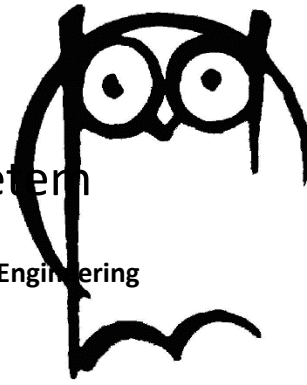


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Comparison and Evaluation of Solar Power Storage Systems

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ABSTRACT

Given the sun's abundance, solar power is on the rise, but energy storage has been a challenge since the beginning of the renewable energy revolution. Recent developments in various technologies, however, have presented encouraging prospects for addressing this problem. These technologies can store extra solar energy throughout the day, allowing it to be used during periods of low sunshine or at night, making solar power a more stable and consistent source of electricity. Energy storage can be a way to flatten the daily load curve (duck curve) and resolve energy demand-supply problem.

The goal of this paper was to find and examine different technologies that are already in use for storing energy. Based on their power rating, storage capacity, durability, charge and discharge time, the technologies would be compared and evaluated for a photovoltaic system. The area of application was also discussed, this includes household, small business owners, industrial and commercial use, and integration of different sources of solar power.

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1.0 INTRODUCTION

The sun has been shining for the whole duration of human life. As far as stars go, the Sun is average in diameter, mass, and brightness. The energy output of the sun has remained constant during the past two billion years. The sun is therefore the major source of energy to earth.

Photovoltaic energy is one of the most promising sources of energy [1]. Photovoltaic power generation is gaining increasing importance as a renewable energy supply [2]. The control of the transmission and distribution system is being negatively impacted by the rapid growth of PV power in regions with high shares of PV power connected to the grid, commonly described in a graph called “the duck curve”.

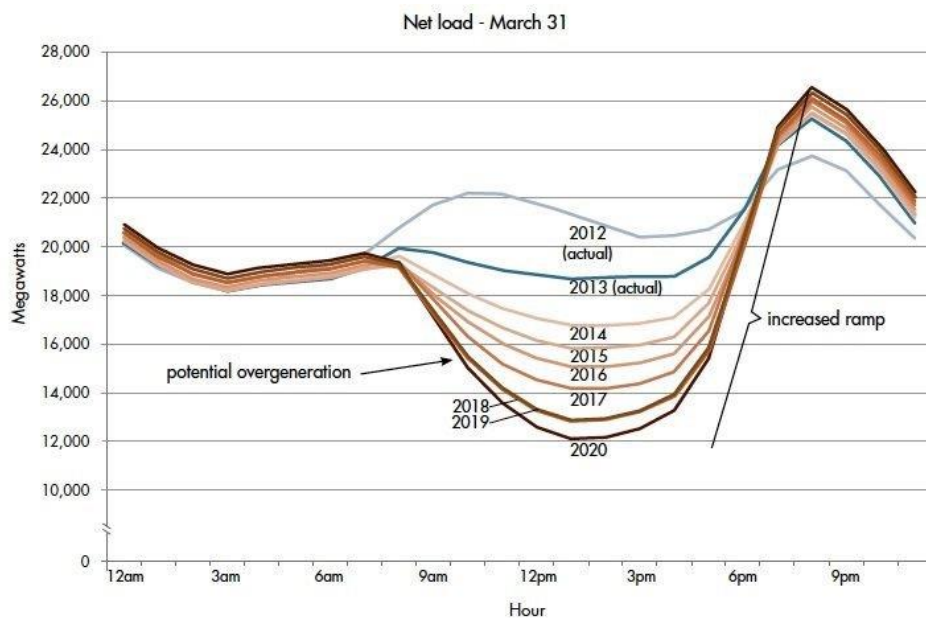


Fig.1.1. The Duck Curve¹

One potential strategy for addressing this phenomenon is the storage of solar energy during periods of surplus power in the electrical grid, which can then be subsequently supplied to the grid at peak periods of the daily load curve [3]. Regardless of the way these limiting efforts are carried out, it is becoming increasingly evident to all parties that energy storage will play a crucial role in boosting the integration of variable renewable sources into global power infrastructures. Based on the figure below, we can see how the daily demand curve is reduced using battery and PV system.

