

Review Article

A Review of Storage Technologies in Smart Power Grid Renewable Energy Systems

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ABSTRACT

Energy storage systems have come to prominence with the sudden rise in renewable energy resources and the power network's growing complexity. The idea of a smart grid that aims at optimising the integration and management of multiple energy resources has been a focuss area in recent years. This research gives a comprehensive analysis of energy storage in smart grids with an emphasis on several technologies and discusses storage technologies used in the smart grid by highlighting their types, advantages, drawbacks, and economics as well. Therefore, it is intended that this review paper will provide a critical evaluation of Energy Storage System (ESS) advancements and identify any research gaps related to reliability studies in modern Renewable Energy (RE) integrated power networks. This research also discusses hybrid energy storage solutions (HESS) which merging various energy storage technologies to enhance operational efficiency and cost-effectiveness and becoming increasingly important as they can tackle both short-term power variations and long-term energy storage requirements. Energy storage can solve intermittent renewable energy problems by giving the system more flexibility and balancing. Moreover, energy storage systems used in

smart grids are analysed and listed with several energy storage methods, including electrical, electrochemical, thermal, and mechanical systems are investigated.

Keywords: Renewable energy, storage system, smart grid, battery energy storage system (BESS), hybrid energy storage system (HESS)

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INTRODUCTION

The most important question of Renewable Energy Technology is why do we need to store energy? (Padmanaban et al., 2022; Dong, 2024) explained how the system should be deliver the total energy required over the period of operation, deliver the energy at the rate it is required such as meet the peak power demand, most energy systems have a varying demand with some short term but large peak power requirements which results in a capacity requirement might only be used for a fraction of the time and finally this capacity requirement can either be met by some form of energy conversion power stations or energy storage. Energy storage (Elalfy et al., 2024) is being researched in Energy storage which is crucial for handling the unpredictability of renewable energy systems, guaranteeing a reliable and stable electricity supply. It enables the balancing of demand in high-demand times and the storage of surplus energy for utilisation in periods of lower generation. (Mottola & Russo, 2023) have been discussed storing energy to handle the fluctuations of renewable energy sources, decrease electricity expenses, minimise peak demand fees, and improve self-consumption. Energy storage solutions are essential for reducing carbon emissions in systems that once depended on fossil fuels. Energy storage technologies (Baker McKenzie, 2022) have the potential to offer ancillary services to the electricity grid in addition to delivering power on demand. These services could help the power system be more efficient and reliable and better match electricity supply to demand.

ENERGY STORAGE SYSTEM TECHNOLOGIES

From (Achhari & Fadar, 2018; Asian Development Bank,2018; Faisal et al., 2018; Worku, 2022) Energy Storage is classified based in the form of energy, Figure 1 & Figure 2 describe it. Humans have been on an unending mission to create new more effective energy storage techniques that are adapted to demands as the need for energy storage has grown. Systems for storing energy (AL Shaqsi et al., 2020; Choudhury, 2021; Shirinda & Kanzumba, 2022 ; Thanapalan & Constant, 2020) can be categorised according to their specialised purpose, response time, amount of time stored, and type of energy stored. Here, the focuss is on defining ESS according to the type of stored energy. Electrical or magnetic fields, as well as mechanical, electrochemical, chemical, or thermal energy, can all be used to store energy. Energy can also be stored as a mixture of two different forms (Gayathri et al., 2022). According to expectations, energy storage for the integration of renewables would generate more than \$23 billion in global revenue by 2026, and by 2030, the amount of energy that must be stored will triple from what it is today (Worku, 2022).

