MULTIDISCIPLINARY INNOVATIONS IN
TECHNOLOGY AND SCIENCE JOURNAL
Vol. No. 01, Issue No. 01, April 2024, pp. 63 - 93

Advanced Energy Storage Technologies: Comparison and Selection for Various Applications

Aniket Pippal [1] , Rakesh Narvey [2],✉ Himmat Singh [3]

[1, 2, 3] Department of Electrical Engineering, MITS, Gwalior

✉ `rakesh_narvey@mitsgwalior.in`

Abstract. The field of energy storage technologies has seen significant advancements in response to the growing demand for efficient and sustainable energy solutions. This research paper offers a comprehensive overview and comparison of advanced energy storage technologies across mechanical, electrical, chemical, and thermal domains. We explore established technologies like Pumped Hydro Energy Storage (PHES), Compressed Air Energy Storage (CAES), and Lithium-ion (Li-ion) batteries, as well as emerging technologies such as Super Capacitors and Sodium Sulfur batteries. Additionally, we highlight promising future storage technologies like Compressed CO2, Nano Diamond batteries, and Metal-Air Batteries. We present a detailed comparison table evaluating these technologies based on key factors, including energy density, efficiency, cycle life, cost, environmental impact, and other significant considerations. Our research employs a weighted product model to select the most suitable energy storage technology for specific applications, offering valuable insights to decision-makers in choosing appropriate energy storage technologies for their intended use.

Keywords: Advanced energy storage, Batteries, Multi criteria decision making, Sselection methodology, Weighted product model.

1 Introduction

The increasing global demand for clean and sustainable energy solutions, coupled with the urgent need to address climate change, has set ambitious goals for achieving carbon neutrality by 2050. To achieve this goal, a fundamental transformation of energy systems is required, with a strong emphasis on renewable energy sources and energy efficiency [1, 2]. As renewable energy generation expands rapidly, the integration of these intermittent sources into the grid becomes a crucial challenge.

Throughout history, the demand for energy has steadily grown as technological advancements and industrialization took place [3-6]. Non-renewable sources such as oil, petroleum, and natural gas were predominantly used to meet energy needs, but their finite nature and environmental impacts have necessitated a shift towards cleaner and renewable energy resources [2, 7]. The continuous growth of the global economy and energy consumption has led to increased CO_2 emissions, contributing to global warming, ocean acidification, smog pollution, ozone depletion, and changes in plant growth and nutrition levels [1].

Renewable energy sources like solar and wind power are less environmentally harmful and inexhaustible. However, their unpredictability and lack of control pose challenges [7]. These sources have significant potential to provide electricity in an environmentally friendly manner, but their intermittent and nondispatchable nature inhibits their widespread adoption [1]. Therefore, one of the major challenges today is to match the available energy with the demand in terms of timing, location, and quantity.

Energy storage plays a crucial role in facilitating this adoption by ensuring a consistent and high-quality electricity supply from renewable energy systems. Furthermore, energy demand is not uniform throughout the day or year, but rather varies significantly within a day and across seasons due to individual needs and climatic effects. This necessitates energy storage. When electrical energy is produced in excess of demand, it must be stored; otherwise, it goes to waste and increases the cost per unit of electricity. Additionally, there are situations where electricity generation exceeds the total demand during off-peak hours, requiring the urgent storage of excess electricity. Energy storage helps maintain a balance between supply (generation) and demand (consumer use), prevents electrical fluctuations, reduces brownouts during peak demand, minimizes environmental pollution, and enhances the efficiency of the electric grid. It stabilizes grid power and improves the overall efficiency of the grid system. Energy storage is a vital mechanism for reliable electricity supply, increased security and economic value, and reduced carbon dioxide emissions [3].

Storing electricity is a complex task that requires specialized devices and mechanisms.Researchers and technologists are continuously improving and innovating in this area. However, selecting the appropriate storage technology remains a significant concern. Currently, considerable effort is being directed towards various battery technologies for energystorage. It is important to note that there is no perfect battery that suits every application. The selection of the right battery for a specific application involves weighing important battery metrics against each other [8]. For example, if an application requires a high-power output, theinternal cell resistance should be minimized, often achieved by increasing the electrode surface area in electrochemical batteries. However, this also results in increased inactive components such as current collectors and conductive aid, leading to a trade-off between energy density and power. When it comes to actual battery performance, it may be necessary to compromise certain design goals to achieve others.

This research paper aims to provide a comprehensive comparison and selection framework for energy storage technologies. It will evaluate a range of storage technologies, including mechanical, electrical, chemical, thermal, and electrochemical systems. Various factors such as energy density, efficiency, cycle life, cost, and environmental impact will be assessed to determine their suitability for different applications. Furthermore, the research willapply a weighted product model derived from operational research techniques to compare andselect the most suitable energy storage technologies for specific applications. By considering different weighting factors based on the goals and requirements of each application, the research aims to identify the optimal technology choice for maximizing performance and efficiency. The findings of this study will contribute to the advancement of energy storage technologies and provide valuable insights for policymakers, industry professionals, andresearchers working towards a sustainable and carbon-neutral energy future. By facilitating theadoption of suitable energy storage solutions, we can accelerate the transition towards a more resilient and environmentally friendly energy system.

2 Overview of Major Energy Storage Technologies

2.1 Mechanical Storage

Pumped Hydro Energy Storage (PHES).

Pumped hydro energy storage systems are the most widely used form of energy storage in power networks, serving various purposes including energy management, frequency regulation, and providing reserve capacity [9]. In the conventional setup of pumped hydroelectric systems, two water reservoirs are positioned at different elevations. The process involves the storage of energy by transferring water from a lower reservoir to a higher one, thereby capturing gravitational potential energy. Typically, surplus electricity, often obtained at a lower cost during off-peak periods, powers the pumps. When electricity demand surges, the accumulated water is released through turbines to generate electricity [6].

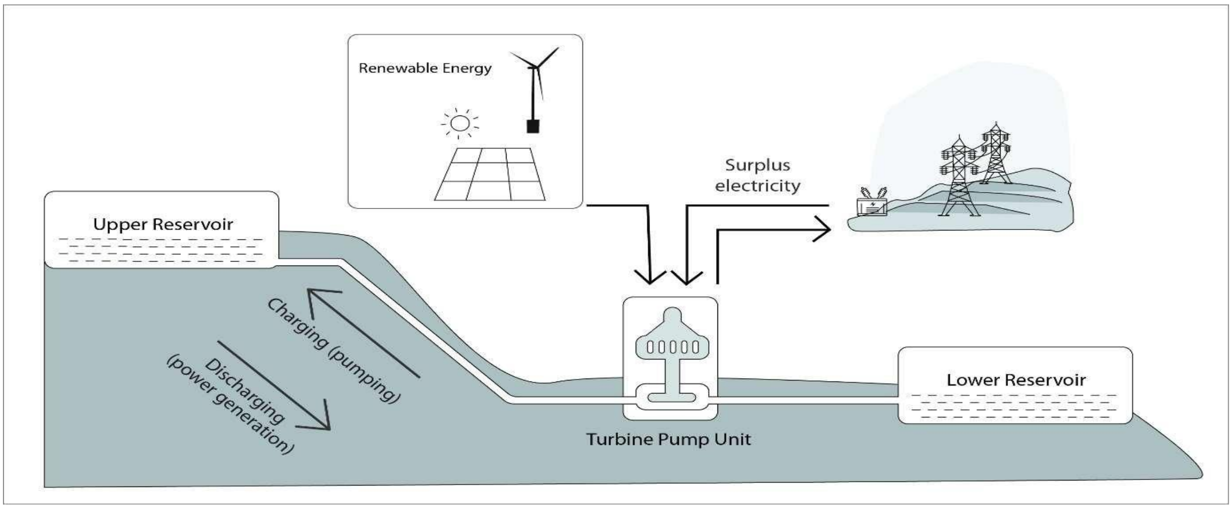


Figure1 Pumped Hydro Energy Storage System

The PHES system is an adaptation of conventional hydroelectric power plants with reversed functionality. Unlike conventional hydroelectric power plants, which use a single reservoir to store water and convert gravitational potential energy into electrical energy, PHESutilizes two vertically positioned reservoirs and a turbine/pumping station. Water from the upper reservoir is released through a generator turbine to generate electricity and is then storedin the lower reservoir. During periods of low demand, the water is pumped from the lower reservoir back to the upper reservoir using the turbine/pumping station. This stored water can be reused multiple times, increasing system efficiency [1]. The primary drawback of PHES is the need for specific site conditions, including suitable geographical height and water availability. Consequently, suitable sites are often foundin hilly or mountainous regions, which may also be areas of natural beauty, giving rise to potential social and ecological concerns. To address these issues, many proposed projects nowaim to avoid highly sensitive or scenic areas, with some considering "brownfield" locations such as disused mines.

Another variant of PHES involves seawater reservoirs. In this configuration, a hollow sphere submerged at significant depths serves as the lower reservoir, while the enclosing bodyof water acts as the upper reservoir [10]. Electricity is generated when water is allowed into the sphere through a reversible turbine integrated into the structure. This configuration offers advantages such as not requiring land area or large mechanical structures. Furthermore, in theevent of a reservoir collapse, the consequences would be limited to the loss of the reservoir itself. Additionally, evaporation from the upper reservoir has no impact on the energy conversion efficiency.

Compressed Air Energy Storage (CAES).

Compressed Air Energy Storage (CAES) is an energy storage technology that functions by compressing air, with the amount of stored energy dependent on variables including the storage container's volume, as well as the pressure and temperature conditions under which the air is stored. CAES was developed as an alternative to Pumped Hydro Energy Storage (PHES) to address challenges associated with the specific geological prerequisites of PHES and the resulting environmental concerns. CAES has gained prominence as a promising energy storage method due to its strong reliability, economic viability, and minimal environmental footprint.

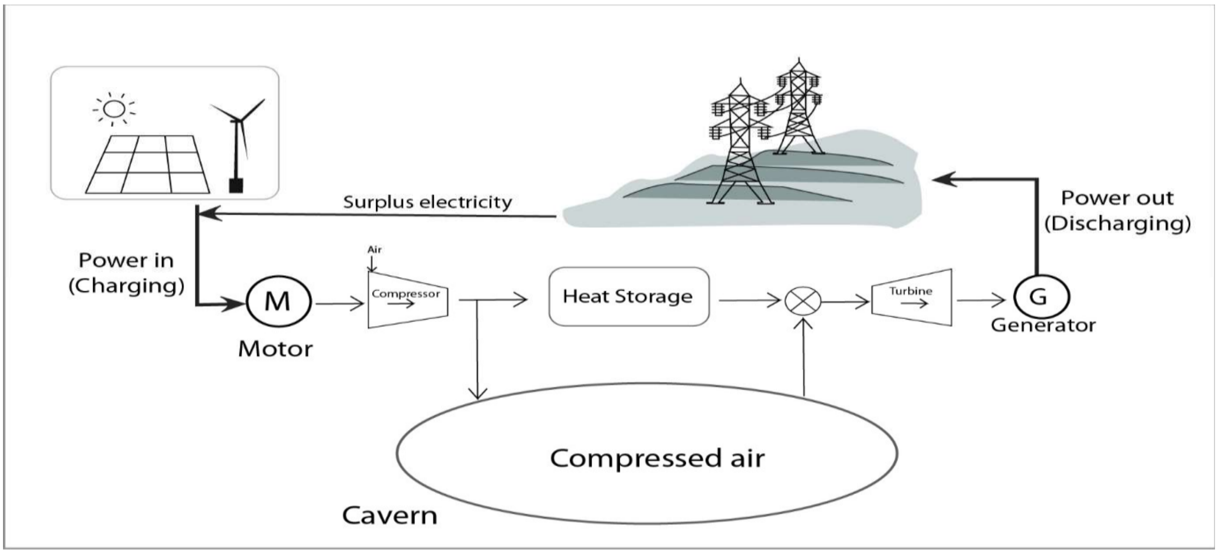


Figure 2 Compressed Air Energy Storage System

A typical CAES system encompasses five key components: a motor for propelling a compressor, a multi-stage compressor for air compression, a storage container or cavity (which can take the form of underground caverns or porous reservoirs) for holding the compressed air, a turbine assembly comprising high and low-pressure turbines, and a generator for converting mechanical energy back into electrical energy for the grid.

