currently under construction or development around the world, including:

- Hydrostor's 500 MW / 4 GWh A-CAES projects in California: These projects are expected to be completed in 2025 and will be the largest non-hydro energy storage systems in the world.
- Eni's 100 MW / 400 MWh A-CAES project in China: This project was commissioned in 2022 and is the first commercial A-CAES system in the world.
- Alliant Energy's 200 MWh A-CAES project in Wisconsin: This project is expected to be completed in 2024 and will be the first A-CAES system in the United States.

Cost of the project is Cr. 274.75 Rs.

Largest capacity acquired

The largest capacity compressed air energy storage (CAES) facility in the world is the Zhangjiakou CAES plant in China. It has a capacity of 400 megawatt-hours (MWh) and can generate up to 100 megawatts (MW) of electricity for four hours.

Specific capacity

0.2-0.5 kWh/m^3

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.

A 1 GW / 4 GWh - 4 million cubic meters of space.

Cost of storing energy

According to a study by the National Renewable Energy Laboratory (NREL), the cost of storing CAES is estimated to be between 2081.49 and 4162.98 Rs per megawatt-hour (MWh).

Positives and Challenges:

The positives of A-CAES include:

> The Angas A-CAES Project could potentially pave the way for the establishment of extensive, large-scale (50+ MW), prolonged-duration (4-24+ hours), durable (50+ years) initiatives across Australia. This expansion would contribute to increased clean energy capacity and enhanced power supply reliability.

The Challenges of A-CAES include:

> One of the main challenges is associated with engineering and modelling to accurately predict performance with limited operating history.

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.

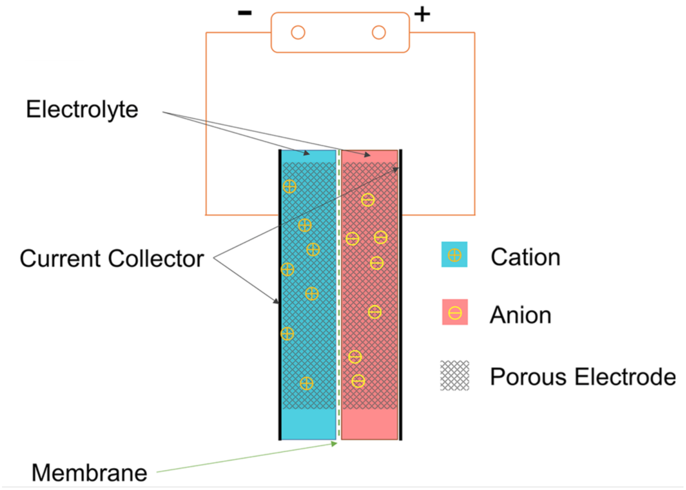
SCES is a promising technology with the potential to revolutionize the way we generate and use energy. SCES systems can help us to reduce our reliance on fossil fuels, improve energy efficiency, and create a more sustainable energy future.

i. SUPERCAPACITORS

Overview

Supercapacitors are electrochemical energy storage devices that can store more energy than conventional capacitors and deliver it at higher power outputs than batteries. They have a high power density, long cycle life, and low self-discharge rate, making them well-suited for applications that require frequent charge/discharge cycles, such as hybrid electric vehicles, electric buses, and renewable energy storage systems.

Working principle



Supercapacitors store energy in two ways:

- Electric double-layer capacitance (EDLC): This is the dominant storage mechanism in most supercapacitors. It occurs when ions from the electrolyte are attracted to the oppositely charged electrodes, creating a layer of charge on each electrode. The amount of charge that can be stored in this way is limited by the surface area of the electrodes.
- Pseudocapacitance: This mechanism is less common, but it can provide a higher energy density than EDLC. It occurs when the electrodes undergo

redox reactions, in which electrons are transferred between the electrode and the electrolyte.

The overall capacitance of a supercapacitor is the sum of the EDLC and pseudocapacitance.

Researching Universities/Institutions/Companies

Oceania: National University of Singapore (NUS), Nanyang Technological University (NTU), Singapore, Chinese Academy of Sciences (CAS), Tsinghua University, China, Seoul National University, South Korea, Indian Institute of Technology (IIT) Madras, India, Tohoku University, Japan, Korea Advanced Institute of Science and Technology (KAIST), South Korea, National Taiwan University (NTU), Taiwan, University of Malaya, Malaysia, Chinese Academy of Sciences (CAS), Peking University, Tsinghua University, Shanghai Jiao Tong University, Shenzhen University, Tokyo Institute of Technology, Kyoto University, Osaka University, Nagoya University, HokkaidoUniversity, Seoul National University, KAIST, POSTECH, Ulsan National Institute of Science and Technology (UNIST), Sungkyunkwan University, National Taiwan University, National Tsing Hua University, Academia Sinica, National Cheng Kung University, National Chiao Tung University.