¹ <https://www.energy.gov/eere/articles/confronting-duck-curve-how-address-over-generation-solar-energy>

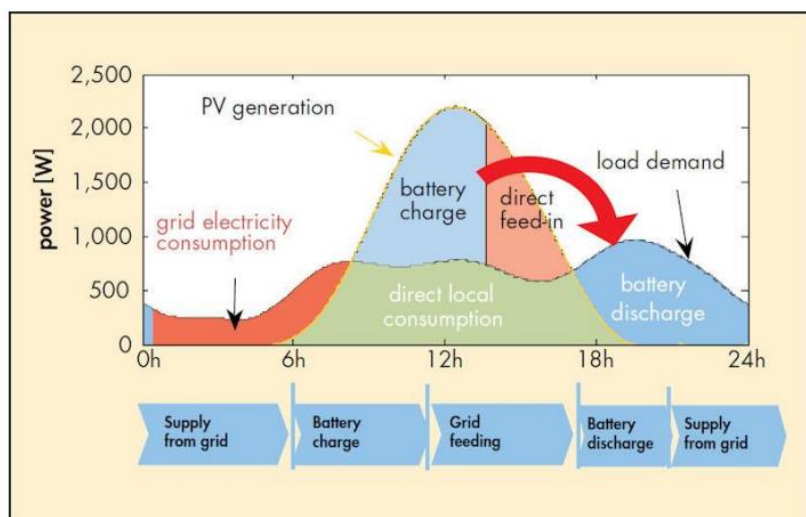


Fig. 1.2 peak demand reduction with PV system and battery storage²

Strategically implemented storage technologies have the potential to reduce peak demand, enhance daily operational dependability, offer backup power during generation disruptions, alleviate load balancing difficulties, lower costs for consumers and utility providers, minimize emissions, and facilitate the integration of distributed and renewable energy sources into the power grid [4]. The aim of this paper is to compare and evaluate the different methods of solar energy storage and suggest the most suitable storage method for both small and large scale.

2.0 Solar Power sources and uses.

2.1 PV (Direct electricity from sunlight)

Photovoltaics (PV) is a widely utilized technology that harnesses solar energy by means of photovoltaic cells, which effectively convert sunshine into electrical power. The constituent parts of these cells include semiconductors, notably silicon, which possess the capability to absorb photons originating from sunshine. When incident photons hit upon the surface of the photovoltaic (PV) cell, they release electrons from their atomic orbits, generating an electric current. Subsequently, said electric current can be effectively utilized and employed as a sustainable and environmentally friendly energy resource. In photovoltaics (PV), the direct current (DC) is transformed into alternating current (AC) by the utilization of an inverter. The function of the inverter is to transform the direct current (DC) generated by the photovoltaic (PV) cells into alternating current (AC), which is the predominant form of electrical energy utilized in residential and commercial settings. This conversion facilitates the smooth

² <https://www.solarpowerworldonline.com/2013/02/solar-white-paper-peak-demand-reduction-using-battery-storage>

integration of the photovoltaic (PV) system with pre-existing electrical networks, enabling the provision of power to a wide range of devices and appliances.

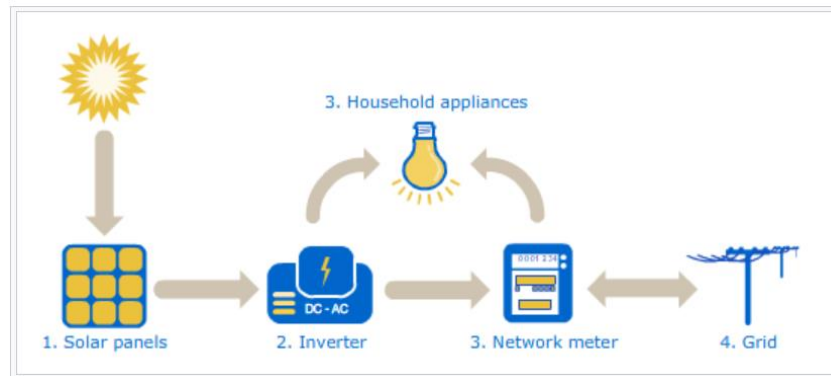


Fig. 2.1 Residential grid-tied solar PV system diagram³

2.2 Concentrated solar power (CSP)

Concentrated Solar Power (CSP) plants are a type of thermal power system built to use direct solar irradiation. These plants concentrate solar energy, converting it into heat and subsequently converting the heat into electricity.