During periods of reduced electricity demand, excess power is utilized to operate the motor, generating mechanical energy to drive the compressor. The compressor elevates the pressure of ambient air, which is subsequently stored in the subterranean cavern. When electricity demand surges, the compressed air from the cavern propels the pressure turbines. These turbines transform the compressed air's energy into mechanical energy, subsequently driving the generator to generate electricity [6]. Recent advancements in CAES involve the utilization of CO_2 gas as a substitute for air, presenting noteworthy advantages.

Flywheel Energy Storage (FES).

The Flywheel Energy Storage (FES) system is a mechanical energy storage device that accumulates energy in the form of rotational energy by harnessing the kinetic energy of a large rotating cylinder.

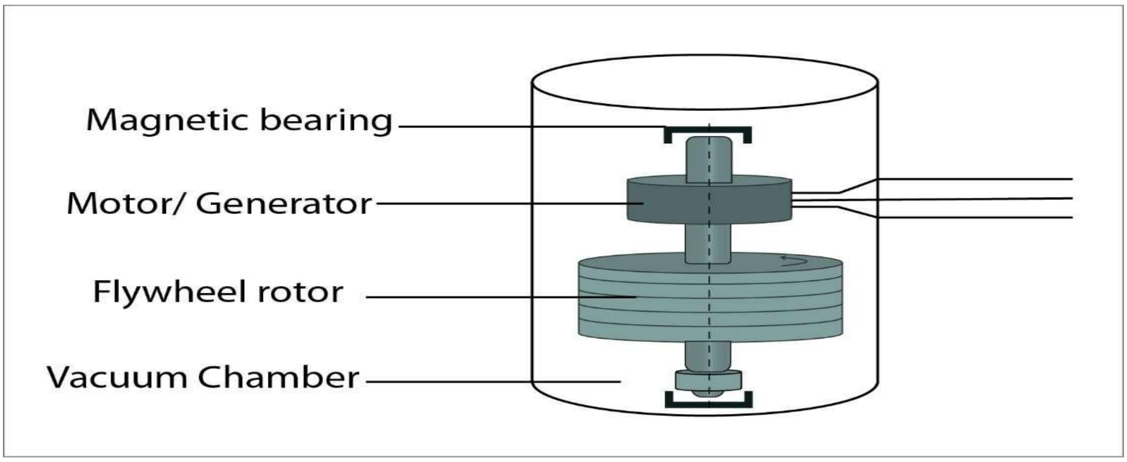


Figure 3 Flywheel Energy Storage

A contemporary flywheel system comprises five fundamental components: a flywheel, magnetic bearings, an electrical motor/generator, a power conditioning unit, and a vacuum chamber. During the charging phase, the integrated reversible electrical machine operates as a motor. It draws electrical power from the grid to spin the flywheel system at high speeds, thus storing kinetic energy. When the system enters the discharging phase and the rotor slows down, the reversible machine functions as a generator. It converts the stored kinetic energy within the flywheel back into electrical energy. In this way, the FES system employs electricity to accelerate or decelerate the flywheel, facilitating the transfer of stored kinetic energy to or from the flywheel through the integrated motor/generator [6].

Flywheel energy storage offers benefits such as high energy and power density, extended cycle life, rapid response, and efficient energy conversion (90%–95%). It provides quick discharge for immediate energy supply. However, drawbacks include high self-dischargerates, limited storage capacity, and relatively high capital costs [3,7,11].

2.2 Electrical Storage

Super Capacitors.

Super capacitors, also referred to as electric double-layer capacitors (EDLC) comprise two conductor electrodes, an electrolyte, and a separator. They store energy by establishing an electrostatic field via a continuous direct current voltage applied between the two electrodes, which are divided by a slender insulator or dielectric material. The electrodes, commonly constructed from activated carbon, possess an extensive surface area, leading to increased energy density. A porous membrane separates the electrodes, enabling charged ions to move unimpeded while preventing direct contact [6].

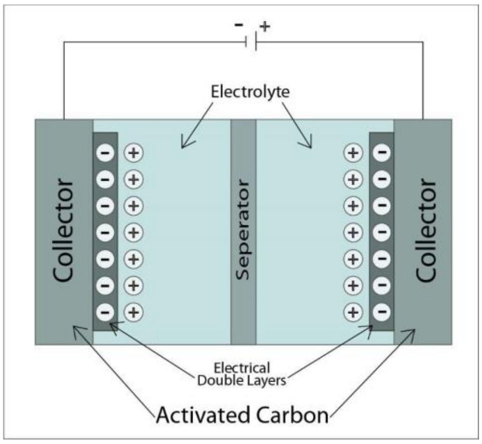


Figure 4 Super Capacitor

Super capacitors possess structural characteristics that fall between batteries and capacitors. Similar to batteries, they consist of two electrodes separated by a porous medium and store energy within an electrostatic field. However, super capacitors exhibit significantly higher capacitance values, often in the range of thousands of farads, and have the capability to charge and discharge rapidly due to their exceptionally low internal resistance [12]. They also offer advantages such as durability, reliability, maintenance-free operation, an extended lifespan, and the ability to operate effectively across a broad temperature range. The lifespan of super capacitors exceeds one million cycles without degradation, except for the chemicals used within capacitors, which degrade over time regardless of the cycle count. Moreover, supercapacitors demonstrate high efficiency, frequently exceeding 90%, and can discharge over durations ranging from seconds to hours.

Nevertheless, super capacitors are not well-suited for long-term energy storage due to their high self-discharge rate, relatively low energy density, and substantial initial investment requirements. However, they excel as uninterruptible power supplies (UPS) for addressing minor power disruptions. In the context of electric vehicles, super capacitors can serve as a buffer system for acceleration and regenerative braking, offering unique applications within this field [4].

Super magnetic energy storage (SMES).

Superconducting Magnetic Energy Storage (SMES) is an advanced energy storage technology that leverages the unique properties of superconductors to store and releaseelectricity efficiently. By using superconducting materials to create strong magnetic fields, SMES systems can store electrical energy as a magnetic field and later convert it back into electrical energy when needed.

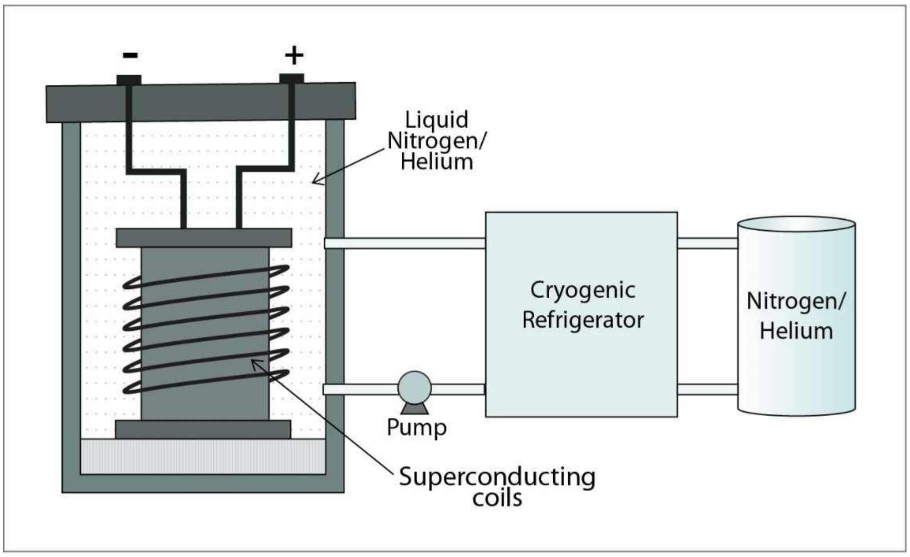


Figure 5 Super Conducting Magnetic Energy Storage

In the SMES system, direct current (DC) is generated within superconducting coils constructed using niobium-titanium (NbTi) filaments, which exhibit no resistance to the flow of electric current. The absence of resistive losses in superconducting coils ensures that the SMES system achieves an overall efficiency exceeding 95%.

When compared to other storage systems, the SMES system boasts a high-power density and an exceptionally short response time, typically in the range of a few milliseconds.Furthermore, it offers extended cycling time and a longer lifespan, and through the implementation of distributed SMES (DSMES), it enables independent control of reactive andreal power.

Nevertheless, the SMES system is not without its inherent drawbacks. Its energy density, both volumetric and gravimetric, is relatively low. Additionally, the introduction of mechanical stress can lead to material fatigue, and the overall cost is a significant consideration.Despite these limitations, the SMES system exhibits remarkable potential in applications suchas load levelling, reduction of intermittency, and peak shaving due to its exceptional efficiencyand minimal response time [1].

2.3 Chemical Storage.

Chemical storage systems harness the principles of endothermic and exothermic chemical reactions. Endothermic reactions require an input of energy to build high-energy chemical bonds, while exothermic reactions release energy, resulting in the formation of lower- energy products. By leveraging these reactions, energy storage systems can store electricity and heat within the bonds of chemical compounds, comprising atoms and molecules, which can be tapped into for future energy supply. Chemical energy storage (CES) systems encompass various technologies such as hydrogen storage, synthetic natural gas, and solar fuel storage.

While CES systems generally exhibit lower overall efficiency compared to pumped hydroelectric storage (PHS) and lithium-ion storage technologies, they offer greater cost efficiency and effectiveness compared to conventional batteries. These systems provide a viable means of storing energy on a large scale and for extended durations, enabling the reliablesupply of energy when needed.

2.3.1. Hydrogen energy storage system.

Hydrogen is widely recognized as an excellent energy carrier due to its cleanliness and carbon-free nature, making it a zero-emission chemical energy carrier. It can be produced through a process called electrolysis, using a hydrogen generation unit like an electrolyzer, which converts electrical energy into hydrogen.