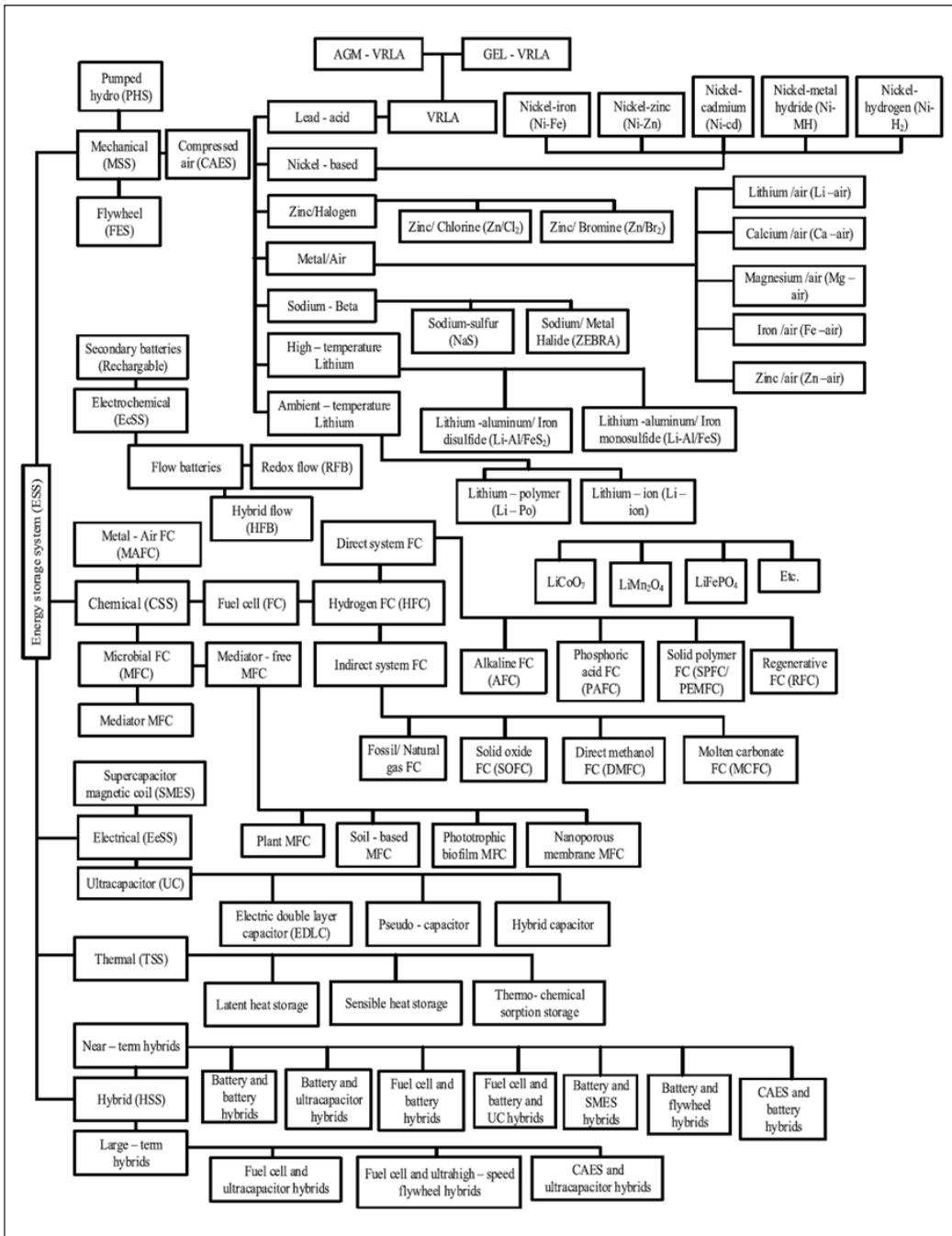


Figure 1. Classification of energy storage technologies

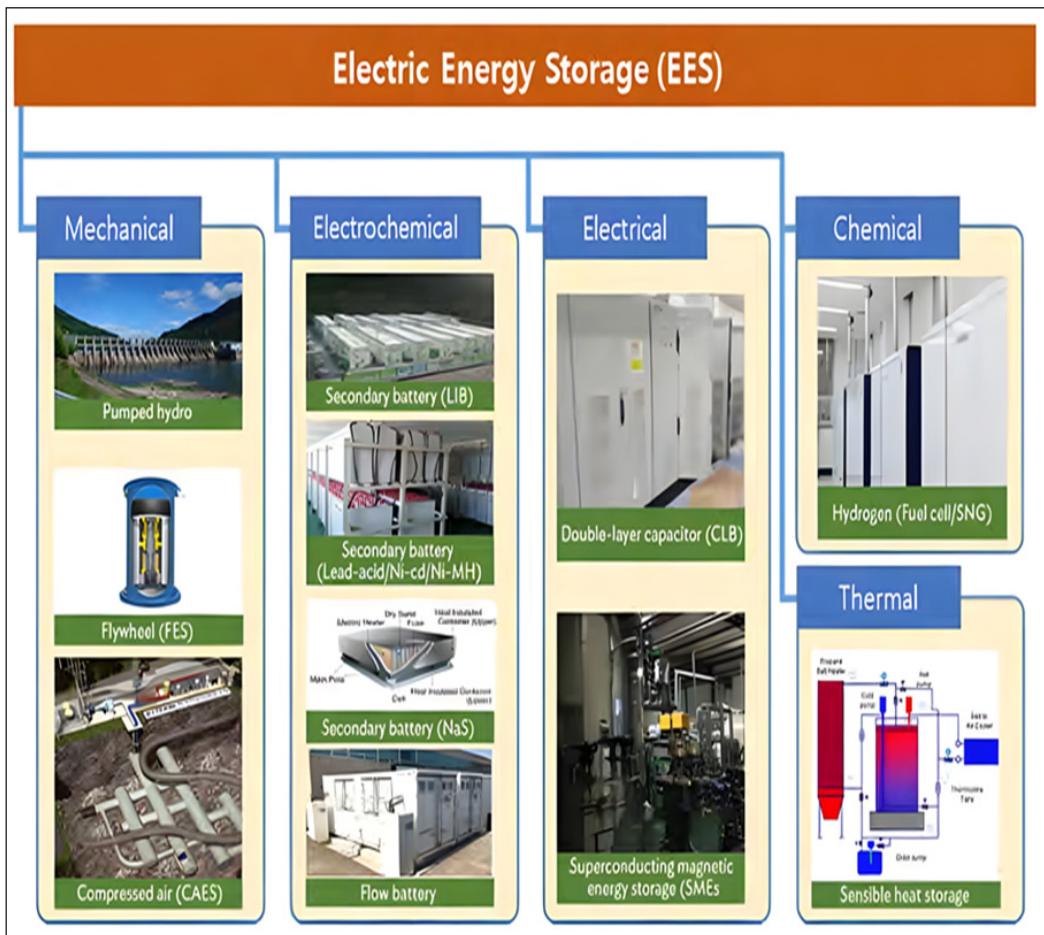


Figure 2. Classification of energy storage technologies

Pumped Hydro Energy Storage (Mechanical Energy Storage)

A mechanical device transform electrical energy between kinetic and potential gravitational energy (Wu et al., 2021; F. Wu , 2019), PHES in Figure 3 (Mohamad et al., 2018) is the most developed and the largest commercially the most in the world electricity storage capacity geological implementation with available ESS technology (Faisal et al., 2018). Two water storage tanks with various heights make up the basic layout of PHES. Pumps (Achhari & Fadar, 2018) are used to move water to the upper reservoir for storage and discharge it into the lower reservoir. The PHES has a 70-80% roundtrip efficiency. The expected lifespan of PHES is 40 to 60 years, Fast response times, advanced technology, and a cost-effective technique to store energy. There are a few suitable locations, significant environmental implications, and a substantial water source requirement which the disadvantages (Blakers et al., 2021).

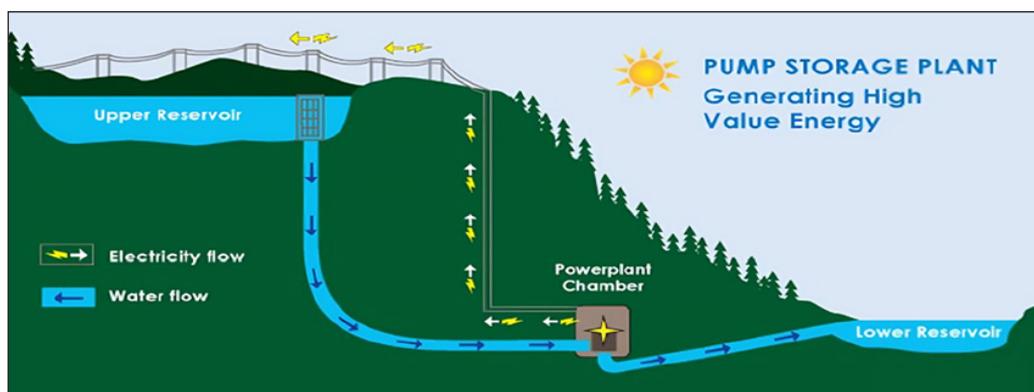


Figure 3. Configuration of a PHES

Flywheel Energy Storage (Mechanical Energy Storage)

The flywheel is a mechanical ESS that converts grid energy into spinning discs and stores it. To store energy, this technology accelerates spin and then releases energy by slowing down. Microgrids can use flywheels, and they can also be combined with other ESS technologies as illustrated in Figure 4 (Mohamad et al., 2018).

It provides high of power density 1000-2000 W/I and industry-wide use of reliable and well-known rotating mass, inverter, and motor technologies The electro-chemical process and reactions have no aging-related consequences. Prolonged useful life less than or equal 20 years. Wider operational temperature ranges than batteries, in comparison. But there are numerous parts that need upkeep (bearings, a vacuum pump, cooling fans, and control sensors all potentially represent single points of failure) and relatively sophisticated, long-lasting, low-loss bearings (Olabi et al., 2021; Choudhury, 2021; Li & Palazzolo ,2021).

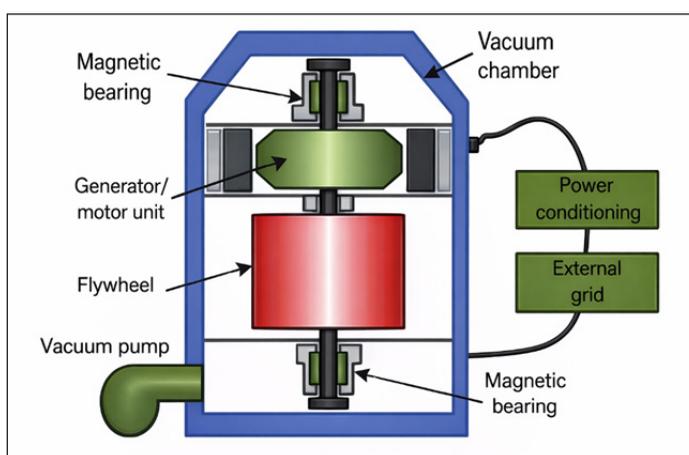


Figure 4. Schematic of a flywheel

Compressed Air Energy Storage (Mechanical Energy Storage)

A mature ESS technology that falls under the mechanical category CAES in Figure 5 (Mohamad et al., 2018) The idea behind CAES is to compress air by using inexpensive energy to store the compressed air and release it upon discharge. The most efficient way to store a lot of energy is via CAES, which also has the lowest initial investment costs. In large-scale systems, CAESS primarily finds use in peak-shaving, load-shifting, improving air quality, maintaining system stability, and controlling voltage and frequency (Gayathri et al., 2022; Wu et al., 2021)

The advantages of this type of storage CAES, with an estimated efficiency of 85% operates effectively for around 40 years, Similar to PHE, capable of storing enormous amounts of energy. quick response times, Low-cost means of energy storage while the disadvantages Would need sealed storage chambers, which is a drawback, not entirely formed yet, just a day's worth of storage is cost-effective (Thanapalan & Constant, 2020).

Electrochemical Energy Storage (Batteries)

An EES system (Salkuti, 2020) is made up of several electrochemical cells that are connected to one another and generate energy through electrochemical process. As shown in Figure 6 each cell consists of two electrodes (one anode and one cathode) and an electrolyte that can be in a solid, liquid, or viscous condition.