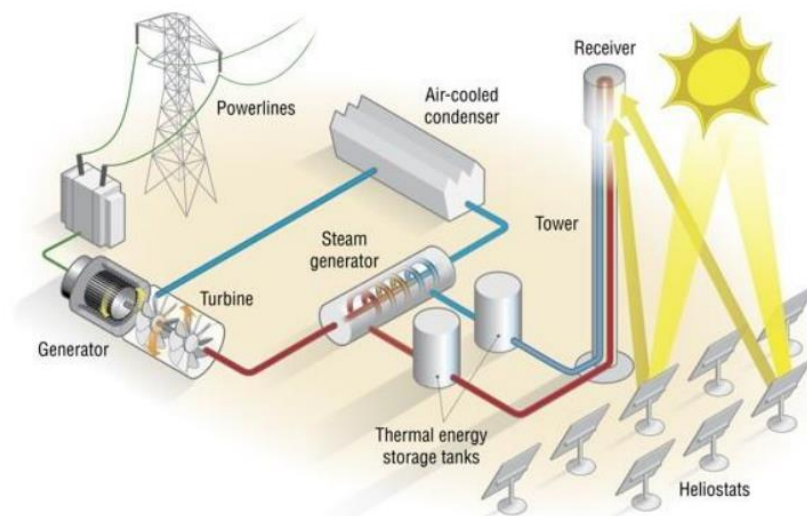


Fig. 2.2 CSP system analysis⁴

Concentrated Solar Power (CSP) plants have resemblance to conventional thermal power plants, with the primary distinction lying in the heat source utilized. Rather than relying on combustive fossil fuels, CSP plants harness solar irradiation as their primary source of heat. Mirrors are utilized to focus solar radiation, resulting in the concentration of solar energy. This

³ https://energyeducation.ca/encyclopedia/Photovoltaic_system

⁴ <https://www.energy.gov/eere/solar/concentrating-solar-thermal-power-systems>

concentrated energy is then used to heat a heat transfer fluid (HTF). The heat transfer fluid (HTF) is then used in the production of steam by undergoing a heat exchange process via a heat exchanger. Steam is subsequently utilized to produce energy through the utilization of a steam turbine [28].

Heat can also be held using a High Temperature Fluid (HTF) known as molten salt, which is contained in storage tanks. Molten salts are characterized by their ability to maintain a liquid state within a temperature range of 300°C to 500°C.

2.3 Integration of PV and CSP

The integration of concentrated solar power (CSP) and photovoltaic (PV) technologies in hybrid solar power plants offers a significant advancement in the optimization of energy production. The combination of concentrated solar power (CSP) thermal energy storage and photovoltaic (PV) direct electricity production enhances the availability and uninterrupted power generation of these hybrid systems, irrespective of weather conditions or the time of day [29]. The integration of the PV system enables the effective use of solar energy over the whole day-night cycle. This is made possible by the storage system's capacity to accumulate surplus heat generated during daylight hours, which may subsequently be transformed into electrical energy later. Moreover, the incorporation of concentrated solar power (CSP) and photovoltaic (PV) technologies in hybrid solar power plants enhances overall efficiency and reduces expenses through the optimization of accessible resources [30].

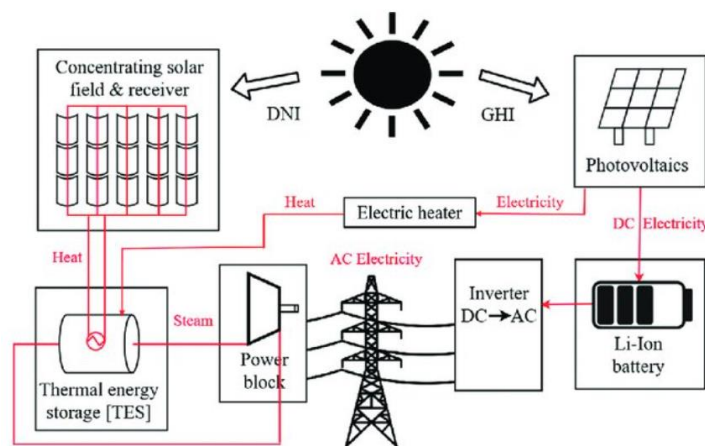


Fig.2.3 combination of PV and CSP⁵

3.0 Energy storage technologies

Because it costs a lot to store electricity, many different types of storage have been created, Mechanical energy, such as that found in pumped hydro system (PHS) and flywheels, can be used to store energy. This energy can also be saved as compressed air energy storage (CAES) and thermal energy storage (TES), and in the form of electrochemical energy all types of batteries and chemical storage in the form of hydrogen (fuel cells). One last way of storing energy is electromagnetic energy that includes super conducting Magnetic energy systems (SMES) as shown in figure 2.0.