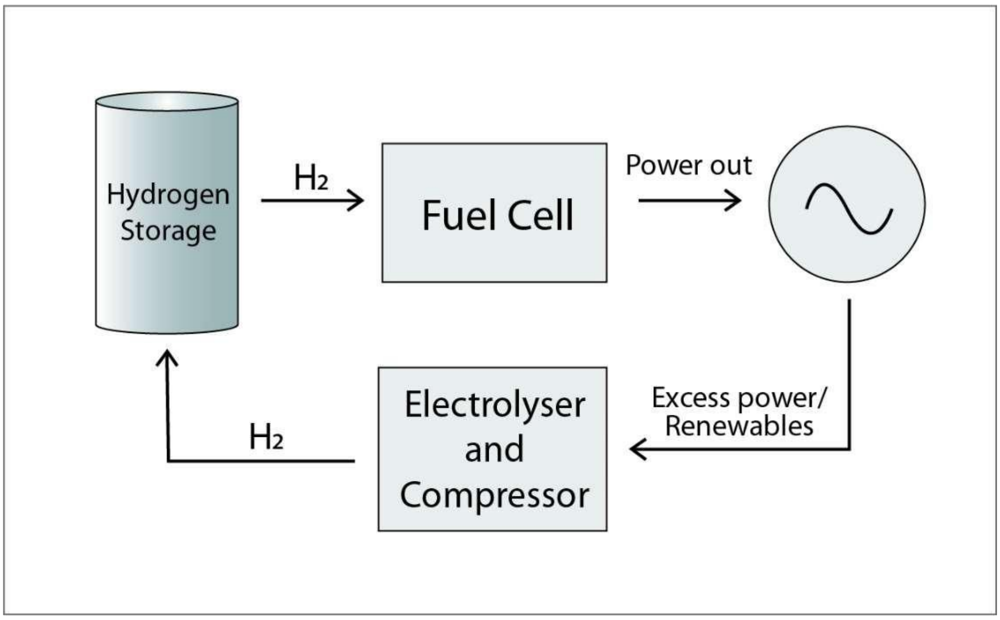


Figure 6 Hydrogen Energy Storage System

In a standard hydrogen energy system, there are three primary components: a hydrogengeneration unit, such as an electrolyzer, responsible for converting electrical energy into hydrogen; a hydrogen storage system; and a hydrogen energy conversion unit, such as a fuel cell, which transforms the stored chemical energy in the hydrogen back into electrical energy.

During the charging process, when there is surplus power available, water is electrolyzed to produce hydrogen, which is then stored in a storage tank. During peak hours orwhen power availability is limited, the stored hydrogen is used to generate electricity through fuel cells. The electrolyzer utilizes electrolysis to break down water into hydrogen and oxygen.The oxygen is released into the atmosphere, while the hydrogen is safely stored in a storage tank [6].

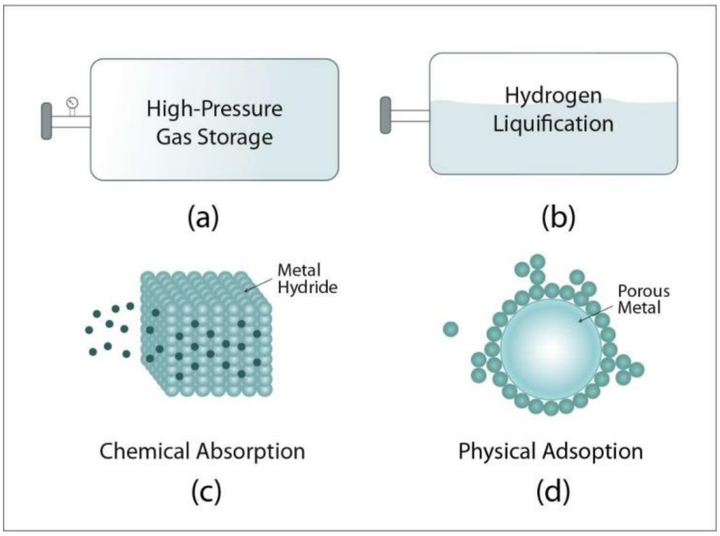


Figure 7 Various Hydrogen Storage Techniques

Hydrogen needs to be either compressed into pressurized vessels or liquefied for storage. Additionally, nanotubes or solid metal hydrides can serve as storage units for hydrogenwith high density [13]. Recent research has focused on improving storage density through advancements in systems like Mg-Li-Al and Mg-Na-Al, which are used for solid-state hydrogen storage [6].

2.3.1.1. <u>Fuel Cell</u>

A fuel cell is a device that directly converts the chemical energy of a chemical reactioninto electrical energy, generating hydrogen and water as by-products. Its primary function is torestore the energy used in the production of hydrogen through the electrolysis of water. Fuel cells combine the best characteristics of engines and batteries. Under load conditions, they operate similar to batteries, while also resembling engines as long as fuel is available [1].

A fuel cell consists of four key components: an anode, a cathode, an electrolyte, and an external circuit. At the anode, hydrogen is oxidized, splitting into protons (positively charged hydrogen ions) and electrons, which power the fuel cell. The positively charged hydrogen ions migrate through the electrolyte to the cathode. At the cathode, oxygen, hydrogen ions, and electrons combine, producing water and heat. During this process, the flow of electrons from the anode to the cathode through an external circuit leads to current flow and the production of electricity [6].

Fuel cells offer several advantages, including a long lifespan of approximately 15 years,high charging and discharging rates, and high energy density. Consequently, fuel cells are highly suitable for both small and large scale energy storage applications, such as peak shaving,load leveling, intermittency reduction, and demand-side management. They are also utilized indistributed power generation, where integration with the grid helps control voltage frequency and enhance power quality.

However, the widespread implementation of fuel cells faces challenges such as low round-trip efficiency, short life expectancy, and associated costs. Researchers are actively engaged in ongoing work to overcome these limitations and unlock the full potential of fuel cells [1].

2.4 Thermal Storage

Thermal storage systems play a vital role in capturing heat from diverse sources and storing it in insulated storage units for later utilization in industrial and residential applications.These systems serve as a bridge between the demand and supply of thermal energy, making them essential for the integration of renewable energy sources.

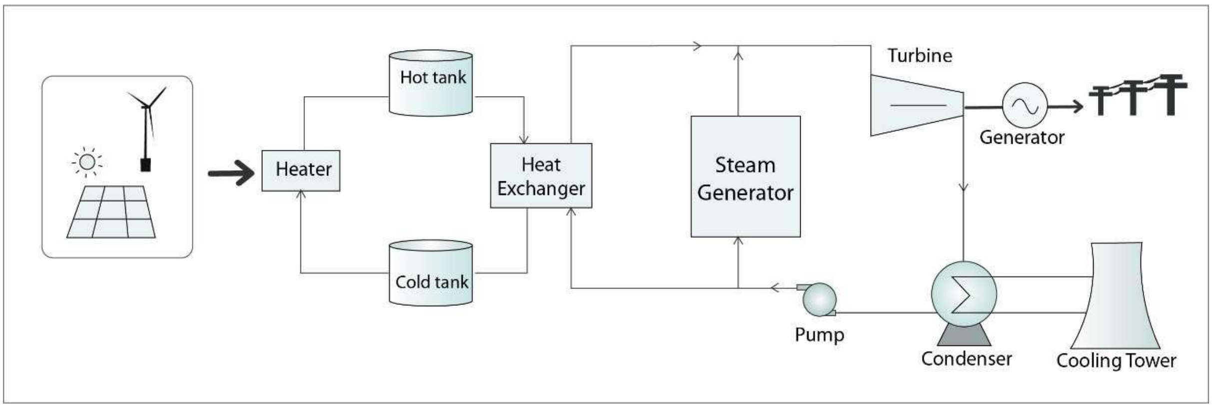


Figure 8 Thermal Energy Storage System

Thermal storage can take three primary forms: sensible heat storage, latent heat storage, and thermo-chemical adsorption and absorption storage. The storage medium employed can beeither a liquid or a solid substance. In the context of thermal storage, energy is stored by alteringthe temperature of the storage medium. The capacity of a thermal storage system is determinedby the specific heat capacity and mass of the chosen medium [4].

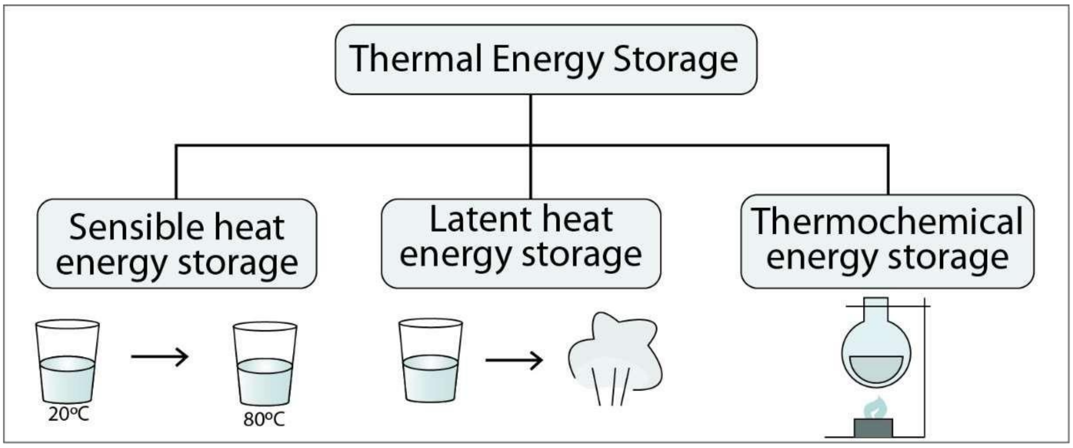


Figure 9 Types of Thermal Energy Storage [6]

For latent heat storage, phase change materials (PCMs) are utilized as the storage medium. These PCMs can undergo a phase transition, such as melting or solidification, duringwhich they absorb or release significant amounts of energy. Organic PCMs, such as paraffin, and inorganic PCMs, such as salt hydrates, are commonly used options for such storage systems. Latent heat refers to the energy exchange that occurs during a phase transition, such as the melting of ice [4].

Thermochemical energy storage (TCES) is a method of storing thermal energy by utilizing chemical reactions. The fundamental principle of TCES involves starting with a chemical compound composed of two or more components. This compound is then broken down through the addition of heat, resulting in the separation of its constituent components. These components are stored separately until a demand for thermal energy arises. During periods of high demand, the components are combined again to reform the chemical compound,releasing heat in the process. The heat released from the reaction represents the stored energy capacity.

Unlike Sensible Heat Storage (SHS) and Latent Heat Storage (LHS), which are often limited in their duration due to heat losses, TCES offers the advantage of bridging longer periods between energy demand and supply. This characteristic makes TCES particularly well-suited for large-scale electricity generation, where the need for reliable and continuous powersupply is crucial [7]. By harnessing the potential of chemical reactions to store and release thermal energy, TCES provides a viable solution for managing energy fluctuations over extended periods. It enables the efficient utilization of excess energy during low-demand periods and allows for its subsequent retrieval when demand increases. TCES has the potentialto contribute significantly to the development of sustainable and resilient energy systems, particularly in the context of large-scale electricity generation.