America: Massachusetts Institute of Technology (MIT), Stanford University, University of California, Los Angeles (UCLA), University of Texas at Austin, University of California, Berkeley, Georgia Institute of Technology, Pennsylvania State University, University of Illinois at Urbana-Champaign, Northwestern University, Argonne National Laboratory, Brookhaven National Laboratory, Lawrence Berkeley National Laboratory, Los Alamos National Laboratory, National Renewable Energy Laboratory, Oak Ridge National Laboratory, PacificNorthwest National Laboratory, Sandia National Laboratories, Stanford University, University of California, San Diego, University of Texas at Austin, Georgia Institute of Technology, Northwestern University, Rice University, University of Illinois at Urbana-Champaign, University of Michigan, University of Pennsylvania, University of Texas at Dallas, University of Washington.

Largest Capacity Acquired

The largest supercapacitor capacity that has been reported is 1000 Farad (F). This was achieved by a team of researchers at the University of California, Berkeley in 2017. The supercapacitor was made using a new type of electrode material called MXene.

Specific Capacity

575Wh/kg.

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

Rs. 8.33 - 833.14 per F

Applications

Supercapacitors are used in a wide range of applications, including:

- Hybrid electric vehicles.
- Electric buses.
- Renewable energy storage systems.
- Power grid stabilisation.
- Medical devices.
- Industrial automation.
- Consumer electronics.

Challenges

The main challenges facing supercapacitors are their low energy density and high cost. However, research is ongoing to improve these properties, and supercapacitors are expected to become more widely used in the future.

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.

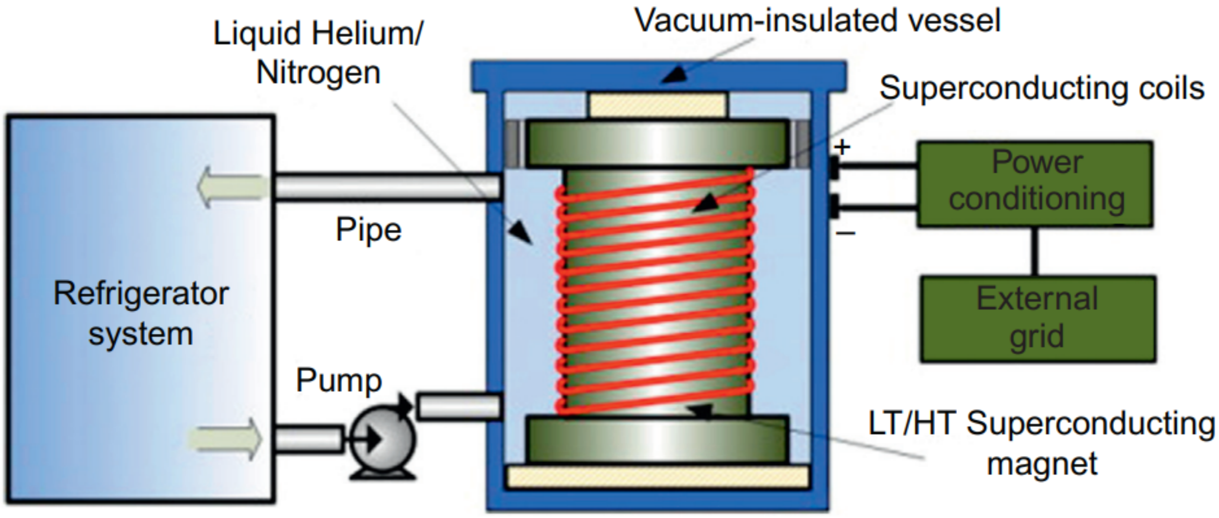
There are two main types of MES systems: superconducting magnetic energy storage (SMES) and inductive magnetic energy storage (IMES).

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) stores energy efficiently in a magnetic field using superconducting coils, but the high cost and cryogenic cooling needed for superconductors limit its application primarily to smaller grid support systems.

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 core component of an SMES system is a superconducting coil or wire made of a high-temperature superconducting material. This coil is maintained at extremely low temperatures, typically close to absolute zero (around -269 degrees Celsius or -452 degrees Fahrenheit), to achieve the superconducting state. During periods when there is excess electrical energy available, the SMES system uses this surplus power to generate a strong and persistent magnetic field within the superconducting coil. This is achieved by passing a current through the coil, which generates the magnetic field. Importantly, due to the zero electrical resistance of the superconducting material, this current can flow indefinitely without losing energy. The energy is stored in the form of a magnetic field in the superconducting coil. Since there is almost no energy dissipation due to the absence of resistance, the magnetic field remains stored for an extended period, which is one of the key advantages of SMES. When electrical power is needed, the magnetic field stored in the superconducting coil is allowed to decay. This change in the magnetic field induces a current in the coil according to Faraday's law of electromagnetic induction. This induced current can be extracted as electrical power through a connected load or a grid connection. One of the notable features of SMES is its ability to respond quickly to changes in power demand. The discharge process can be initiated almost instantaneously, providing a rapid injection of electrical power to the grid or connected devices. SMES systems can undergo numerous charge and discharge cycles with minimal degradation, resulting in a long operational life. This makes them suitable for various applications, including grid stability and energy storage.