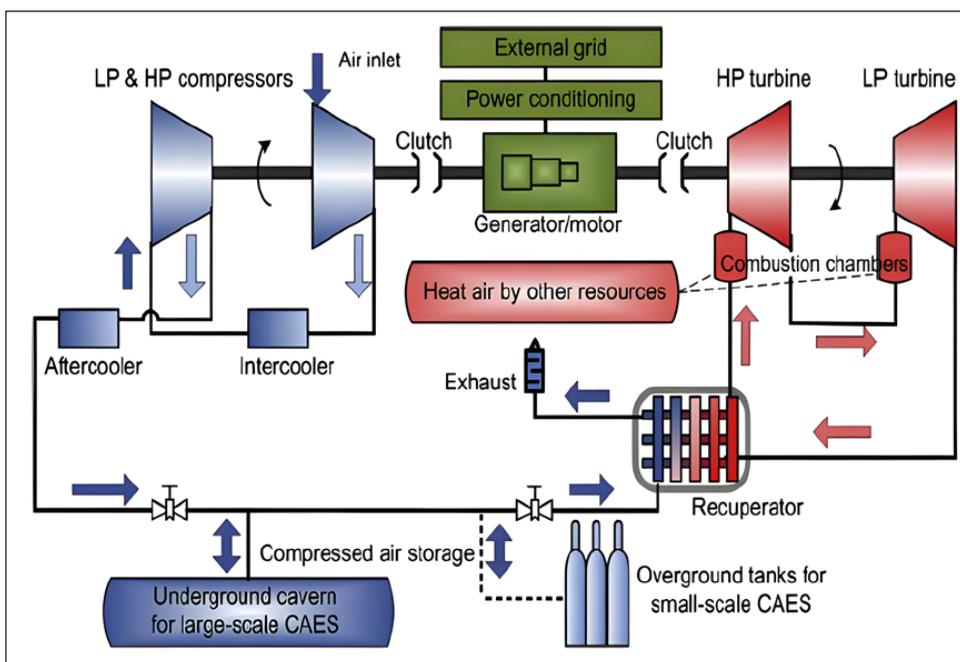


Figure 5. CAES storage

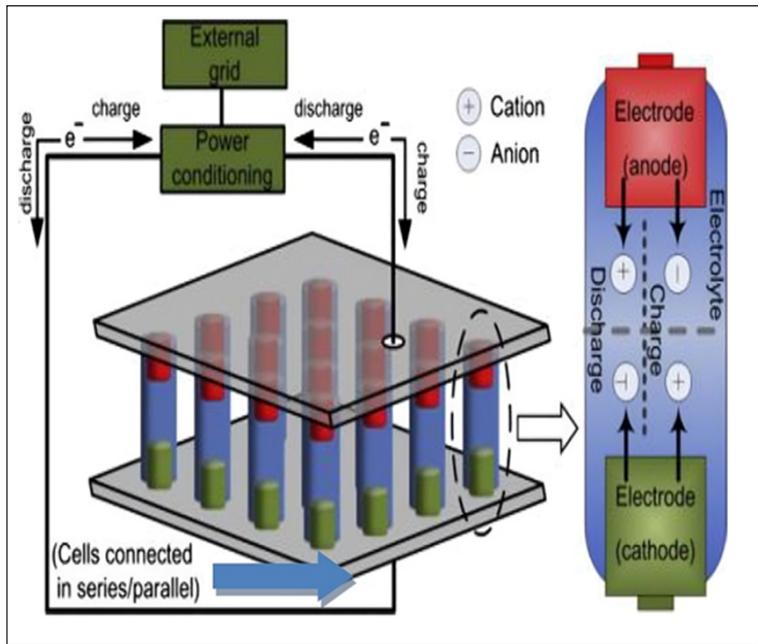


Figure 6. Battery energy storage system operation

There are many benefits of this type of storage which are cheap and simple to create, advanced technology with more than 150 years of development and experience, recycling is simple, commercial batteries have the highest energy density and the most potential. There are abundant supplies of lithium and graphite while the disadvantages having a significant amount of weight and bulk, environmental issues, despite being generally safe, some substances are highly poisonous, and exposure to them can have serious negative effects on both people and animals, corrosion brought on by chemical processes, cells are completely destroyed by discharge and degrades even when not in use (Molina, 2017; Salkuti, 2020; Sufyan et al., 2019).

Electrical Energy Storage

Super Capacitors

Super capacitors as shown in Figure 7 use electrodes with a larger surface area and thinner dielectrics to produce larger capacitances while still being subject to the same basic equations as regular capacitors. By doing so, super capacitors can maintain the usual high power density of conventional capacitors while also reaching elevated energy densities (Mohamad et al., 2018; P. Sharma et al., 2022).

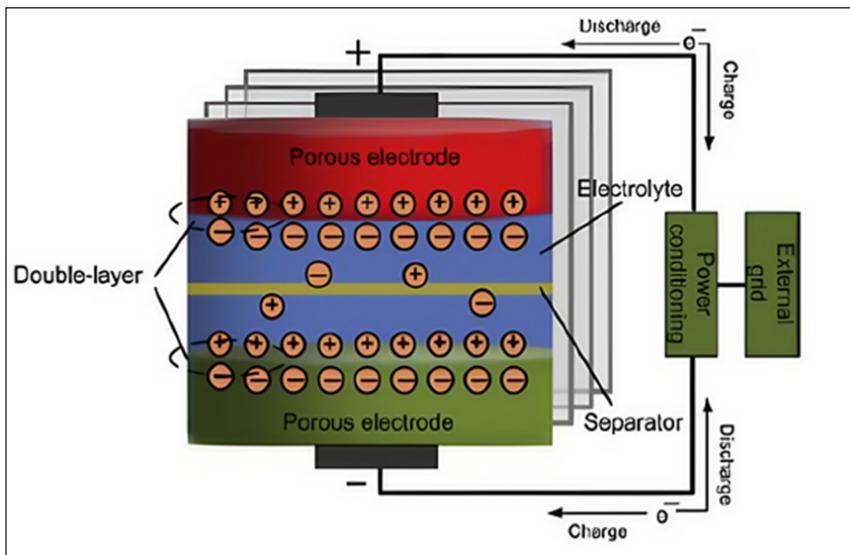


Figure 7. Schematic of a super capacitor

The advantages : Extended cycle life, high current capacity, extremely high efficiency, and wide temperature range, and wide voltage range.

The disadvantages : Low voltage cells, serial connections are necessary to obtain greater voltages. When over three super capacitors are connected in series, a voltage balancing component is needed in the circuit, and in comparison to electrochemical batteries, there is a greater self-discharge (AL Shaqsi et al., 2020; Maksoud et al., 2021).

Superconducting Magnetic Energy Storage (SMES)

The system depicted in Figure 8 (Mohamad et al., 2018) consists of three core components: a coil, a power conditioning unit (PCS), and a cooling mechanism. The theory hinges on the observation that a current continues to flow through a superconductor even after the voltage applied across it has been removed. Because the superconductor coil exhibits minimal resistance when cooled past its superconducting critical temperature, current will keep flowing (even after the voltage source is disconnected). The magnetic field generated by the current in the superconducting coil functions as an energy storage medium. The coil can be released to free it. EESS accumulates energy and produces electricity to supply power to the load when required. In this context, storage is usually accomplished with capacitors or superconducting magnets (Behabtu et al., 2020; V. S. V. G & Madichetty, 2017).

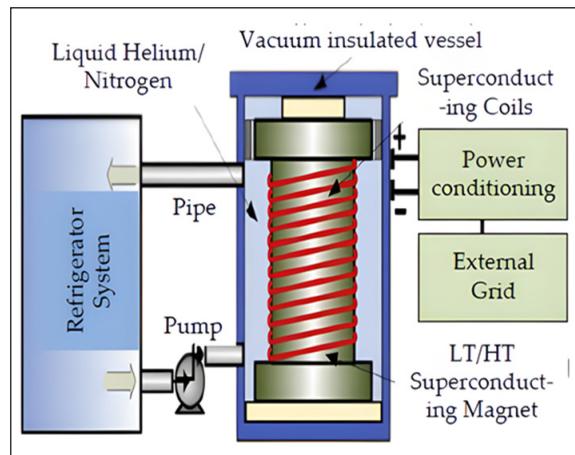


Figure 8. The main component of SMES system

This system has fast response times, the ability to discharge partially or deeply, little environmental risk, a low moving component count, and good cycling effectiveness. The disadvantages could be high production maintenance costs, and reduced efficiency as a result of the necessary cooling process's high power requirements (Mukherjee & Rao, 2019; Oskouei et al., 2022; Thanapalan & Constant, 2020).

Hydrogen Energy Storage and Methanation (Chemical Engineering Storage)

The most adaptable and practical method for storing renewable energy on a large, long-term scale is water electrolysis technology. The Proton Exchange Membrane (PEM) divides water into its component elements, hydrogen and oxygen, which may be stored in standard tanks using extra renewable electricity in Figure 9 (Achhari & Fadar, 2018; Cano et al., 2018; Manoharan et al., 2019).

A zero-carbon fuel (Hydrogen 2022; The Road to Energy Storage, 2022) is a solution for the zero-carbon future. Hydrogen is that fuel. On Earth, hydrogen does not naturally occur in the same quantities as natural gas (methane). To produce hydrogen, fuels containing hydrocarbons (C_xH_y) must be used, which releases carbon dioxide. Alternatively, hydrogen can be derived from water (H_2O), a plentiful resource, which emits no carbon at all (McPherson et al., 2018).

This type of storing energy capable of storing enormous amounts of energy for days or even months and also has clean and environmentally friendly method of energy storage but it has low efficiency (30–40%), energy loss throughout a single cycle (from hydrogen creation to fuel cell electricity output), requires an extremely complex grid (Blanco & Faaij, 2018; Chaudhary et al., 2021).

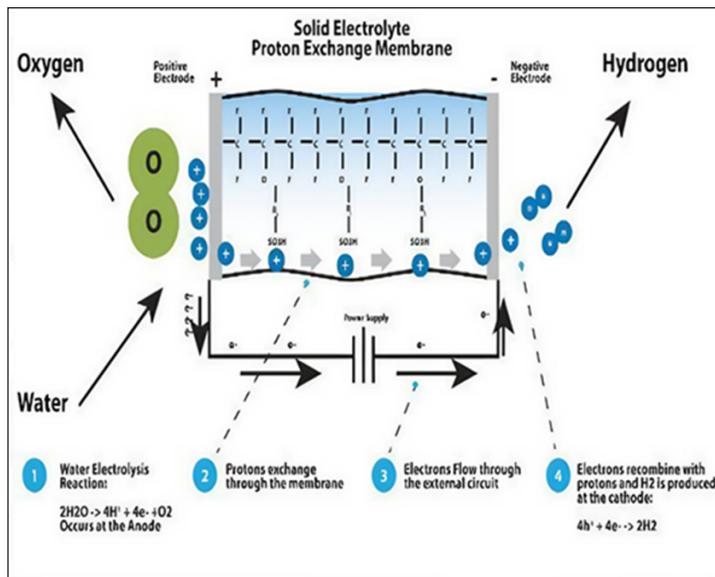


Figure 9. Chemical process of hydrogen production

Thermal Storage

Extra energy is used by the CES (Cryogenic energy storage) to produce cryogenic fluid, which is then converted into electricity by a cryogenic heat engine. This storage has a High energy density, Low cost and Long storage time but its efficiency low and classified as immature Technology (Mazzoni et al., 2019; Sharma et al., 2021)

- HT-TES (High temperature thermal energy Storage-High temperature thermal energy storage)

It is used to transform energy by storing heat in many mediums, including water, molten salt, solar, and more. It has Low cost, Simple manufacture and high discharge time (Al-Maliki et al., 2021; Tetteh et al., 2021; Worku, 2022).