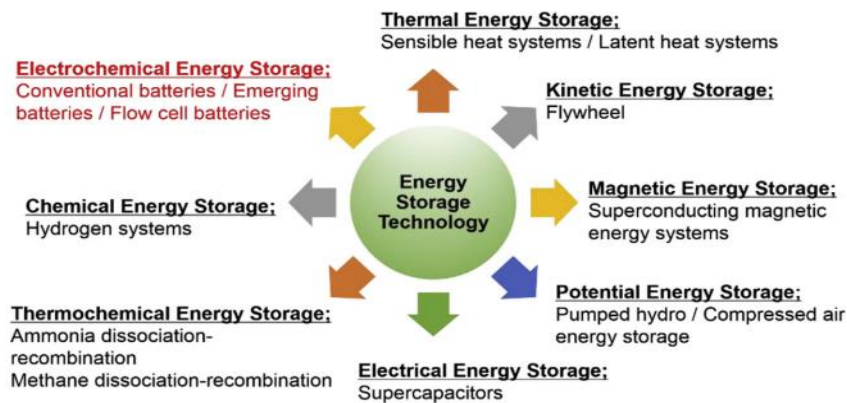


Fig. 3.0 Energy storage technologies [47]

3.1 Mechanical Energy Storage

3.1.1 Flywheels

Flywheels store energy in the form of kinetic energy and are commonly used in various applications such as energy storage systems and transportation. They work by spinning a rotor at high speeds, which stores the energy in its rotational motion. This stored energy can then be released when needed, providing a reliable and efficient source of power. Flywheel-based energy storage systems are suitable whenever numerous charge and discharge cycles are needed with medium to high power during short periods (seconds) [5]. Flywheels offer several advantages over other energy storage methods, including high power density, fast response times, and long cycle life. They are also environmentally friendly as they do not produce any emissions during operation. Flywheels exhibit rapid response times for both charging and discharging operations; however, they are limited in their ability to store large amounts of energy (see Figure 3.1.1). This characteristic renders them more appropriate for grid quality control. In addition, they exhibit low resistance to external mechanical impacts that cause vibrations and subsequently lead to power loss, results in major changes in both the amplitude and frequency of the output voltage [6].

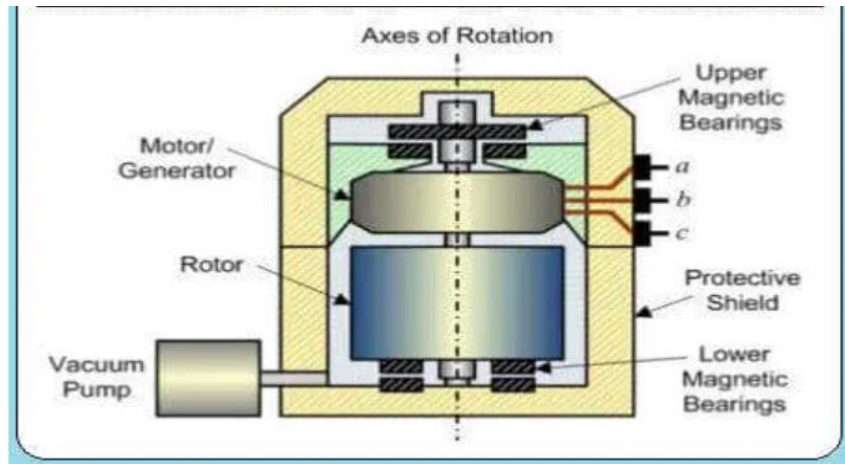


Fig.3.1.1. Flywheel energy storage device.⁶

3.1.2 Pumped Hydro Energy Storage (PHES)

Pumped hydro energy storage is the predominant energy storage method utilized inside energy systems on a significant scale [7]. It involves using excess electricity to pump water uphill into a reservoir, and then releasing the water downhill through turbines to generate electricity when demand is high. Pumped hydro storage systems have a long lifespan and can provide large amounts of energy for extended periods of time, making them an important component of grid stability and renewable energy integration.