2.5 Electrochemical Storage

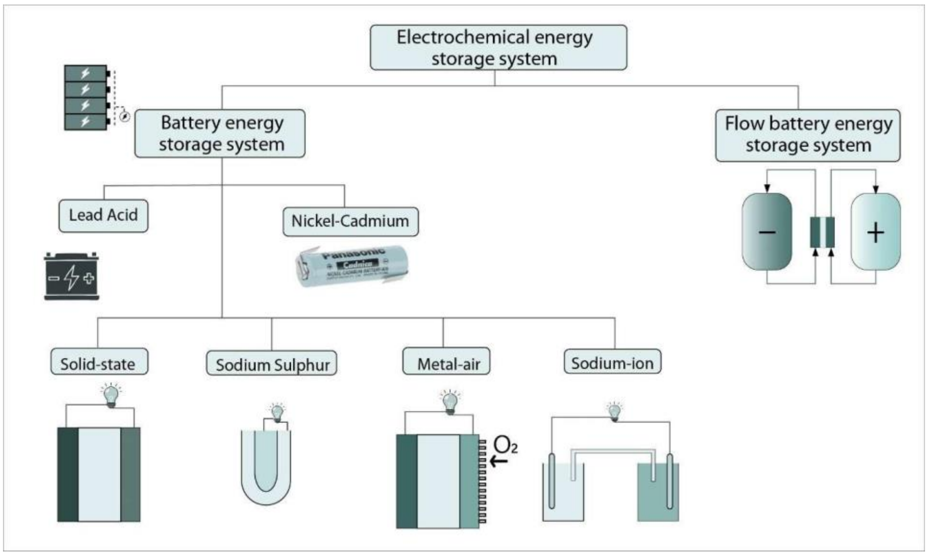
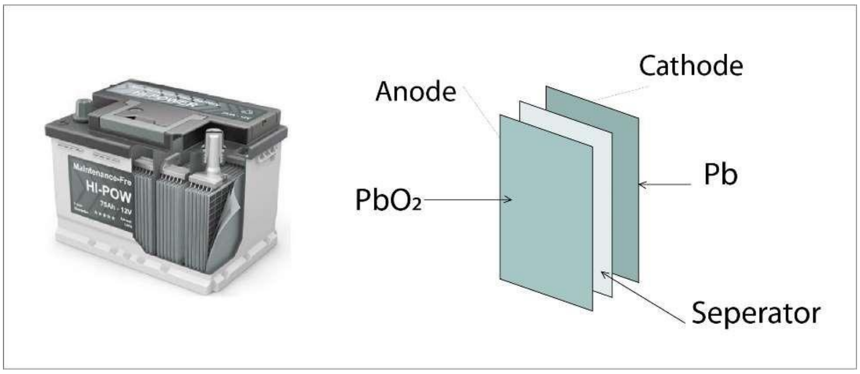


Figure 10 Various Electrochemical Storage Systems [6]

Lead Acid Battery.

The lead acid battery stands as a pioneering breakthrough as the first practical rechargeable battery, with its revolutionary ability to charge through reverse current application [1]. Representing a mature and globally accepted technology, lead acid batteries have solidified their reputation as a highly reliable energy storage solution.

Figure 11 Lead Acid Battery



Constructed typically with lead oxide (PbO2) cathodes and lead (Pb) anodes immersed in electrolyte, lead acid batteries comprise interconnected cells. Commonly utilizing sulfuric acid (36%) and water (64%) as the electrolyte, these batteries facilitate energy storage through intricate chemical processes. During discharge, the lead in the negative plate dissolves into the electrolyte, releasing electrons that flow through the circuit to the positive plate. This results in a reduction of dissolved sulfuric acid in the electrolyte, eventually transforming it primarily into water. The discharge process leads to the plates becoming chemically similar, weakening the acid and a drop in voltage [1,14].

While their energy density may be surpassed by other batteries, lead acid batteries excel in delivering substantial currents, making them highly suitable for applications like car starting.In the electric vehicle realm, their affordability and widespread availability grant them significance as storage devices. However, the drawback lies in their weight, resulting in highercosts per distance travelled due to fewer life cycles. Lead-acid batteries find widespread application in various industries, including telecommunications, power systems, radio and television systems, solar energy, uninterruptible power supplies (UPS), electric vehicles,automobiles, forklifts, and emergency lighting systems [1].

Environmental concerns surrounding lead-acid batteries stem from the emission of toxic lead, a heavy metal with bioaccumulation impacts and potential health risks. Nonetheless,their ability to be recycled multiple times stands as a testament to their success, positioning them among the most effectively recycled consumer products.

Nickel Cadmium.

Nickel Cadmium (NiCd) batteries have long been a reliable choice in the realm of rechargeable energy storage. Their enduring popularity arises from their robustness, ability to handle high discharge currents, and exceptional cycle life of around 1500 cycles. NiCd batteries consist of a nickel oxide hydroxide cathode and a cadmium anode, immersed in an alkaline electrolyte. These batteries offer consistent performance across a wide range of temperatures and are capable of delivering steady power output. However, the use of toxic cadmium and lower energy density compared to newer technologies has led to their gradual displacement by more environmentally friendly options like lithium-ion batteries. Despite this, NiCd batteries still find applications in industries requiring high discharge rates, reliability, and resilience. These batteries were widely used in applications such as two-way radios, emergency medical equipment, professional video cameras, and power tools [1,15].

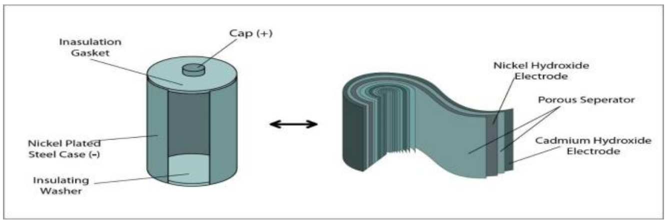


Figure 12 Nickel Cadmium Battery

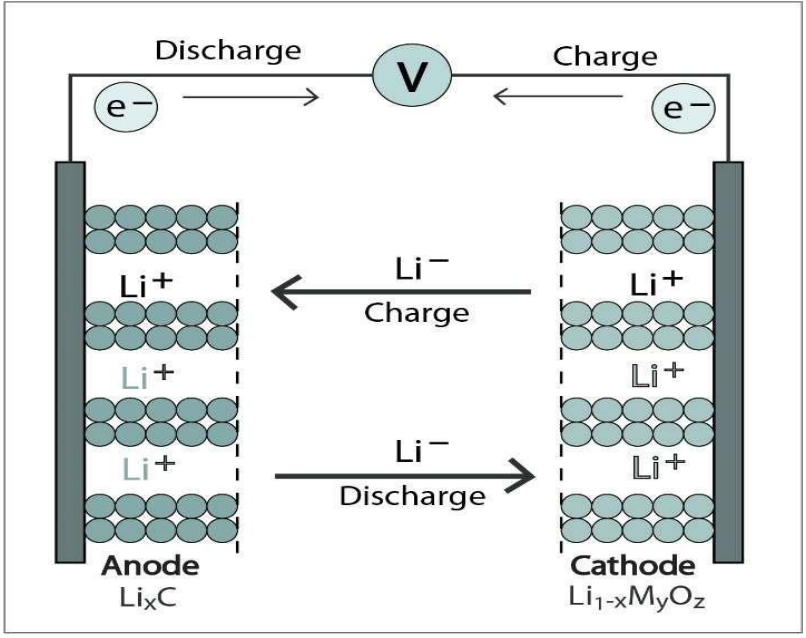
Nickel metal Halide.

Nickel Metal Hydride (NiMH) batteries have gained recognition as a versatile rechargeable energy storage solution. Their composition includes a hydrogen-absorbing alloy anode and a nickel-based cathode, paired with an alkaline electrolyte [1]. NiMH batteries offera higher energy density compared to NiCd batteries and have become popular alternatives dueto their reduced environmental impact and absence of toxic cadmium. With good cycle life and less susceptibility to memory effect, NiMH batteries find applications in various devices, including portable electronics and hybrid vehicles. However, the widespread adoption of lithium-ion batteries has gradually replaced NiMH batteries in many applications due to their superior energy density and performance.

Li-ion Battery.

The lithium-ion (Li-ion) battery is composed of a positive electrode (anode), a negative electrode (cathode), a separator, electrolyte, and two current collectors. The anode typically consists of lithiated metal oxide, such as LiCoO2, LiMO2, or LiNiO2, while the cathode is composed of graphitic carbon with a layered structure. The electrolyte is a solution of lithium salt, usually LiPF6, dissolved in organic carbonates. Current is generated when lithium ions migrate between the anode and cathode. During the charging cycle, lithium cations travel through the electrolyte to the carbon anode. They combine with external electrons and are deposited as lithium atoms within the carbon layers. This process is reversed during the discharge process.

Figure 13 Li-ion Battery



Li-ion batteries have emerged as the preferred choice for numerous applications due totheir high energy density, increased capacity, improved performance, lightweight design, and cost-effectiveness. Additionally, they exhibit a low self-discharge rate of approximately 1.5%per month. Repeatedly charging Li-ion batteries after partial discharge does not negatively impact their maximum capacity, thereby minimizing any memory effect. Li-ion batteries also offer higher open-circuit voltage compared to aqueous batteries such as lead-acid, nickel-metalhydride, and nickel-cadmium. They can typically endure thousands of charge-discharge cycles.Currently, Li-ion batteries find extensive use in electronics and transportation industries, particularly in power grid applications and plug-in hybrid electric vehicles, due to their superior charge density compared to other rechargeable batteries [1,6].

Safety is a prominent concern in Li-ion batteries due to potential thermal instability inmetal oxide electrodes at high temperatures, leading to explosions from overcharging or overheating. Monitoring devices and voltage regulation circuits are integrated to prevent risks. Li-ion technology's evolution emphasizes safety enhancements and novel materials for electrodes and electrolytes. Additionally, environmental and health implications from lithiummining calls for ongoing monitoring and exploration of alternative materials.

Lithium polymer (Li-Po).

Li-polymer (Li-Po) batteries, belonging to the family of Li-ion batteries, share many similarities with conventional Li-ion batteries. However, the differentiating factor lies in the type of electrolyte utilized. Li-Po batteries employ a dry solid polymer electrolyte. The dry polymer electrolyte simplifies the fabrication process of Li-Po batteries. However, it also results in high internal resistance, limiting their suitability for high-current applications. To address this issue, modern Li-Po batteries incorporate a gelled electrolyte in addition to the drypolymer electrolyte. This combination overcomes the poor conductivity challenges and enables Li-Po batteries to excel in high-current applications with exceptionally high discharge rates. Li-Po batteries are known for their slim and lightweight design [1].

Sodium Sulfur.

Sodium sulfur (NaS) batteries have established themselves as a prominent technology in the current energy storage market. Offering a remarkable energy density ranging from 150 to 240W and a robust power output of 150 to 230W/kg, NaS batteries stand out as a formidable choice for various applications. These batteries exhibit a lifespan of up to 2500 cycles, indicating long-term reliability.