USING BATTERY ENERGY STORAGE FOR SMART GRID APPLICATIONS

Lead-based Batteries

Since lead-based batteries as shown in Figure 10. (Asian Development Bank, 2018; Fan et al., 2020; Salkuti, 2020) have been well-established in industrial applications for more than 100 years, grid operators and end users can benefit from their suitability in a number of on-grid applications. Nowadays, lead-acid technology makes up around 80% of the total installed capacity of industrial batteries for stationery and motor applications. The following performance features apply to lead-based batteries for on-grid BES:

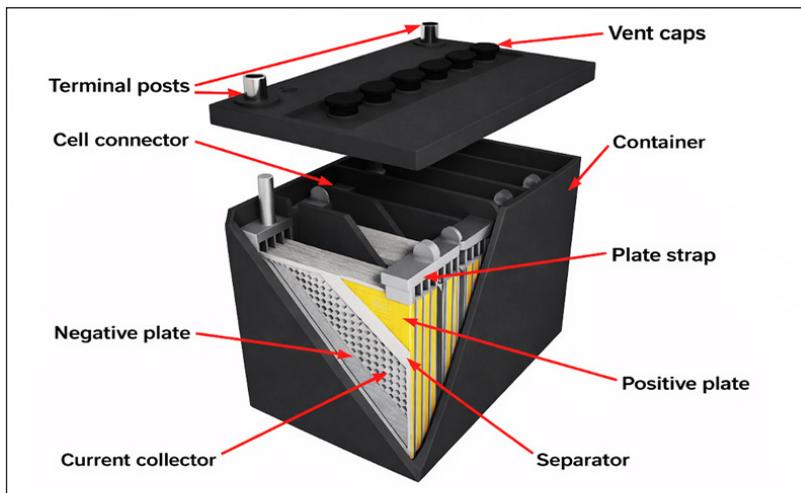


Figure 10. Lead acid batteries

- Power Rating: 100 MW
- Energy density – 25-50 Wh/kg (60-40 Wh/l)
- Energy Efficiency – Higher than 80 %
- Calendar life – 20 years
- Cycle life - >2,000 cycles @ 80% depth of discharge (state of the art)
- Operation temperature range -30°C up to +50°C

Further development:

- Enhanced power will result from applying advanced additives to the active materials and designing with reduced internal resistance
- Improved Cycling Capabilities: Lead-acid batteries' cycling abilities have been improved, enabling them to tolerate deep cycling and frequent charge-discharge cycles.
- Advanced Lead Alloys: To improve the performance of lead-acid batteries, researchers have looked at the usage of advanced lead alloys. These alloys may result in greater charge acceptance, less sulfation, and better battery performance in general. (Huang et al., 2023; Kebede et al., 2022; Salkuti, 2020).

Lithium-based Batteries

Li-ion technology in Figure 11 (Asian Development Bank, 2018; Fan et al., 2020; Salkuti, 2020) has several benefits, including its adaptability to virtually any voltage, power, and energy demand. Its power to energy ratios can range from extremely high power (i.e.

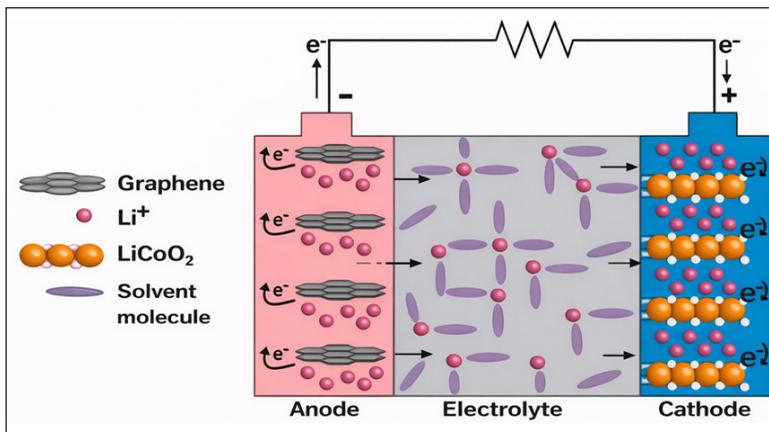


Figure 11. Li-ion batteries

10kW / kWh) to extremely high energy. On the one hand, Li-ion batteries are a complex technology since they require sophisticated control circuits, but they also provide accurate management and state of charge control in "smart" applications. lithium-ion batteries have:

- Power Rating: 100 MW
- High energy density (150-200 kWh/m³, 140 kWh/ton at battery level)
- High efficiency (near 100%)
- Long cycle life (>5,000 cycles @ 80% depth of discharge) combined with long calendar life of 20 years+
- Maintenance-free design.
- Versatility: electrodes can be optimised for different power /energy patterns.

Tesla Li-ion Batteries

Tesla's Li-ion batteries (Shi, 2023; Qiao, 2023) rank among the top in energy density, efficiency, and intelligent features. They are especially ideal for systems that store energy at home and integrate solar power. Tesla's lithium-ion batteries, especially the Tesla Powerwall and Tesla Powerpack variants, are some of the most recognised and frequently utilised in both residential and commercial settings. Tesla's lithium-ion batteries, like those found in the Powerwall, are engineered for high energy density. This indicates they can hold greater energy within a compact physical size, rendering them appropriate for home and business applications. Tesla's batteries boast an exceptional lifespan, ensuring over 10 years of reliable performance. Tesla provides a comprehensive warranty with performance assurances for the Powerwall and Powerpack. Tesla batteries are combined with intelligent energy management systems. Via the Tesla app, users can track battery efficiency, charging

and discharging cycles, and even manage when to save or utilise energy according to immediate demand. Tesla provides scalable options such as the Powerpack for extensive commercial uses and Powerwall for residential applications. This enables users to create a tailored energy storage system. Tesla is recognised for its advanced technology in electric cars and energy storage solutions. Their batteries (Gregori et al., 2020) are supported by extensive research and have been steadily enhanced with every new version. If you're designing an off-grid system or require a solution for extensive commercial uses, it's beneficial to evaluate Tesla's products alongside those from leading brands such as LG Chem, BYD, and Sonnen.

Further development:

- Energy density, cycle, and life duration will continue to grow as technology advances. Future system costs will be lower as a result.
- The creation of solid-state batteries has been the subject of contemporary research. These batteries use a solid electrolyte substance in place of the liquid electrolyte present in conventional Li-ion batteries.
- Lithium-Sulphur Batteries: Due to their high theoretical energy density, lithium-sulphur (Li-S) batteries have attracted attention. Sulphur is widely available, inexpensive, and environmentally safe.
- The performance, security, and lifespan of Li-ion batteries are closely monitored and optimised by smart battery management systems (BMS). (Kebede et al., 2022; Shaukat et al., 2018)

Nickel-based Batteries

Nickel-based batteries as shown in Figure 12 (Asian Development Bank, 2018; Chen et al., 2024; Fan et al., 2020; Salkuti, 2020; Young & Yasuoka, 2016) are the second most prevalent form of electrochemical energy storage following lead-acid batteries. They serve specialised markets that need energy storage in challenging weather, during cycling, or in rapid charging conditions. There are specific performance characteristics in the:

- Power Rating: 40 MW
- Nominal energy density – From 20- 80Wh/kg (50-300 Wh/l)
- Energy efficiency - >90% (dependent on application)
- Calendar Life – 25 years
- Cycle Life – >3,000 cycles (of nominal capacity)
- Operating temperature range: -40°C to +60°C

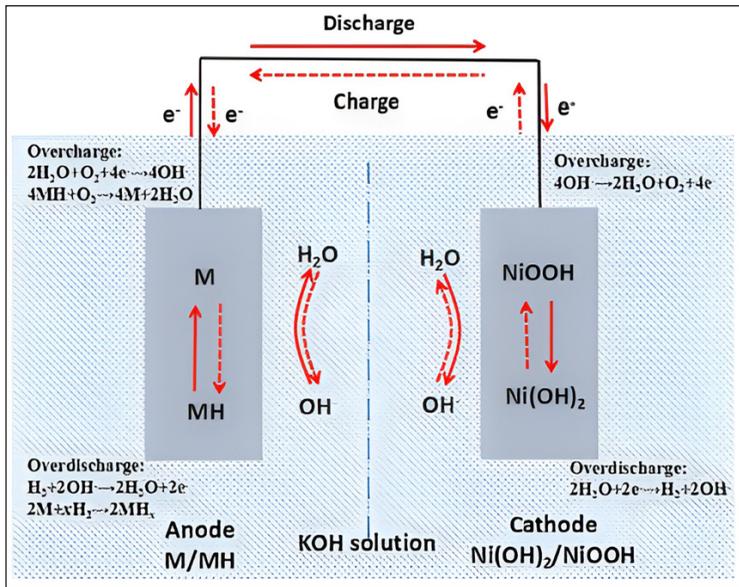


Figure 12. Na-MH batteries

Further development:

- This advancement will concentrate on extending the temperature range, lowering self-discharge, and enhancing cycle life.
- To improve the performance of the electrodes and boost the capacity of NiMH (Nickel-Metal Hydride) batteries, researchers have concentrated on creating new hydrogen storage alloys. NiMH batteries are now better suited for uses like renewable energy storage and hybrid electric vehicles (HEVs), which demand a higher energy density.
- Batteries made of Nickel-Cadmium (NiCd), cadmium-related environmental issues led to a substantial phase-out of NiCd batteries, there have been efforts to enhance their performance and lessen their environmental impact. To improve the cycle life, energy density, and efficiency of NiCd batteries, research has been done on creating new electrode materials and electrolytes.
- Specific Applications for Nickel-Based Batteries: In some niches where their distinct qualities are helpful, nickel-based batteries are still used. NiCd batteries are still utilised in some industrial applications, for instance, where high discharge rates and reliable performance in harsh environments are necessary. NiMH batteries are also used in several consumer electronics, including rechargeable AA/AAA batteries and portable power tools. (Chen et al., 2024; Gregori et al., 2020; Kairies, 2017; Kebede et al., 2022; W. H. Zhu et al., 2014; Young & Yasuoka, 2016).

Sodium-based Batteries

Batteries made of sodium nickel chloride as shown in Figure 13 (NaNiCl_2) (Asian Development Bank, 2018; Fan et al., 2020) were first made available for use in electric and hybrid vehicles, making them a relatively recent technology. In terms of stationary backup, rail backup, and on-grid/off-grid energy storage, a greater selection of products is now available. The following performance characteristics are present in them:

- Power rating: 8 MW
- Nominal energy density – 120 Wh/Kg / 140 Wh/l (battery level)
- Energy efficiency - 92% at C/4 rate
- Calendar life – 10+ years in stationary float applications at any ambient temperature.
- Cycle life – > 4500 cycles @ 80% DOD (SOC 10% to 90%)
- Operating temperature range -30°C to +60°C without power reduction.

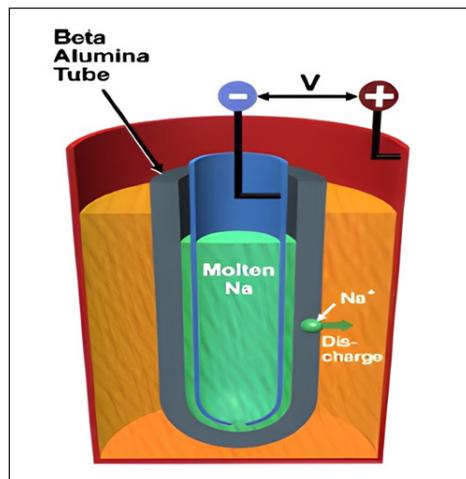


Figure 13. Sodium-based batteries

Further development:

- Even after only 15 years in use, there is still a great deal of room for technological advancement. With the introduction of cutting-edge additions, the specific power of NaNiCl_2 batteries is being enhanced through positive active materials and lower resistance ceramics in the solid electrolyte.
- To increase the ionic conductivity and lower internal resistance of NaNiCl_2 batteries, researchers have investigated various formulations and compositions of the electrolyte. The total efficiency and cycling stability of the batteries are to be improved by this optimisation.

- Operation at High Temperatures: NaNiCl_2 batteries are made to function at high temperatures, usually between 270 and 350 °C. To increase these batteries' performance and safety, improvements have been made to their thermal stability and heat management. (Kebede et al., 2022).

COMPARISON BETWEEN BATTERY STORAGE SYSTEMS

As shown in Figure 14 (Asian Development Bank, 2018; Fan et al., 2020), its clearly view that there is a factor of energy storage technology to be considered:

- **The applications** :(power rating – module size)
- **The duration of the application**: (second – Min-hours)
- **The rates of charge**: (Power supply storage devices need to be recharged. For prospective energy sources, the resource must be replenished before it can be used to generate electricity once more).

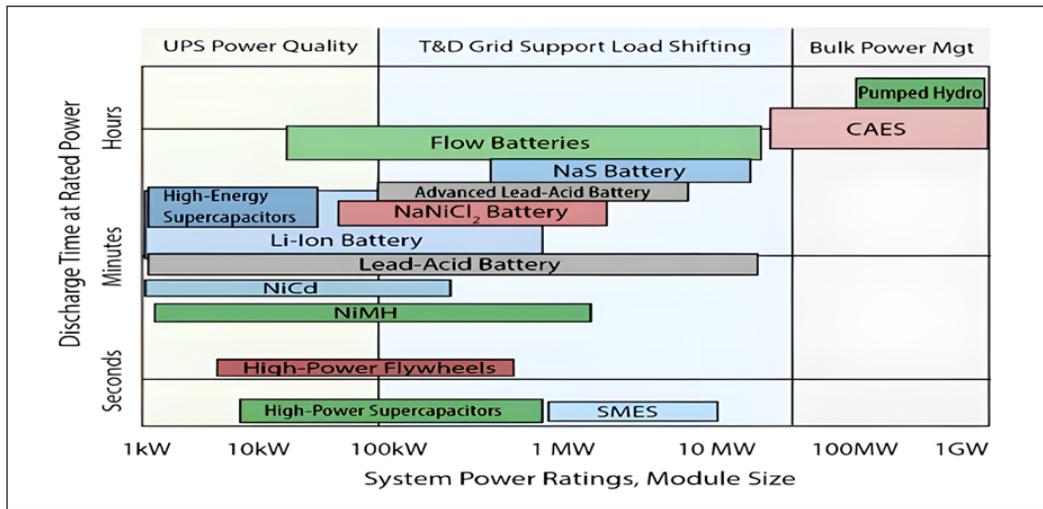


Figure 14. Positioning of energy storage technologies for grid services

BATTERY ENERGY STORAGE SYSTEM (BESS)

As shown in Figure 15, BESS advantages described by (Andrey Solovev, 2021), such as its quick and dependable response time, adaptability, manageability, environmental friendliness, and geographic independence. BESS (Hidalgo-Leon et al., 2018; Juma et al., 2021) is considered as a potential substitute for conventional energy sources. the main topic of article (Kairies,2017; Mudakir et al., 2024; Okafor & Folly, 2023) providing the solutions for installing BESS in a power distribution network with both conventional and wind power sources due to their adaptability and quick response times, battery energy

storage devices might technically be incorporated into a distribution network for a variety of purposes. significantly reduces frequency deviations and voltage fluctuations, enhancing grid stability and supporting renewable energy integration.

Features of Battery Energy Storage Systems (BESS)

- It may be small-scale setups, such as residential or business systems, or it can involve large-scale systems featuring extensive storage. It comprises the Battery Management System, Power Conversion System, Energy Management System, and Safety System.
- Capable of using a range of battery technologies, including as lithium-ion (Li-ion), lead-acid, flow, and others.
- They are frequently used for grid stabilisation (balancing supply and demand), peak shaving (reducing high energy demand during peak periods), load shifting (shifting energy consumption from high-demand to low-demand periods), renewable energy integration, and backup power during outages. Play an essential role in the grid's integration of renewable energy sources like solar and wind (Chavhan et al., 2024; Hidalgo-Leon et al., 2018).