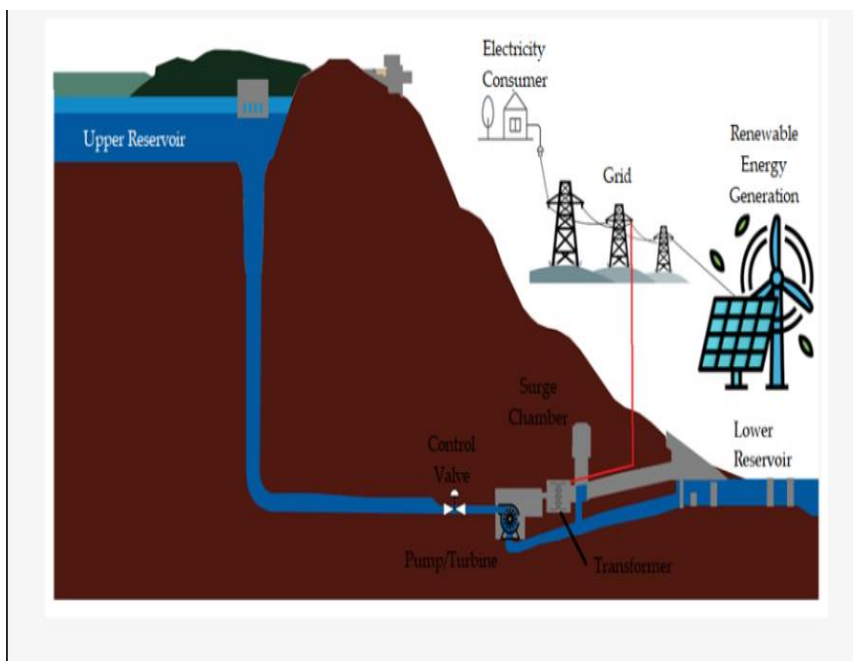


Fig 3.1.2. Schematic diagram of a pumped hydro storage plant⁷

⁶ https://electricalfundablog.com/flywheel-energy-storage-calculations-rotor/?utm_content=cmp-true

⁷ https://en.wikipedia.org/wiki/Pumped-storage_hydroelectricity

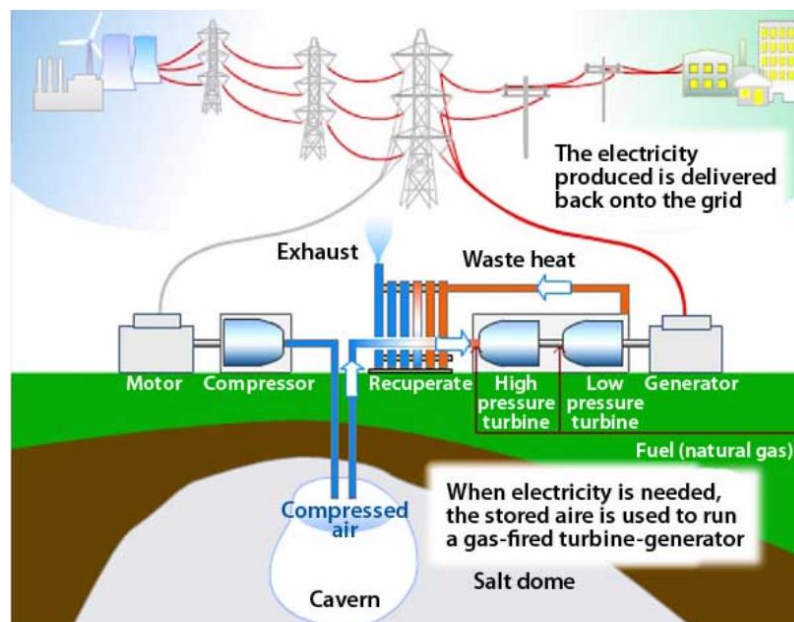
Due to its large capacity, PHES is used in storing and producing energy on a large scale, but it has the geographical challenge as it requires some geographical features like good elevation difference and access to water source. The installation of pumped hydro storage plants might incur high expenses because of the requirement for substantial infrastructure.

Notwithstanding these limitations, pumped hydro storage continues to be a key technology for ensuring the dependability of power grids, facilitating the incorporation of renewable energy sources, and enabling large-scale energy storage.

3.1.3 Compressed air energy storage (CAES)

Compressed air energy storage (CAES) has been widely recognized as a well-established and very promising technique for the storage of energy on a large scale [9]. It is considered one of the most mature technologies for grid-scale storage.