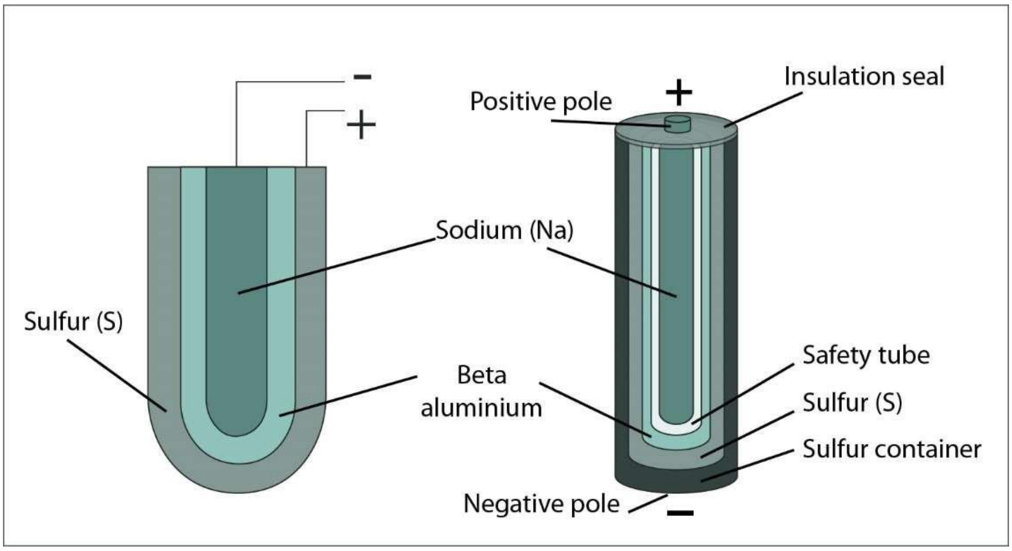


Figure 14 Sodium Sulfur Battery

The composition of NaS batteries includes cost-effective materials, contributing to their attractiveness for widespread use. The distinctive design involves molten sulfur as the positive electrode and molten sodium as the negative electrode. Acting as both the electrolyte and separator, a solid beta alumina ceramic material segregates the active components. This allows selective passage of sodium ions from the positive to the negative electrode, facilitating recombination with sulfur to form sodium polysulfides. During discharge, sodium releases electrons and transitions into Na+ ions, generating a voltage of 2.0V. These electrochemical reactions are reversible, enabling the sodium polysulfides to release Na+ ions through the electrolyte, which later recombine to form elemental sodium.

Operating within a temperature range of 300 to 360°C is ideal for NaS batteries, wherevariations in temperature occur during charging and discharging, leading to fluctuations in electromotive force due to the charge-discharge cycles. A compelling advantage of NaS batteries is their exceptional DC conversion efficiency, reaching 85%, positioning them as strong contenders for future distribution systems centered on DC power. This feature renders NaS batteries promising candidates for various applications, including load leveling, peak shaving, renewable energy integration, emergency power, and power reliability [1,9,34].

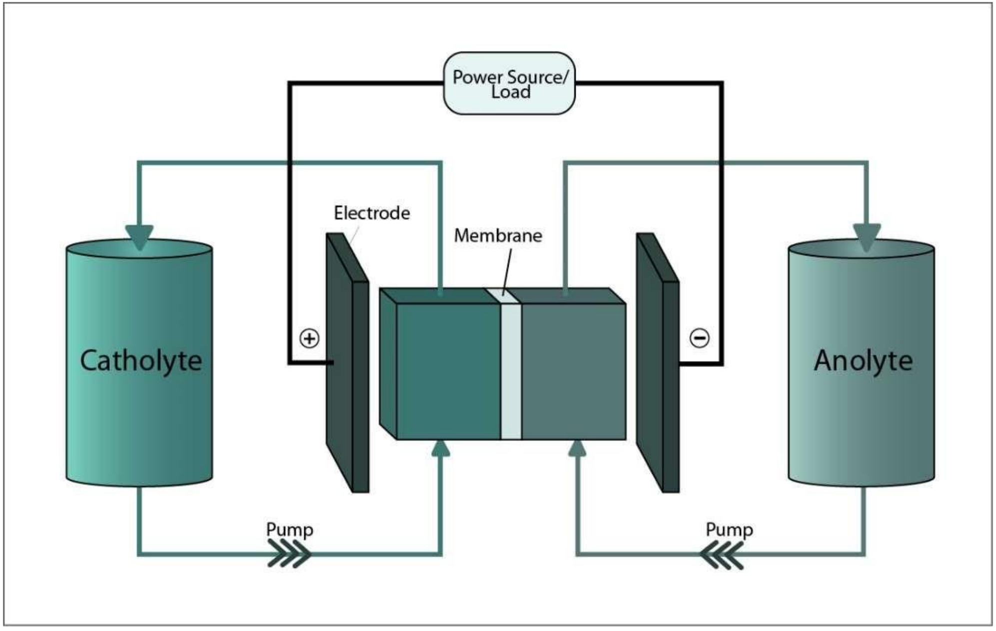
Sodium Metal Halide.

Sodium metal halide (Na-MX) batteries, also known as ZEBRA batteries, share similarities with Na-S batteries as they utilize inorganic molten salt as the electrolyte. ZEBRA batteries exhibit a high tolerance to overcharging and discharging, along with a high energy density and long cycling life. Additionally, they operate within a wide temperature range (523- 623 K) and have low self-discharge rates and excellent pulse power capabilities. These batteries are maintenance-free and possess high mechanical strength, making them well-suited for stationary power quality and heavy-duty transportation applications. They are predominantly utilized in utility-scale energy storage systems. In Na-MX batteries, liquid sodium serves as the negative electrode, while a solid metal halide acts as the positive electrode. The electrodes are separated by a ceramic beta alumina separator. The electrolytes are immersed in asecondary electrolyte called sodium chloro-aluminate [1].

Redox Flow battery:

A flow battery is an advanced aqueous electrolytic battery that combines a hybrid of batteries and traditional fuel cells. Flow batteries are different from traditional batteries in that they contain two tanks filled with liquid electrolyte, one for the cathode and one for the anode. These tanks hold chemicals in different oxidation states.

Figure 15 Redox Flow Battery



When the battery is discharged, the chemical energy stored in it is converted into electrical energy through a process called reduction-oxidation (redox). As the battery charges, this process is reversed. The large size of the tanks and pumps make flow batteries more suitable for stationary applications, such as in homes or on a larger scale in power grids, due to their flexibility in design. One advantage of flow batteries is that they are easily scalable. If more power is needed, additional stacks can be added. If more storage capacity is required, additional electrolytes and storage tanks can be added.

Vanadium Redox Flow Battery.

Vanadium Redox Flow Batteries (VRFBs) are a promising energy storage technology known for their unique design and characteristics. These batteries utilize the redox reactions ofvanadium ions in different oxidation states (V^{2+} and V^{3+}) to store and release energy. The VRFB consists of two electrolyte tanks containing vanadium-based electrolyte solutions with different oxidation states. During charging and discharging, electrolytes flow through separatechambers, while an ion-selective membrane prevents mixing and enables ion exchange.

VRFBs offer advantages like long cycle life, high efficiency, and the ability to maintaina constant capacity over many charge-discharge cycles. Their scalability and low environmental impact due to the use of vanadium salts further enhance their appeal. However,challenges such as lower energy density compared to some other technologies and relatively larger system footprint remain areas of improvement [1,6].

Polysulphide Bromide Battery.

Polysulfide Bromide batteries, a type of redox flow battery, present an innovative approach to energy storage. These batteries employ a combination of polysulfide and bromine-based electrolytes that undergo redox reactions during charging and discharging processes. Polysulfide Bromide batteries consist of two tanks containing the respective electrolytes, whichare circulated through an electrochemical cell during operation. This design allows for energystorage and release without degradation of the active materials, contributing to their long cyclelife and durability. Polysulfide Bromide batteries offer advantages such as high energy density,scalability, and the potential for cost-effective energy storage solutions. They are still in the experimental stage and face challenges like electrode stability and efficiency optimization [9].

3 Emerging and Future Energy Storage Technologies

3.1 Gravity Battery

Gravity batteries, also known as gravity energy storage systems, are a new type of energy storage technology that uses the force of gravity to store and release energy. Unlike traditional batteries that use chemical reactions to store and release energy, gravity batteries rely on the interaction between a heavy object, often a weight or a piston, and gravity to store and release energy. The basic principle behind a gravity battery is to use gravity to lift a heavyobject to a higher elevation, where it is held in place by a locking mechanism. When energy isneeded, the heavy object is released, and as it falls, it turns a turbine or generator to produce electricity. The process is then reversed to recharge the battery by lifting the heavy object backto its original position using electricity from the grid or by using renewable sources.

One of the main advantages of gravity batteries is their long life cycle. They can last for decades, making them a more cost-effective option for long-term energy storage. Another advantage of gravity batteries is their high energy density. Because the stored energy is in the form of a heavy object, a small amount of space can store a large amount of energy. This makesgravity batteries a good option for applications where space is at a premium, such as in urban areas or on offshore platforms. Gravity batteries also have a very high efficiency, as they can convert up to 90% of the stored energy into electricity. This makes them a more efficient optionthan traditional batteries, which typically have an efficiency of around 70%.

Despite these advantages, there are also some limitations to gravity batteries. One of the main limitations is the cost of building and maintaining the storage systems, as they requirea significant amount of infrastructure and equipment. Additionally, the location for theinstallation of gravity battery must have a suitable topography for the movement of heavy object, which can limit the deployment of this technology [16,17].

3.2 Compressed CO2

Carbon dioxide (CO2), a well-known contributor to global warming, has the potential to play a pivotal role in the development of an environmentally friendly battery system that can be widely adopted worldwide. While renewable energy sources are crucial in combating climate change, their intermittent availability necessitates a cost-effective and long-lasting storage solution. Utilizing CO2, despite its role in global warming, presents a unique opportunity.

Energy Dome, a research and development firm, is working on developing new and innovative ways to store and use compressed CO2. The Energy Dome technology operates on a closed-loop thermodynamic system, where surplus renewable electricity is used to charge thesystem. CO2 is drawn from a large dome-shaped gas holder and stored as a highly dense liquid at ambient temperature and pressure. During discharge, the stored heat is recovered and used to convert the liquid CO2 back to vapor, generating electricity through a turbine. The CO2 is then returned to the dome for the next charging cycle, completing the loop.

In comparison to other gas-based storage methods such as Compressed Air Energy Storage (CAES) and Liquid Air Energy Storage (LAES), the Energy Dome's CO2 battery offershigher energy density, increased efficiency, and lower operational costs. CAES systems requirelarge spaces and have lower energy density, limiting scalability. LAES systems can store more energy but suffer from lower efficiency due to cryogenic-cooling and warming processes. By storing CO2 at ambient temperature, the Energy Dome system minimizes operational costs andenergy penalties. With its simple design and two-step process of compression and evaporation, the Energy Dome achieves high round-trip efficiency of 75-80%. In conclusion, compressed CO2 storage presents a promising alternative to conventional compressed air storage, offering enhanced efficiency, cost-effectiveness, and sustainability. The advancements made by EnergyDome in this field are noteworthy and are expected to have a significant impact on the energy storage industry [18,19].

3.3 Nano diamond battery

Nano diamond batteries are a new type of energy storage technology that harnesses theunique properties of diamond to store and release energy. The technology is based on the fact that diamond is an exceptional conductor of both electricity and heat, and it has a very high thermal conductivity.