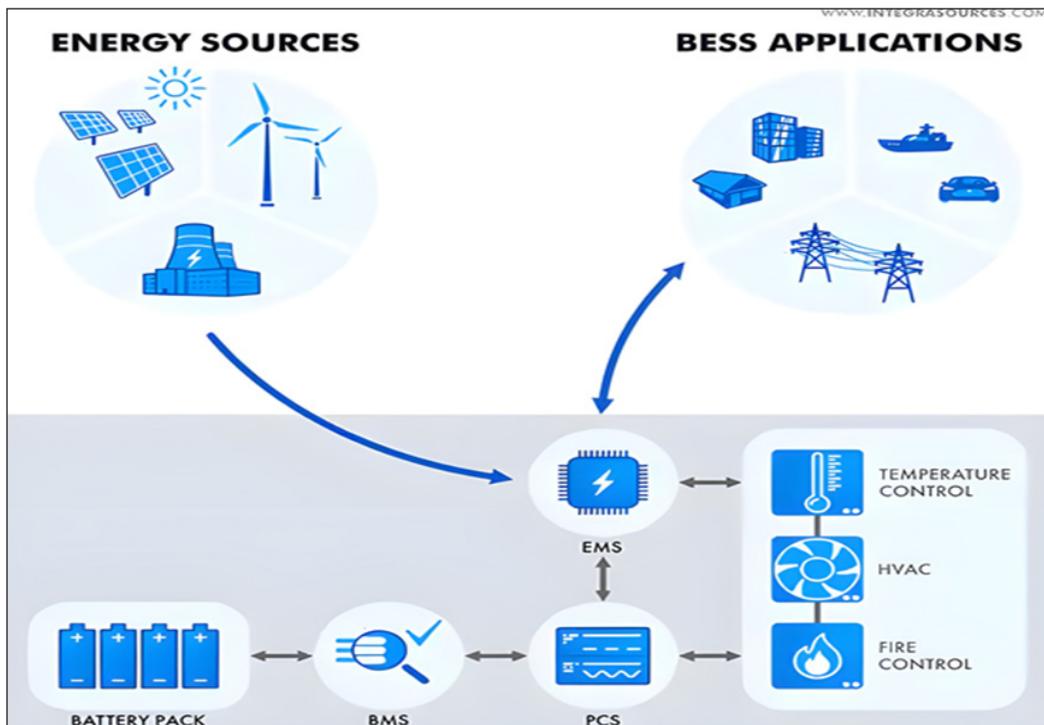


Figure 15. A typical BESS structure

HYBRID ENERGY STORAGE SYSTEM

Renewable Energy Systems have concerns with instability, frequency control, poor power quality, intermittency, and imbalanced load, among others. A normal Micro Grids typically results in the Energy Storage System experiencing (Hajiaghasi et al., 2019) The majority of studies have employed HESS to reduce wind and solar power variability. ESS can be integrated to help with some of the problems brought on by sources of power production that fluctuate, including solar and wind energy.

A wide range of energy storage hybrids can arise because of the numerous types of energy storage technologies, each of which has unique properties in Figure 16.

Researchers have devised a Supercapacitor-battery hybrid energy storage system to increase the cycle life of battery banks by reducing the stress caused by charge-discharge owing to variable power exchange (W. Jing et al., 2018). To maximise the service life of the lithium battery pack, (Y. Jing et al., 2022) streamlines an appropriate balance of the Supercapacitor pack's daily charging and discharging durations to the daily cycle durations of the lithium battery pack. The goal of (Citalingam & Go, 2022) is to create an improved hybrid energy storage system that combines batteries and SuperCapacitors to support a sizable solar PV system. the goal of (Reilly et al., 2022) is to enhance comprehension of the technologies used in wind-storage hybrid systems and to identify the best strategies for incorporating these technologies into a distributed system that delivers primary energy and grid support services.

Further Development of Hybrid Energy Storage System

- While some academics are investigating the application of HESS to supply backup power for vital infrastructure.

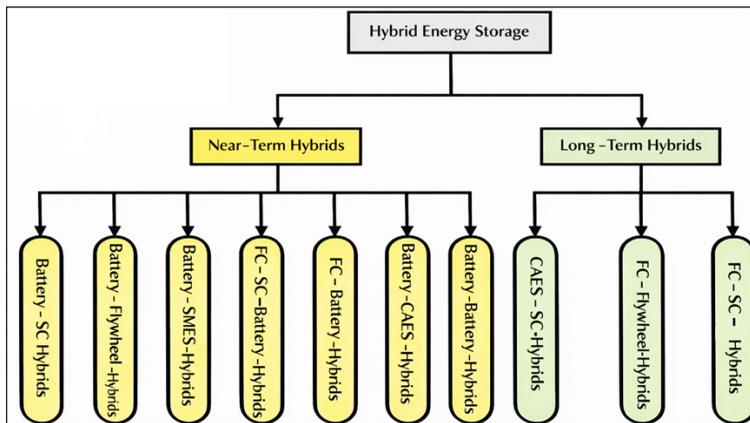


Figure 16. Hybrid energy storage

- New algorithms are being created by researchers to improve the HESS's performance in real time.
- Many studies are being conducted to create new and enhanced battery technologies that provide greater energy densities, longer lifetimes, and faster charging rates. (Atawi et al., 2022; Shirinda & Kanzumba, 2022)

Projects of Hybrid Energy Storage System

- Tesla announced the creation of a brand-new battery technology called the Megapack. A modular battery system that can be utilised to store a lot of energy is called the Megapack.
- The U.S. Department of Energy (DOE) revealed a new research initiative to create a hybrid energy storage device that can use both hydrogen and compressed air.
- Aquion Energy, a firm, announced the creation of a revolutionary flow battery technology for 2020. A form of energy storage device known as a flow battery stores energy using liquid electrolytes (*Quino Energy Was Formed to Commercialise the Aqueous Organic Flow Battery Technology Pioneered at Harvard University*)

ENERGY STORAGE SYSTEM SOFTWARE

In (Nguyen & Byrne, 2021) research, software tools for Energy Storage System evaluation and design are reviewed. Along with a review of analysis tools for assessing the technical effects of energy storage deployments. Here some best software could be used for ESS in Table 1.

Table 1
Energy storage system software

Software	Description	References
Homer Energy	A platform for designing, simulating, and enhancing a variety of energy storage systems. Homer Energy is a common option for both domestic and industrial uses.	(https://homerenergy.com/)
Energy Toolbase	An additional popular software system for energy storage. A web-based platform called Energy Toolbase gives users access to many different tools and materials for energy storage, such as design, simulation, and optimisation tools.	(https://www.energytoolbase.com/)
BatterySIMM Suite	A set of tools for modelling and simulating battery energy storage systems. Engineers and academics that need to model and simulate the performance of battery energy storage systems frequently choose it.	(https://www.ascendanalytics.com/)

Table 1 (continued)

Software	Description	References
QuEST	A software that can be used to develop, model, and improve electric grid energy storage systems. Utility companies and other businesses who need to optimise the utilisation of energy storage on the grid frequently choose it.	(https://www.sandia.gov/ess/tools-resources/quest)
StorageVET	A software for designing, simulating, and improving energy storage systems for business and industrial purposes. Businesses who need to employ energy storage to increase their energy effectiveness and lower their energy expenditures frequently choose it.	(https://www.epri.com/)
REopt	NREL researchers utilise echno-economic decision support platform to optimise energy systems for structures, campuses, communities, microgrids, REopt suggests the ideal mixture of renewable energy, conventional generating, and energy storage solutions.	(https://reopt.nrel.gov/tool)

ENERGY STORAGE SYSTEM MARKETING

The wide range of services based on efficient, affordable power storage will be essential to the development of future energy systems. There are numerous service needs with varied performance levels. Requirements, implying a significant role for numerous storage technologies. If the countries keep boosting the share of renewable energy sources in the worldwide energy framework by twofold, the overall power storage capacity is expected to expand threefold in energy terms by 2030. By 2030 as shown in Figure 17 stationary

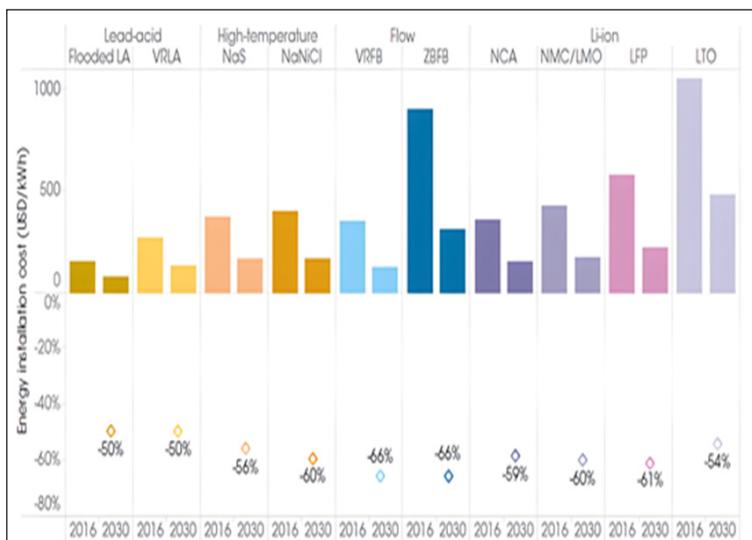


Figure 17. Battery electricity storage system installed 2016-2030

applications could see an additional 54-61% reduction in the total installed cost of a Li-ion battery. (Ralon et al., 2017). Electricity markets frequently fail to take into account the system value of storage, leading to so-called "missing money" market revenues that are insufficient for investors to support projects and resulting in less-than-ideal deployment of electricity storage (Gregori et al., 2020). Analysing the various technologies and fairly comparing their costs and performances becomes more crucial as the grid storage sector continues to expand and evolve (Viswanathan et al., 2022).