A-CAES is a highly efficient and environmentally friendly method for integrating renewable energy sources and managing peak energy demands. This technology is characterized by its substantial capacity, efficient operation, and little carbon emissions [8]. The system has the capability to store and release energy through the compression and expansion of air, without relying on a thermal fluid.



*Fig. 3.1.3. How a CAES works.*⁸

⁸ <https://www.powermag.com/revived-energy-storage-technology-offers-major-grid-benefits>

3.2 Electrochemical Energy Storage

Electrochemical energy storage is a key part of making sure that renewable energy sources are stable and reliable. It does this by storing excess energy when production is high and releasing it when demand is high. Additionally, progress in this area has led to the creation of batteries that perform better and cost less, which makes them perfect for powering portable electronics and accelerating up the acceptance of electric transportation [10]. Electrochemical storage devices can be in the form of batteries, supercapacitors, and fuel cells(hydrogen).

3.2.1 Supercapacitors

Supercapacitors, which are also called ultracapacitors or electrochemical capacitors, are energy storage devices that are getting a lot of interest because of their high-power density, have a long lifespan, and charge and discharge quickly. Instead of chemical reactions, supercapacitors store energy by separating positive and negative charges on the electrodes' surfaces. Because of their special way of working, supercapacitors can store and release energy quickly and efficiently. This makes them perfect for uses that need short bursts of power, like electric cars and regenerative braking systems [11].

3.2.2 Hydrogen fuel cells

Hydrogen (H_2) is the most abundant element in the universe (75%), the lightest, and the one with the highest density (ρ) of energy around 120 kJ/g. Hydrogen is not considered a sustainable energy source; rather, it serves as a means of storage and energy delivery. It can be derived from either renewable sources or fossil fuels. Hydrogen gas (H_2) has a high degree of versatility due to its ability to be stored in large amounts and its nonpolluting nature. The combustion of hydrogen only releases moisture, hence exhibiting an acceptable environmental impact [6].

Fuel cells are electrochemical devices that facilitate the conversion of chemical energy that's present in a fuel, such as hydrogen, into electrical energy by means of an electrochemical process. These devices possess notable attributes such as great energy efficiency, low emissions, and reduced operational noise, rendering them appealing for a wide range of uses, including mobility, stationary power generation, and portable electronics. Fuel cells possess the capacity to fundamentally transform the way we generate power for our vehicles and households. This is because of the way they generate electricity without involving the process of combustion, so leading to a decrease in the emission of greenhouse gases and an enhancement in the quality of air. In addition, fuel cells possess the benefits of easy refueling and extended lifespans in comparison to conventional batteries, rendering them a highly attractive prospect for the

attainment of a sustainable energy future [12]. The utilization of hydrogen in fuel cells currently constitutes a very little proportion in the market, although it holds significant potential for future expansion.

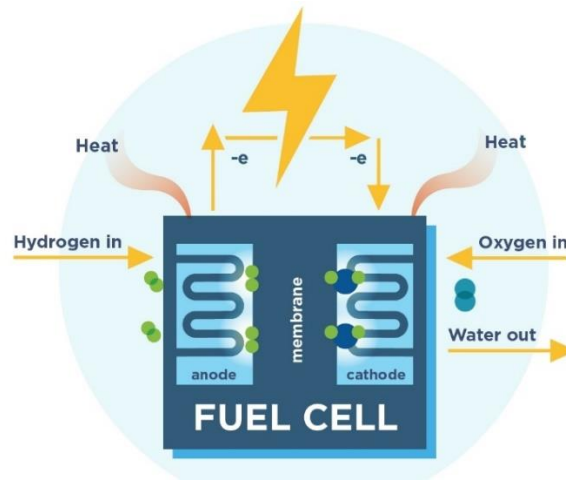


Fig. 3.2.1. Hydrogen fuel cell⁹

3.2.3 Conventional batteries

Battery storage plays a crucial role in the utilization of solar power by addressing the intermittent nature of solar energy [13]. The integration of battery systems with solar power offers numerous benefits, including managing peak demands, improving grid reliability, and facilitating the integration of renewable energy sources. Several types of batteries are being explored for grid applications.

Sodium-sulfur batteries are commercially available, has a high energy density and also field proven and have been used for grid-scale energy storage, but one challenge is the shuttle effect, which refers to the migration of polysulfide species between the cathode and anode during charge and discharge cycles, and also sodium sulfur has a high operating temperature, this can lead to capacity loss and poor cycle life, although, strategies to immobilize polysulfides and prevent their migration have been explored to mitigate this issue [14].