NDB (Nano Diamond Battery), is a company that is pioneering the development of a revolutionary energy storage technology known as the nano diamond battery. The company iscreating these batteries by converting carbon-14, a radioactive isotope found in natural diamond, into a stable form of carbon. They plan to use nuclear waste as the source of carbon-14, which means the availability of this isotope shouldn't be a problem. Using nuclear waste asa source of carbon-14 for nano diamond batteries can help reduce the cost of producing these batteries, as well as help address the issue of nuclear waste management. NDB produces electricity similar to that of a solar cell, but instead of sunlight, it uses radiation from radioactive decay. The main components of a NDB battery are: isotope, transducer, and storage unit. The isotope decays and releases radiation, which is then converted into power by the transducer. The excess energy is stored by the storage unit for future use during inactivity.

One of the main advantages of nano diamond batteries is their extremely long life cycle.The half-life of carbon-14 is 5,730 years, which means that these batteries can last for thousands of years without needing to be replaced. Another advantage of nano diamond batteries is their safety characteristics. Unlike traditional batteries that use chemicals and can be dangerous if they overheat or are punctured, nano diamond batteries are completely safe. The diamond lattice is a solid-state material, and it does not catch fire or explode. The carbon-14 isotope is sealed inside the diamond lattice and is not exposed to the environment. The levelof radiation emitted by the carbon-14 isotope is very low, much lower than the natural background radiation that we are exposed to on a daily basis. The long life cycle of nano diamond batteries makes them an ideal power source for space exploration missions or medicaldevices such as pacemakers, that are expected to last for decades or even centuries [20,21,36].

3.4 Aluminium-based batteries

Aluminium-based batteries are a promising new technology in the field of energy storage. These batteries offer a number of advantages over traditional lithium-ion batteries, including higher energy density, faster charging times, and lower cost. Aluminium has a high charge capacity, which means that these batteries can store more energy in a smaller space thantraditional lithium-ion batteries. This makes them an ideal choice for portable electronic devices and electric vehicles, where space is at a premium. These batteries can be charged much faster than traditional lithium-ion batteries, which means that they can be used more frequently without needing to be recharged. This makes them a great choice for applications such as electric vehicles or portable electronic devices. Aluminium is a more abundant and lessexpensive material than lithium, which makes it more cost-effective to produce aluminium- based batteries.

Despite these advantages, there are still some challenges to be overcome beforealuminium-based batteries can be widely adopted. One of the main challenges is finding a suitable electrolyte that can withstand the high voltage and high current needed for aluminium-based batteries. Researchers are currently working on developing new electrolytes that can meet these requirements. Another challenge is the safety of aluminium-based batteries. Aluminium can react with water to produce hydrogen gas, which can be dangerous if not properly ventilated. Researchers are working on developing safe and reliable designs for aluminium-based batteries to address this issue.

There are several types of aluminium-based batteries that are currently available or under development. These include: Aluminium-Graphite batteries, Aluminium-Carbon Nanotube batteries, Aluminium-Polysulfide batteries, Aluminium-Ion batteries and Aluminium-Air batteries [22,23,24].

3.5 Metal-Air Batteries

Metal-air batteries are a type of battery that utilizes a metal anode and an air cathode to generate electricity through the reaction of the metal anode with oxygen from the air. This process can be reversed for recharging the battery. The choice of electrolyte depends on the specific battery design and can be either an alkaline aqueous solution, a neutral aqueous solution of a salt, or a non-aqueous solution of a base metal salt. The positive electrode of a metal-air battery contains oxygen from the surrounding air, taking advantage of its strong oxidizing properties, lightweight nature, and abundant availability. This allows for a larger capacity as most of the battery interior can be used for the negative electrode material. For the negative electrode material to be suitable in a metal-air battery, it needs to fulfill certain criteria.It should have a strong reducing power, a low molecular weight, high density, and a large valence change to provide a high battery voltage and capacity. Promising candidates for the negative electrode include lithium, aluminium, magnesium, zinc, and iron.

Zinc-air batteries are seen as a promising technology for replacing lead-acid batteries in various applications, such as electric vehicles, due to their higher energy density and longerlifespan. They also have potential for use in grid-scale energy storage. Another example is lithium-air batteries, which have the potential to store even more energy than zinc-air batteries.

Despite their advantages, metal-air batteries have limitations that need to be overcomebefore they can be widely adopted. The corrosion of the metal anode limits the battery's lifespan, and they often have poor cycle life and low recharging efficiency. Lithium-air batteries face safety risks due to lithium's reactivity to air and humidity. These challenges needto be addressed to enable the widespread use of metal-air batteries as a replacement for existingtechnologies [25,26,35].

3.6 Organic polymer batteries

Organic polymer batteries are a type of battery technology that uses organic polymers as the electrodes and electrolytes. They have been under development for several decades and have several potential advantages over traditional lithium-ion batteries, including the ability toproduce large-scale and low-cost batteries, high flexibility, and safety. One of the main advantages of organic polymer batteries is that they can be made using low-cost and readily available materials. This is because the active materials in organic polymer batteries, such as polymers and small molecules, can be synthesized in large quantities using relatively simple and inexpensive chemical synthesis methods.

Additionally, organic polymer batteries are highly flexible, which means that they can be bent and folded without affecting their performance. This allows for the creation of new form factors for battery-powered devices andsystems. Organic polymer batteries also have high safety, as they do not typically pose a risk of thermal runaway.

However, there are still some challenges that need to be addressed before organic polymer batteries can be widely adopted. One of the main challenges is their relatively low energy density compared to lithium-ion batteries. This means that they need larger capacity tostore the same amount of energy. Additionally, their cycle life is also lower than lithium-ion batteries and their charging process is not as efficient [27].

3.7 Zinc–bromine non-flow batteries

Gelion, a research and development firm, has developed a unique type of zinc-brominebattery called the Endure, which is different from traditional redox-flow batteries (RFBs). Instead of using the typical RFB design of pumps and tanks, the Endure uses a similar plate format and casing to a lead-acid battery. It replaces lead and sulfuric acid with a bromide- positive plate and a zinc-negative plate, with a layer of gel acting as the electrode in the middle. Using gel-based electrolytes, the Endure eliminates pumps and tanks for a compact design. This plate configuration also eradicates the need for specialized maintenance, auxiliarypower sources, and backup systems. The chemical process inside, however, remains constant. When the battery is charged, zinc ions migrate to the negative electrode, accept electrons, andthen reduce to zinc.

Table 1 Comparison Of Storage Technologies [1,4,6,11,12,30]

Technology	Energy Density (Wh/L)	Power Density (W/L)	Specific Energy (Wh/Kg)	Specific Power (W/Kg)	Energy Capital Cost ($/KWh)	Response Time	Discharge Time	Self-Discharge (%) per day	Round Trip Efficiency (%)	Life Cycles	Environmental Impact
Lead Acid	25-90	10-700	30-50	75-300	200-400	150ms-sec	s-10h	0.1–0.3%	70–80	2000	Medium: Toxic remains
Li-ion	200-500	1300-10,000	30-300	150-350	600-2500	150ms-sec	15 min-8 h	0.1–0.3%	85-95	4500	Very Low: Toxic residues
Ni-Cd	60-150	75-700	10-80	50-300	800-1500	150ms-sec	s-8h	0.2–0.6%	60–80	3000	Very Low: Toxic residues
Sodium sulfur	150-345	50-180	150-250	150-260	300-500	150ms-sec	s-7h	~20%	75-85	2500	Very Low: Toxic residues
Vanadium Redox Flow (VRF)	10-70	30-60	10-75	30-60	150-1000	1s -10s	sec-10h	1-1.5	65-75	12,000+	Low: Toxic remains
Pumped Hydro Storage (PHES)	0.5-1.5	0.1-0.2	0.5-1.5	0.1-0.2	5-100	1 min-10 min	1 - 24h+	0.005-0.03	70–85	>100,000	High: Destruction oftrees and green land for reservoirs
Flywheel	20-80	5000	5-130	400-1600	1000-5000	<4 ms	ms-15 min	100%	90-95	> 100,000	Very Low
Compressed Air Energy Storage (CAES)	3-6	0.1-0.2	30-60	1-2	2-50	1 min-15 min	1 - 24h+	1-2	40-60	>13,000	Medium: Emissions from combustion of natural gas
Super-capacitors	10-30	100,000+	2.5-15	500-5000	300-2000	<5 ms	1ms-1h	20–40%	85-97	>100,000	Medium
Superconducting Magnetic Energy Storage (SMES)	0.2-2.5	1000-4000	0.5-10	500-2000	1000-10,000	<5 ms	1 ms-1h	10–15%	95-98	>100,000	Low: Strong magnetic fields

- Flow batteries like the Endure offer distinct advantages, particularly regarding depth ofdischarge and safety. They can be fully discharged without harm, whereas some lithium-ion batteries suffer degradation below 20%. Flow batteries avoid lithium-ion safety concerns by using non-flammable elements and water-based electrolytes, with bromine acting as a natural fire retardant. Vanadium flow batteries (VFBs) share low fire risk and unique benefits, but facecost and toxicity challenges. Zinc-bromine batteries offer affordability and eco-friendliness, though with lower energy density. They compete well in round-trip efficiency (85-90%) and boast a wide temperature range, eliminating air conditioning needs. The Endure battery's tank-free design, long lifespan (5,000 cycles), and recyclability further enhance its appeal as an energy storage solution.

- However, zinc-bromine batteries could potentially face the challenge of zinc dendrite formation, which can damage the battery. Gelion has addressed this issue by using a porous membrane that blocks the growth of dendrites. Zinc-bromine batteries are best suited for providing electricity to homes, solar or wind farms, or remote areas, but may not be practical for mobile or portable use due to their bulkiness [5,28,29,34].

- **Energy density**: The energy stored per unit volume of the storage material, measured in kWh/L.
- **Power density:** The power output per unit volume of the storage material, measured in kW/L.
- **Specific energy:** The energy stored per unit mass of the storage material, measured in kWh/kg.
- **Specific power**: The power output per unit mass of the storage material, measured in kW/kg.
- Energy capital cost: The capital investment required to produce a unit of energy, measured in $/kWh. Higher energy capacity typically results in lower cost per unit energy.
- **Response time:** The time it takes for an energy storage system (ESS) to begindischarging energy to a load after receiving a command or a signal.
- **Discharge time (at rated power):** The time required for an energy storage system to fully discharge its stored energy at its rated power output.
- **Daily self-discharge:** The amount of energy lost by a storage system due to self- discharge during non-use periods, typically expressed as a fraction of the total storage capacity.
- **Round-trip efficiency:** The ratio of energy put into an energy storage system during charging to the energy retrieved from it during discharging, expressed as a percentage. It represents the efficiency of the storage system in storing and retrieving energy.
- **Life cycles:** The number of complete charging and discharging cycles that an energy storage system can perform throughout its lifetime. It indicates the durability and longevity ofthe storage system.
- **Environmental Impact:** It refers to the effects that the storage system has on the environment, which can include emissions, waste, land use, and other factors. These impacts can include air and water pollution, deforestation, and habitat destruction, as well as the releaseof greenhouse gases and other pollutants into the air.