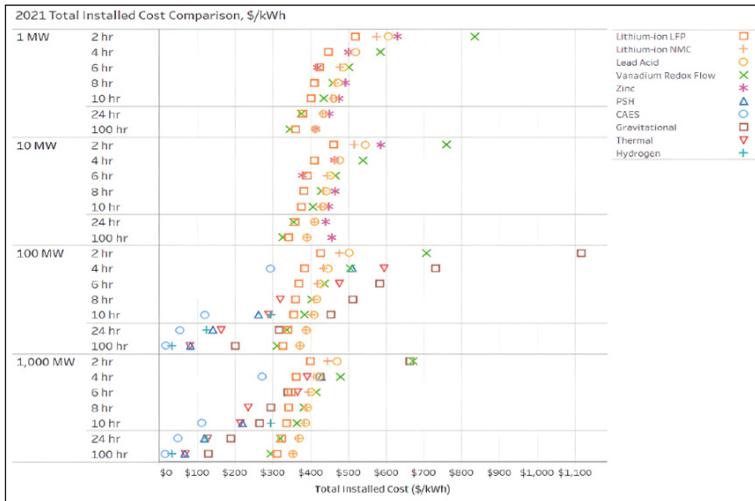


Figure 18. Electricity storage system cost 2021

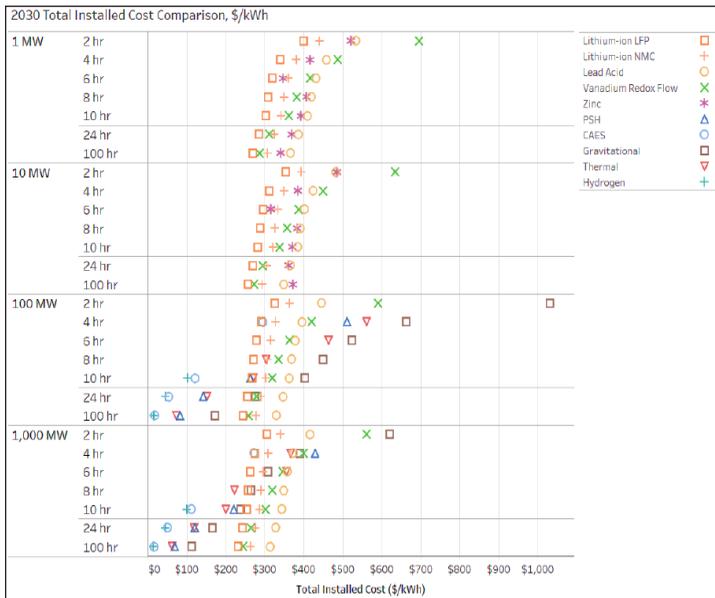


Figure 19. Electricity storage system cost estimates 2030

Table 2

Comparison between the electricity storage system total installed ess cost figure 18. 2021 & figure 19. 2030

EES	Capacity MW	Duration	Cost \$/kWh in 2021	Estimated cost \$/ kWh in 2030
Li-ion LFP	1000	2 hr	400	300
Li-ion NMC	1000	2 hr	450	320
Lead Acid	1000	2 hr	470	410
vanadium RF	1000	2 hr	680	560
Zinc	10	2 hr	590	490
PSH	1000	10 hr	220	220
CAES	1000	4 hr	270	270
Gravitational	1000	2 hr	690	620
Thermal	1000	4 hr	390	370
Hydrogen	1000	10 hr	290	100

Table 2 based on discussions with technology developers and industry stakeholders, publications, commercial datasets, and reported storage costs for systems implemented throughout the United States, cost and performance information for the necessary categories and components was gathered.

ENERGY STORAGE SYSTEM FOR SMART GRID

The basis of smart grids (Aydın & Demir, 2019; P. Sharma et al., 2022) will always be conventional systems. With the integration of several disciplines into conventional systems, we realise that the development of microprocessor-based imaging, protection, control, and data acquiring devices is becoming increasingly crucial today. The smart grids required today can be employed in electric vehicle charging stations and can provide a simple method of integrating renewable energy sources into the grid. Technologies for energy storage offer a lot of potential improvements to the grid's performance and operation. Figure 20. describe it.

When fuel cells, photovoltaics (PVs), wind power, and battery storage are brought into integration, numerous challenges confront the smart grid. The energy storage system (ESS), which continuously helps supply power to the grid in fulfilling load demands by controlling power system frequency and increasing the ability of the transmission line, is tasked with increasing the integration of renewable energy sources. ESS reduces renewable energy fluctuations and saves excess power during peak generation so that it is used at peak load. Moreover, ESS increases the effectiveness of the electrical system by reducing grid congestion.

In a smart grid power system, Figure 21 illustrates the flow of electricity from the generators at the power plants to the client end (Sufyan et al., 2019). The future Smart

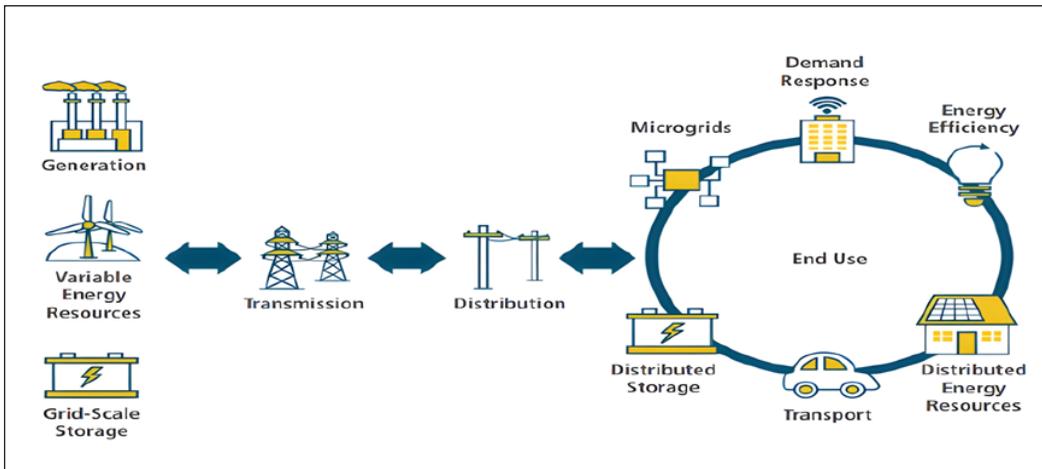


Figure 20. Smart grid overview

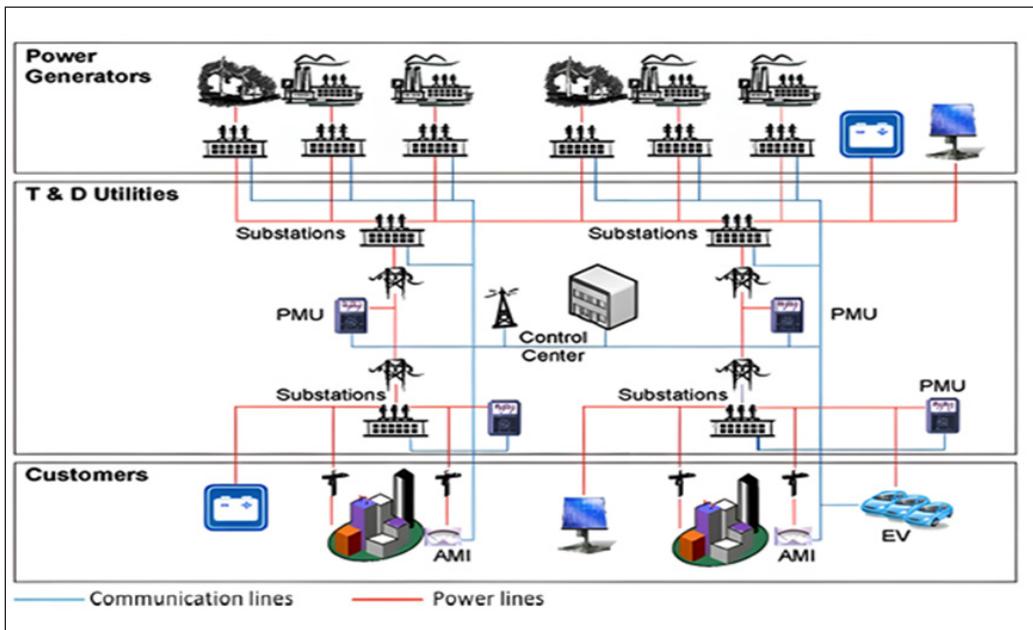


Figure 21. Flow of electricity in a smart grid system

Grid (SG) requires energy storage to stabilise the changing output of renewable energy sources (Salkuti, 2024; Shaukat,2018).

By improving the bi-directional flow of information between consumers and electricity operators in Figure 22., the introduction of smart grid technology offers numerous opportunities to enhance grid operation. Technologies for energy storage offer a lot of potential improvements to the grid's performance and operation. It is ideally suited to react

rapidly and effectively to signals throughout the smart grid due to its capability to provide application-specific energy services across various grid components (Zame et al., 2018).