Largest capacity acquired

The largest SMES system in operation is a 1 MW / 3 MW-hour system at the Bonneville Power Administration (BPA) in Washington state, USA.

Specific capacity

Specific energy of SMES is typically between 20 and 60 kWh/kg.

Space needed to implement

1 MW/1 MWh : 100 square meters.

10 MW/10 MWh : 1,000 square meters.

100 MW/100 MWh : 10,000 square meters.

Cost of energy storage

According to a study by the National Renewable Energy Laboratory (NREL), the cost of storing SMES is estimated to be between Rs. 83314.00 and Rs. 166628.00 per MWh.

Use of SMES

Initially, SMES devices were envisioned as massive energy storage systems similar in capacity to pumped storage hydropower plants, but due to high costs, current technology focuses on smaller, more efficient micro-SMES units, commonly used for rapid grid support and power quality control. The potential for larger SMES systems for grid stability and renewable energy storage exists, but cost challenges remain a barrier to their development.

The potential for large SMES systems relies on the advancement of more affordable superconducting materials, especially high-temperature superconductors with improved characteristics. The ultimate aim is to find materials that exhibit superconductivity at room temperature. Although there have been intriguing indications in scientific literature, achieving this goal remains a distant possibility.

Researching Universities/Institutions/Companies

1. Massachusetts Institute of Technology (MIT): MIT's Plasma Science and Fusion Center was conducting research on advanced magnet technologies, which included work on superconducting magnets for applications like SMES.

2. University of Houston: The University of Houston's Texas Center for Superconductivity was actively engaged in various superconductivity-related research areas, including energy storage using superconducting materials.

3. SuperPower Inc.: SuperPower Inc. is a company specializing in high-temperature superconducting (HTS) wire and magnetic solutions. They have been involved in developing SMES systems for grid applications.

4. American Superconductor Corporation (AMSC): AMSC is a global company that offers a range of superconductor-based technologies, including SMES solutions for grid-scale energy storage.

5. TECO-Westinghouse Motor Company: TECO-Westinghouse was known for its efforts in developing SMES systems for grid stability and energy management.

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:

- High operational costs: The need for cryogenic cooling systems can be expensive.
- Limited by cooling technology: Advances in cryogenic cooling technology are required to make SMES more practical and widespread.
- Material limitations: Superconducting materials have critical temperature constraints, and research into higher-temperature superconductors is ongoing.

Future Prospects

Ongoing research in the field of superconductivity is focused on several key areas. First, scientists are working diligently to develop new superconducting materials with higher critical temperatures and improved performance characteristics. These advanced materials have the potential to make superconductivity more practical for a wider range of applications. Additionally, researchers are exploring innovations in cryogenic cooling systems and power electronics to reduce operational costs and increase the overall efficiency of superconducting systems.

These developments are crucial for making superconducting technology economically viable. Moreover, there is a growing emphasis on integrating superconducting technologies with renewable energy sources and existing grid infrastructure. This integration not only enhances grid stability but also plays a significant role in facilitating a transition towards cleaner and more sustainable energy solutions.

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

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.

Researching Universities/Institutions/Companies

Massachusetts Institute of Technology (MIT), Stanford University, University of California, Berkeley, Technical University of Munich, National Renewable Energy Laboratory (NREL)

Hydrogenics, Nel Hydrogen, Plug Power, Bloom Energy, Air Liquide

Largest Capacity Acquired

The largest HESS that has been installed to date is located in South Korea. The system, which was developed by H2 Energy, has a capacity of 100 megawatts (MW). The system is used to store solar energy.

Specific capacity

The specific energy of liquid hydrogen is about 33 kWh/kg, and the specific energy of compressed hydrogen gas is about 4.5 kWh/kg.

Space needed to implement

High-pressure tank - 0.05 m^2/Kg of H_2

Underground salt cavern - 0.10 m^2/Kg of H_2

Abandoned mine - 0.10 m^2/Kg of H_2

Cost of energy storage

According to a study by the National Renewable Energy Laboratory (NREL), the cost of storing HES is estimated to be between Rs. 83.31 and Rs. 249.94 per kilogram (kg) of hydrogen.

Positives and Challenges:

HESSs have a number of advantages, including, they can store large amounts of energy for long periods of time, emissions-free, used to store renewable energy.

However, HESSs also have some challenges, including, they are expensive to build and operate, not yet as efficient as other energy storage technologies, such as batteries, and the infrastructure for transporting and distributing hydrogen is not yet well-developed.

Future Prospects

HESSs are a promising technology for storing renewable energy. As the cost of hydrogen production and storage technologies continues to decline, and the infrastructure for transporting and distributing hydrogen is developed, HESSs are expected to become more widespread.

We continually encounter new and effective technologies every day, demonstrating that we have yet to reach the limits of innovation….

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