4 Selection Methodology

With the increasing demand for energy storage solutions and the emergence of new battery technologies, decision-makers face the challenge of evaluating and selecting the most suitable option among a range of alternatives. Multi-criteria decision making (MCDM) can be employed as a systematic approach to address the complexity of battery selection. By considering multiple parameters such as energy density, power density, cost, environmental impact, lifespan, safety, and availability, a comprehensive evaluation of battery alternatives can be conducted. The first step in the MCDM process involves clearly defining the problem and identifying the specific parameters relevant to the application. Each parameter or criterion is assigned a weight (w) to reflect its relative importance, which is determined based on the preferences and priorities of the decision-maker. Subsequently, battery alternatives are evaluated against these parameters using a weighted scoring system to obtain a performance score, which is then used to rank the battery technologies [31,32].

The weighted product model (WPM)

The weighted product model (WPM) is a decision-making method that will be utilizedin this research for battery selection. The WPM is similar to the weighted sum model (WSM) but differs in its calculation approach, as it involves multiplication rather than addition. One notable advantage of the WPM is its dimensionless analysis, which eliminates the reliance on units of measurement. This feature allows the WPM to be applied to decision-making problemswith varying dimensions. Additionally, the method allows for the use of relative values instead of actual values, enhancing flexibility in the evaluation process.

Let, a_i {for i = 1, 2, 3, ..., m} be a (finite) set of storage technology alternatives,c_j {for j = 1, 2, 3, ..., n} be a (finite) set of parameters or criteria

In order to evaluate the battery technologies, the parameters can be categorized as either non-beneficial or beneficial. To ensure fair comparison, the quantified values of non-beneficialparameters are normalized using the ratio of the minimum value to the actual value
{Min(a_i)/a_i}, while the beneficial parameters are normalized using the ratio of the actual valueto the maximum value {a_i/Max(a_i)} for each parameter (c_j). Let's call this value X_{ij} for both thecases. This normalization process yields a set of normalized performance values. Uponanalysing the parameters, it is observed that all parameters fall under the category of beneficial, indicating that higher parameter values correspond to better battery technology performance [31,33].

Next, following the weighted product model (WPM), weights are assigned to each parameter based on their relative importance. These weights reflect the significance of each parameter in achieving the desired performance. The values of all parameters are then multiplied together, raised to the power of their respective weights, to obtain the performancevalue of each battery technology.

Weights determination (*wj*)

The determination of weights in the weighted product model is based on the specific requirements and priorities of the given application. These weights reflect the significance of each parameter in achieving the desired performance. The sum of all weights must be 1.

Let’s say for a specific application A (akin to Electric Vehicles), the allocation of weightage percentages for the different parameters are:

1. Energy Density: 0.09
2. Power Density: 0.09
3. Specific Energy: 0.09
4. Specific Power: 0.09
5. Energy Cost: 0.13
6. Response Time: 0.04
7. Discharge Time: 0.04
8. Self-Discharge % /day: 0.03
9. Round Trip Efficiency: 0.13
10. Life Cycle: 0.15
11. Environmental Factors: 0.12

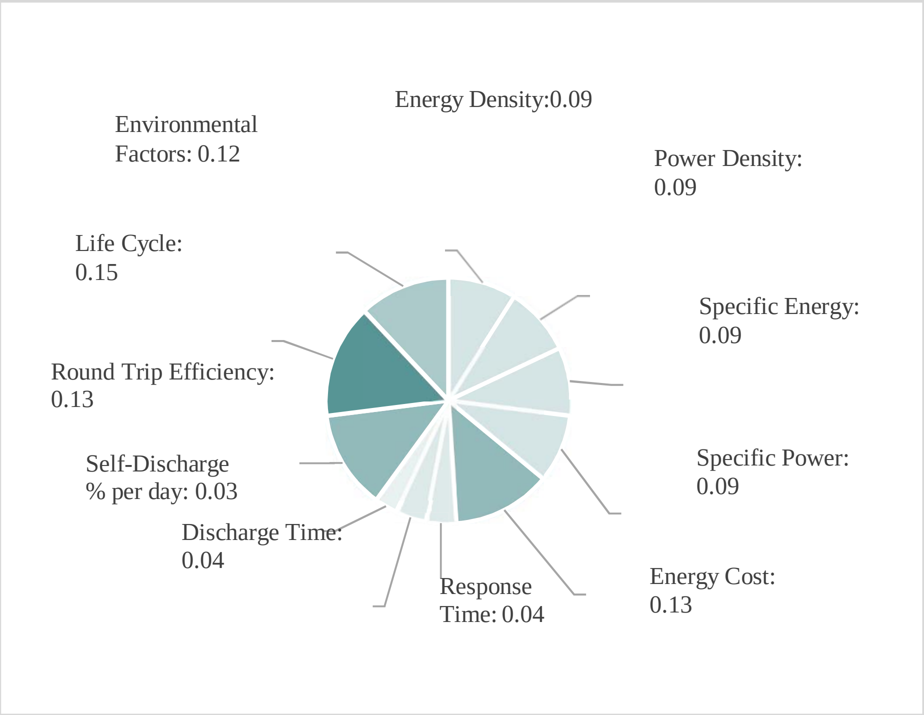


Figure 16 Case A- akin to electric vehicles

Similarly, for another application **B** (akin to Frequency Regulation):

1. Energy Density: 0.08
2. Power Density: 0.08
3. Specific Energy: 0.07
4. Specific Power: 0.07
5. Energy Cost: 0.12
6. Response Time: 0.15
7. Discharge Time: 0.05
8. Self-Discharge % /day: 0.04
9. Round Trip Efficiency: 0.15
10. Life Cycle: 0.14
11. Environmental Factors: 0.05

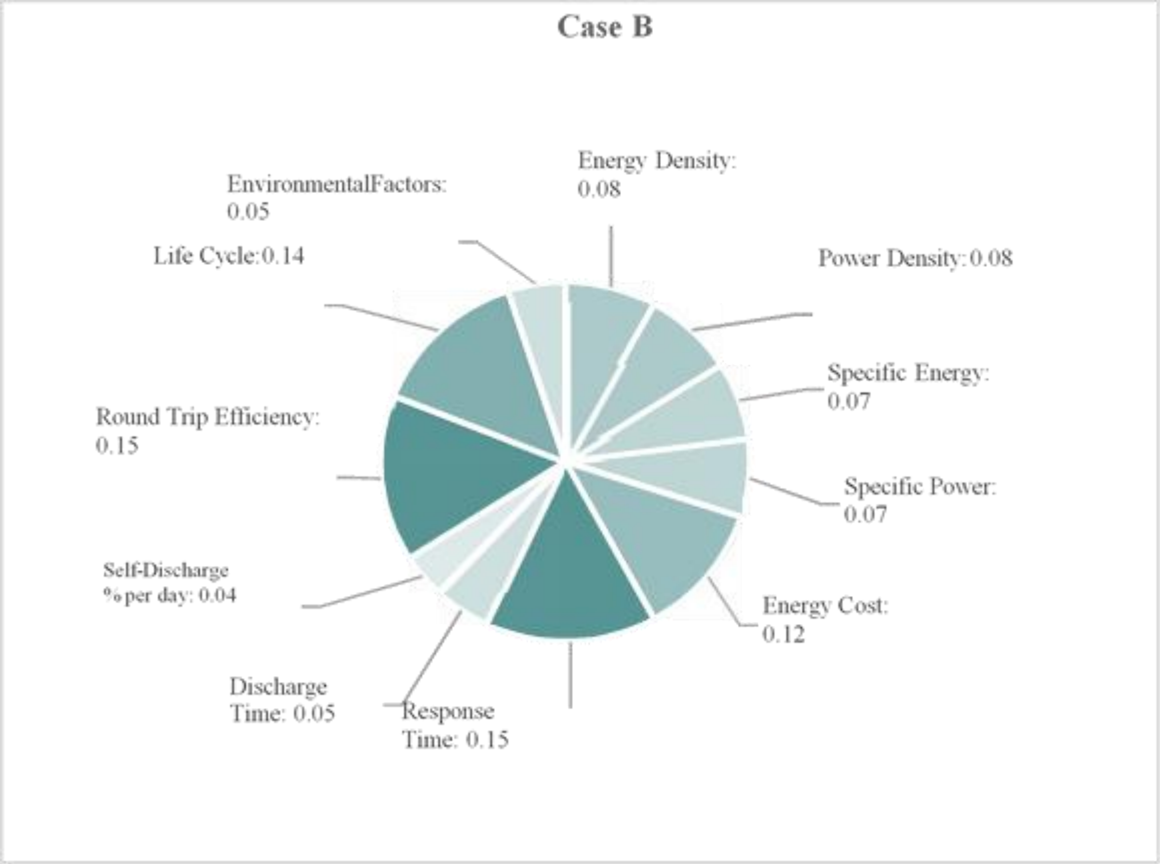


Figure 17 Akin to Frequency Regulation

Table 2. Simplified Performance Values

Technology	**Energy Density (Wh/L)**	**Power Density (W/L)**	**Specific Energy (Wh/Kg)**	**Specific Power (W/Kg)**	**Energy Capital Cost ($/KWh)**	**Response Time (ms)**	**Discharge Time**	**Self-Discharge(%) per day**	**Round Trip Efficiency (%)**	**Life Cycles**	**Environmental Impact**
Lead Acid	90	700	50	300	200	150ms	10h	0.1	80	2000	3
Li-ion	500	10000	300	350	600	150ms	8 h	0.1	95	4500	1
Ni-Cd	150	700	80	300	800	150ms	8h	0.2	80	3000	1

Sodium sulfur	345	180	250	260	300	150ms	7h	20	85	2500	1
VRF	70	60	75	60	150	1sec	10h	1	75	12000	2
PHES	1.5	0.2	1.5	0.2	5	1 min	24h	0.005	85	100000	4
Flywheel	80	5000	130	1600	1000	4 ms	15 min	100	95	100000	1
CAES	6	0.2	60	2	2	1 min	24h	1	60	13000	3
Super-capacitors	30	100000	15	5000	300	5 ms	1h	20	97	100000	3
SMES	2.5	4000	10	2000	1000	5 ms	1h	10	98	100000	2

- For our calculations, we simplify values by considering the best-case scenario, where we take the maximum value forbeneficial parameters and the minimum value for non-beneficial parameters.

Table 3. Normalized Performance Values (Xij)

Technology	**Energy Density**	**Power Density**	**Specific Energy**	**Specific Power**	**Energy Capital Cost**	**Response Time**	**Discharge Time**	**Self-Discharge**	**Round Trip Efficiency**	**Life Cycles**	**Environmental Impact**
Lead Acid	0.18	0.007	0.16667	0.06	0.01	0.02667	0.41667	0.05	0.816327	0.02	0.75
Li-ion	1	0.1	1	0.07	0.00333	0.02667	0.33333	0.05	0.969388	0.045	0.25
Ni-Cd	0.3	0.007	0.26667	0.06	0.0025	0.02667	0.33333	0.025	0.816327	0.03	0.25
Sodium sulfur	0.69	0.0018	0.83333	0.052	0.00667	0.02667	0.29167	0.00025	0.867347	0.025	0.25
VRF	0.14	0.0006	0.25	0.012	0.01333	0.004	0.41667	0.005	0.765306	0.01	0.5
PHES	0.003	0.000002	0.005	0.00004	0.4	6.6667	1	1	0.867347	1	1
Flywheel	0.16	0.05	0.43333	0.32	0.002	1	0.0104167	0.00005	0.969388	1	0.25
CAES	0.012	0.000002	0.2	0.0004	1	6.6667	1	0.005	0.612245	0.13	0.75
Super-capacitors	0.06	1	0.05	1	0.00667	0.8	0.0416667	0.00025	0.989796	1	0.75
SMES	0.005	0.04	0.03333	0.4	0.002	0.8	0.0416667	0.0005	1	1	0.5

SAD

Conclusion

In this study, we conducted a comprehensive review of advanced energy storage technologies and batteries, exploring their characteristics, advantages, and limitations. We also discussed emerging technologies that are currently in the research phase, highlighting their potential to shape the future of energy storage.