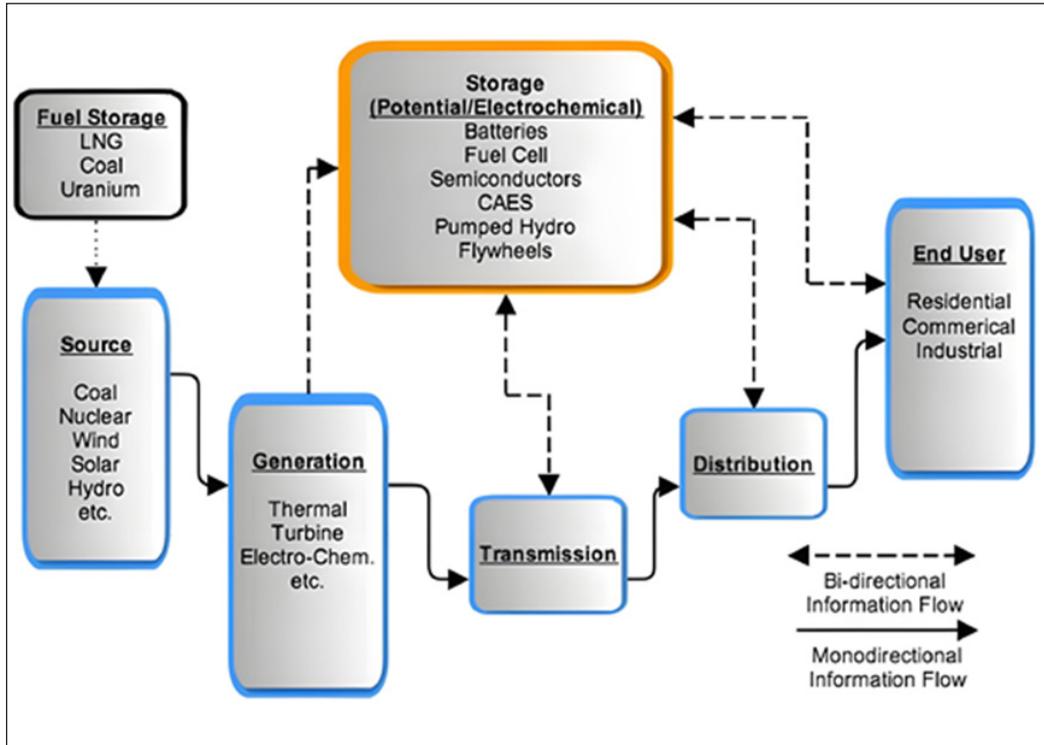


Figure 22. Information flow in an energy storage-based smart grid

Further Development:

- Providing power backup in cases of power outages, energy storage systems have the potential to make the grid more reliable.
- Energy storage systems can cut power expenses by saving energy in off-peak hours and releasing it in peak hours.
- Energy storage systems must be designed with long lifetimes so that they require minimal maintenance and replacement.
- With energy storage technologies, new sources of renewable energy can be brought into the grid. (Salkuti, 2022).

Table 3
Summary of a comparison between Energy Storage Systems (EES's)

Comparison/ EES	Pumped-hydro storage	Compressed air energy storage	Flywheel energy storage	Superconducting magnetic energy storage	Lithium-ion batteries	Flow batteries	Hydrogen energy storage
Energy density (Wh/kg)	Low	Low	Very low	Very low	High	Medium	High
Power density (W/kg)	Low	Medium	Very high	Very high	High	Medium	Low
Efficiency (%)	High	High	High	High	High	High	Low
Lifetime (years)	Long	Long	Medium	Long	Medium	Long	Long
Cost (\$/kWh)	Low	Medium	High	Very high	High	Medium	High
Applications	Peak shaving, load levelling, frequency regulation, renewable integration	Peak shaving, load levelling, frequency regulation, renewable integration	Power quality, frequency regulation, black start	Power quality, frequency regulation, black start	Peak shaving, load levelling, vehicle electrification, renewable integration	Peak shaving, load levelling, renewable integration	Renewable integration, vehicle electrification
Pros	High efficiency, long lifetime, low cost	High efficiency, long lifetime, modular	High power density, fast response time	Very high-power density, fast response time	High energy density, fast response time	Long lifetime, low maintenance	High energy density, long lifetime
Cons	Large land area requirement, slow response time	High capital cost, low power density	Short lifetime, high cost	High capital cost, low energy density	High cost, limited lifetime	Low power density, slow response time	High capital cost, low power density

Table 3 (continued)

Comparison/ EES	Pumped-hydro storage	Compressed air energy storage	Flywheel energy storage	Superconducting magnetic energy storage	Lithium-ion batteries	Flow batteries	Hydrogen energy storage
Note.	$=\rho * g * h * Q$	$0.5 * m * (P2 * V2 - P1 * V1)$	$=\frac{1}{2} * I * \omega^2$	$=0.5 * L * I^2$	$E = V * Q$	=Cell Voltage (in volts) x Flow Rate (in litres per hour) x Electrolyte Volume (in litres)	Mass of hydrogen x Higher Heating Value (HHV) of hydrogen
Mathematical Equations E__{stored}	ρ = the density of the fluid (in kg/m ³) $g = 9.8 \text{ m/s}^2$ h = height difference (in meters) Q = the volume flow rate of the fluid (in m ³ /s)	$P1$ = the initial pressure of the air $P2$ = the final pressure of the compressed air $V1$ = the initial volume of the air. $V2$ = the final volume of the compressed air m = the mass of the compressed air	I = the moment of inertia. ω = the angular velocity	L = the inductance of the inductor I = the current flowing through the inductor	Voltage (in Volts) x Q (in Ampere- hours)		

Table 4
Summary of some Hybrid Energy Storage System (HESS)

Energy Storage System	Advantages	Disadvantages	Applications
Lithium-ion Battery + SuperCapacitor	High power density. Fast response time. Most commonly and most practical used in HESS.	Limited energy density compared to other batteries systems. SuperCapacitors have limited energy storage duration.	<ul style="list-style-type: none"> Renewable energy integration. grid stabilisation, electric vehicle (EV) fast charging.
Compressed Air Energy Storage (CAES) + Battery	High energy capacity. High power output.	Requires significant infrastructure. Energy losses during compression and expansion.	<ul style="list-style-type: none"> Grid-scale energy storage. load shifting. Renewable energy integration.
Flywheel Energy Storage + Battery	Fast response time. high power output.	Limited energy storage duration. High cost compared to other options.	<ul style="list-style-type: none"> Backup power systems. frequency regulation, short-duration energy storage.
SuperCapacitor + Compressed Air Energy Storage (CAES)	High power output. fast response time from SuperCapacitors, coupled with high energy capacity from CAES.	Limited energy density of SuperCapacitors. Energy losses during compression expansion of CAES. Requires significant infrastructure.	<ul style="list-style-type: none"> High-power applications grid. stabilisation, rapid energy release.
Hybrid SuperCapacitors + Fuel Cell	High power output. fast response time from SuperCapacitors. Clean and efficient power generation from Fuel Cell.	Limited energy storage capacity of SuperCapacitors. Complex system integration and control. Higher upfront cost compared to standalone systems.	<ul style="list-style-type: none"> Hybrid electric vehicles (HEVs) portable power systems. backup power for critical applications.
Hybrid BESS + Fuel Cell	High energy storage capacity. Fast response time from BESS. Clean and efficient power generation from Fuel Cell.	Complex system integration and control. Higher upfront cost compared to standalone systems.	<ul style="list-style-type: none"> Microgrids. off-grid power systems. backup power for critical infrastructure.

CHALLENGING OF ENERGY STORAGE SYSTEM

Multiple challenges can affect the implementation and efficiency of energy storage systems. The following are some of the major issues with energy storage systems:

- The cost of energy storage devices is one of the main obstacles.
- The storage capacities and durations of various energy storage methods vary.
- Energy storage systems are not simple to scale up to meet large-scale grid demands.
- The environmental implications of energy storage systems are a critical point to consider.
- Energy storage systems need to be made reliable and secure.
- Market design and regulatory conditions are key drivers that influence the deployment and economic viability of energy storage systems.

CONCLUSION

In this paper, the most important features of the new ways of storing energy have been researched and made for smart grid power systems summarised in Table 3 & Table 4. It provides a comparative analysis that addresses various topics and describes the most significant parameters that define the behaviour of various energy storing technologies. Renewable energy sources like wind and solar and others can't meet energy demands sometimes because of fluctuation of weather conditions during the day which can produce limited electrical generation. Energy storage technologies are a solution that can be integrated into the power system in combination with other sources of renewable energy, increased the share of energy derived from renewable sources, promoted efficient usage, helped balance supply and demand, reduced greenhouse gas emissions, minimised grid connection costs, and enhanced the management and controlled of the power system. These recommendations may aid in ensuring the maturity of HESS-integrated RE systems because RESs and Energy Storage are anticipated to rule the electricity market in the future. These recommendations may also be a strong starting point for future HESS development towards optimal and affordable green energy for energy system researchers. In conclusion, it appears that the implementation of HESSs will be a future-proof choice for a range of RE applications. To show their practicality and enhance their utility for green energy and sustainable development, however, more research and development is needed.

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