To facilitate the selection process, we developed a comparison table that considered more than 10 different factors crucial for energy storage technology evaluation. The comparison table served as a valuable tool for assessing and comparing various battery technologies. It's worth noting that while our comparison table provides general values, real- world decision-makers should exercise caution and select values with meticulous consideration, ensuring they align with the unique context and goals of their specific application. Decision-makers should be aware that certain energy storage technologies may notbe suitable for specific applications, such as PHES or CAES being impractical for mobile phone batteries due to size and infrastructure constraints.

Furthermore, we employed the weighted product model of multi criteria decision making (MCDM) to determine the most suitable energy storage technology for two distinct applications. By assigning different weights to the evaluation factors based on the objectives of each application, we successfully identified Li-ion batteries as the optimal choice for applications like EVs and super capacitors as the preferred technology for applications like frequency regulation. The widespread use of Li-ion in the automotive industry further supportstheir effectiveness in this application. In contrast, super capacitors showcased their superiorityby offering rapid response times, and long operational lifespans. These attributes make them particularly suitable for applications where frequent charge and discharge cycles are essential to stabilize grid frequency.

It's important to note that selecting the most suitable energy storage technology for a specific application relies heavily on the unique objectives, constraints, and operational contextof the system. The assigned weights for evaluation factors can be adjusted to accommodate varying priorities across different applications, and ongoing research and technological advancements may introduce additional factors for consideration in the decision-making process.

In conclusion, our research provides valuable insights into the selection of advanced energy storage technologies and batteries for different applications. The comparison table andthe weighted product model serve as effective tools to assist decision-makers in choosing the most appropriate technology based on their specific requirements. It is crucial to recognize thatenergy storage technologies are not one-size-fits-all; they vary significantly in size, infrastructure needs, and application suitability. Decision-makers must carefully consider thesevariant-specific values to make informed choices that align with their unique contexts and goals.

As energy storage technologies continue to advance, it is essential to remain attentive to ongoing research and development efforts that may introduce even more efficient and tailored solutions for various applications. Ultimately, the continued exploration and utilization of advanced storage technologies, along with the recognition of variant-specific values, will contribute to the widespread adoption of sustainable and efficient energy systems.

In future research, we aim to consider a wider range of factors, including variant- specific values, explore the latest technological advancements, and seek synergies among various storage technologies. These efforts will foster ongoing improvements in energy storage systems, enabling more efficient and versatile use across diverse applications.

References

[1] Hossain E, Faruque HMR, Sunny MdSH, Mohammad N, Nawar N. A Comprehensive Review on Energy Storage Systems: Types, Comparison, Current Scenario, Applications,Barriers, and Potential Solutions, Policies, and Future Prospects. *Energies*. 2020;13(14):3651. doi:10.3390/en13143651

[2] Ling C. A review of the recent progress in battery informatics. *Npj Computational Materials*. 2022;8(1). doi:10.1038/s41524-022-00713-x

[3] Shaqsi ASA, Sopian K, Al-Hinai A. Review of energy storage services, applications, limitations, and benefits. *Energy Reports*. 2020;6:288-306. doi:10.1016/j.egyr.2020.07.028

[4] Chakraborty MR, Dawn S, Saha PK, Basu JK, Ustun TS. A Comparative Review on Energy Storage Systems and Their Application in Deregulated Systems. *Batteries*. 2022;8(9):124. doi:10.3390/batteries8090124

[5] May, G., Davidson, A. J., & Monahov, B. (2018). Lead batteries for utility energy storage: A review. *Journal of Energy Storage*, *15*, 145–157. https://doi.org/10.1016/j.est.2017.11.008

[6] Mitali J, Dhinakaran S, Mohamad AA. Energy storage systems: a review. *KeAi Publishing*. 2022;1(3):166-216. doi:10.1016/j.enss.2022.07.002

[7] Johanna Gustavsson. Energy Storage Technology Comparison - A knowledge guide to simplify selection of energy storage technology. https://www.diva-portal.org/smash/get/diva2:953046/FULLTEXT01.pdf

[8] Challa V. Selecting the Right Battery for Your Application: Important Battery Metrics. https://www.ansys.com/en-in/blog/important-battery-metrics

[9] Fast Response Energy Storage Devices Technology Descriptions and Overview. *scottmadden.com*. https://www.scottmadden.com/content/uploads/userFiles/misc/80279278a617721d1711623bff4f6616.pdf

[10] Vilanova, M. R. N., Flores, A. T., & Balestieri, J. a. P. (2020). Pumped hydro storage plants: a review. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *42*(8). https://doi.org/10.1007/s40430-020-02505-0

[11] Luo X, Wang J, Dooner MS, Clarke J. Overview of current development in electrical energy storage technologies and the application potential in power system operation.

[12] Krishan, O., & Suhag, S. (2018). An updated review of energy storage systems: Classification and applications in distributed generation power systems incorporating renewable energy resources. *International Journal of Energy Research*, *43*(12), 6171– 6210. https://doi.org/10.1002/er.4285

[13] SY, Lee JH, Kim YH, Kim JM, Lee KJ, Park SJ. Recent Progress Using Solid-StateMaterials for Hydrogen Storage: A Short Review. *Processes*. 2022;10(2):304. doi:10.3390/pr10020304

[14] Kp, Lakshmi & .B, Pruthvija. (2020). Review on Battery Technology and its Challenges.

[15] *International Journal of Scientific and Engineering Research*. 11. 1706

[16] Lipu MSH, Mamun AA, Ansari S, et al. Battery Management, Key Technologies, Methods, Issues, and Future Trends of Electric Vehicles: A Pathway toward Achieving Sustainable Development Goals. *Batteries*. 2022;8(9):119. doi:10.3390/batteries8090119

[17] Fyke AD. The Fall and Rise of Gravity Storage Technologies. *Joule*. 2019;3(3):625-630. doi:10.1016/j.joule.2019.01.012

[18] D. K. Chaturvedi, S. Yadav, T. Srivastava and T. Kumari, "Electricity storage system: AGravity Battery," 2020 Fourth World Conference on Smart Trends in Systems, Security and Sustainability (WorldS4), London, UK, 2020, pp. 412-416, doi: 10.1109/WorldS450073.2020.9210321

[19] Liu, S., Wu, S., Hu, Y., & Li, H. (2019). Comparative analysis of air and CO2 as workingfluids for compressed and liquefied gas energy storage technologies. *Energy Conversionand Management*, *181*, 608–620. https://doi.org/10.1016/j.enconman.2018.12.031

[20] Energy Dome. *CO2 battery | Energy Dome*. https://energydome.com/co2-battery/

[21] Diamond_battery_FAQs_Nov_2016. University of Bristol. https://www.bristol.ac.uk/media-library/sites/cabot-institute-2018/documents/Diamond_battery_FAQs_Nov_2016.pdf

[22] Arkenlight – Brilliant Power for Very Useful Things. https://www.arkenlight.co.uk

[23] Elia, G. A., Marquardt, K., Hoeppner, K., Fantini, S., Lin, R., Knipping, E., Peters, W., Drillet, J., Passerini, S., & Hahn, R. W. (2016). An overview and future perspectives of aluminum batteries. *Advanced Materials*, *28*(35), 7564–7579. https://doi.org/10.1002/adma.201601357

[24] Mori, R. (2020). Recent developments for Aluminum–Air batteries. *Electrochemical Energy Reviews*, *3*(2), 344–369. https://doi.org/10.1007/s41918-020-00065-4

[25] Elia, G. A., Kravchyk, K. V., Kovalenko, M. V., Chacón, J., Holland, A., & Wills, R. (2021). An overview and prospective on Al and Al-ion battery technologies. *Journal of Power Sources*, *481*, 228870. https://doi.org/10.1016/j.jpowsour.2020.228870

[26] Wang, C., Yu, Y., Niu, J., Liu, Y., Bridges, D., Liu, X., Pooran, J., Zhang, Y., & Hu, A. (2019). Recent progress of Metal–Air Batteries—A mini Review. Applied Sciences, 9(14), 2787. https://doi.org/10.3390/app9142787

[27] Arai H, Hayashi M. SECONDARY BATTERIES – METAL-AIR SYSTEMS | Overview (Secondary and Primary). In: *Elsevier EBooks*. ; 2009:347-355. doi:10.1016/b978- 044452745-5.00099-x

[28] Goujon N, Casado N, Patil N, Marcilla R, Mecerreyes D. Organic batteries based on justredox polymers. *Progress in Polymer Science*. 2021;122:101449. doi:10.1016/j.progpolymsci.2021.101449

[29] Chen H, Cong TN, Yang W, Tan C, Li Y, Ding Y. Progress in electrical energy storage system: A critical review. *Progress in Natural Science: Materials International*. 2009;19(3):291-312. doi:10.1016/j.pnsc.2008.07.014

[30] *Gelion's EndureTM battery - Gelion - inspired energy*. (2021, August 3). Gelion -

[31] Inspired Energy. https://gelion.com/gelion-endure-battery

[32] Georgious R, Refaat R, Garcia JA, Daoud A. Review on Energy Storage Systems in Microgrids. *Electronics*. 2021;10(17):2134. doi:10.3390/electronics10172134

[33] M. K. Loganathan, C. Ming Tan, B. Mishra, T. A. M. Msagati and L. W. Snyman, "Review and selection of advanced battery technologies for post 2020 era electric vehicles," 2019 IEEE Transportation Electrification Conference (ITEC-India), Bengaluru, India, 2019, pp. 1-5, doi: 10.1109/ITEC-India48457.2019.ITECINDIA2019-254

[34] Shimin VV, Shah VA, Lokhande MM. *Electric Vehicle Batteries: A Selection Based on PROMETHEE Method*.; 2016. doi:10.1109/poweri.2016.8077224

[35] Triantaphyllou E, Shu B, Sanchez SN, Ray TG. Multi-criteria decision making: An operations research approach. *ResearchGate*. February 1998.

[36] Cho J, Jeong S, Kim YS. Commercial and research battery technologies for electrical energy storage applications. *Progress in Energy and Combustion Science*. 2015;48:84- 101. doi:10.1016/j.pecs.2015.01.002

[37]Ma J, Li Y, Grundish NS, et al. The 2021 battery technology roadmap. *Journal of PhysicsD*. 2021;54(18):183001. doi:10.1088/1361-6463/abd353

[38] Prabakaran V. Future of Battery Technologies. *ResearchGate*. January 2021.https://www.researchgate.net/publication/348631115_Future_of_Battery_Technologies.