The power output of a Redox flow battery can be easily adjusted by changing the size of the electrode and the flow rate of the electrolyte, allowing for more flexibility in meeting different power demands. Redox-flow batteries offer the advantage of scalability and suitability for a large-scale storage, but it has a low energy density and expensive compared to other batteries [15].

⁹ <https://www.fchea.org/h2-day-2019-events-activities/2019/8/1/fuel-cell-amp-hydrogen-energy-basics>

Lead acid batteries are the most used in energy storage including PV system, it is the oldest rechargeable battery in existence, widely available, deep discharge capability, good performance at high and low temperatures, cheap and easy to manufacture and suitable for off grid application [16]. However, it has low specific energy, long charge and not environmentally friendly [6].

Maybe the most spreading type of batteries now is Lithium ion, although the lithium element is rare, but it is the most used currently. They can be made smaller and lighter, has a high energy density and low self-discharge rate [17]. It can overheat and cause an explosion if not properly managed, long time availability of Lithium is not ensured [18].

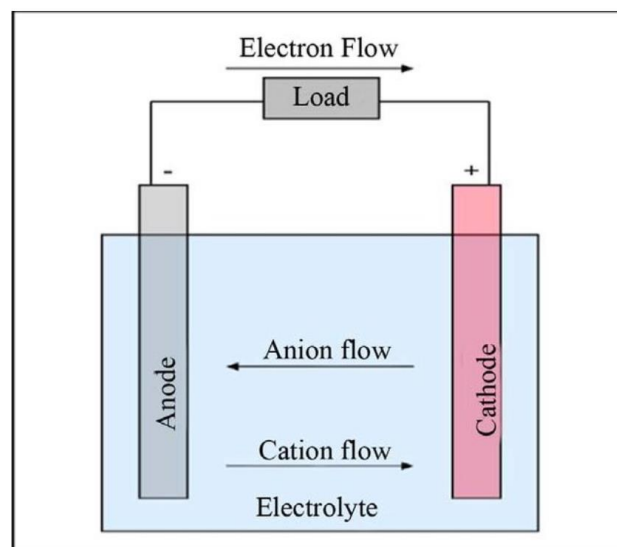


Fig. 3.2.3 Operation of a battery [31]

3.3 Thermal Energy Storage (TES)

Thermal energy storage (TES) is mostly used in concentrated solar power plant, In the field of thermal energy storage (TES), materials are commonly classified into three distinct categories: sensible heat storage (SHS), latent heat storage (LHS), and thermochemical heat storage (THS). Sensible heat storage encompasses materials such as water, air, oil, rocks, brine, concrete, sand, and soil. It involves storing thermal energy within the storage medium by increasing temperature without undergoing any phase transformation [25]. Latent heat storage involves the use of organic and inorganic substances, eutectics, and low-melting-point metals. It is important to think about the materials and uses of phase change energy storage to figure out the cost, power density, and discharge time of latent heat storage. Phase change materials (PCM), also referred to as latent heat storage, are favored over sensible storage due to their

notable storage density and limited phase transition range [19]. Phase change materials (PCMs) are very important in latent heat thermal energy storage systems (LHS) because they can take in, store, or release a lot of latent heat through changes in phase [23]. Nevertheless, phase-change materials (PCMs) exhibit the drawback of possessing low thermal conductivity. Both sensible and latent heat storage systems have the capability to store heat for a specific duration, often lasting a few hours. These thermal energy storage (TES) systems are incapable of retaining energy for an extended duration, such as a whole season. Specifically, they lack the ability to accumulate excess energy during the summer months, characterized by longer periods of sunlight, and subsequently utilize this stored energy throughout the winter season. In terms of achieving the desired objective, THS is considered a more feasible option due to its utilization of high-energy-intensive endothermic processes [20]. The gas-solid reaction is used in thermochemical heat storage methods. Thermochemical heat storage (THS) exhibits considerable potential as a method for the effective conversion and storage of underutilized thermal energy. It presents numerous benefits in comparison to alternative energy storage methods, including a relatively high energy density which can reach levels up to ten times higher than that of latent heat storage. and the ability to store energy for extended periods of time at ambient temperature conditions [22]. Thermochemical heat Storage (THS) possesses the capability to be employed in forthcoming power generation facilities that operate at elevated temperatures.

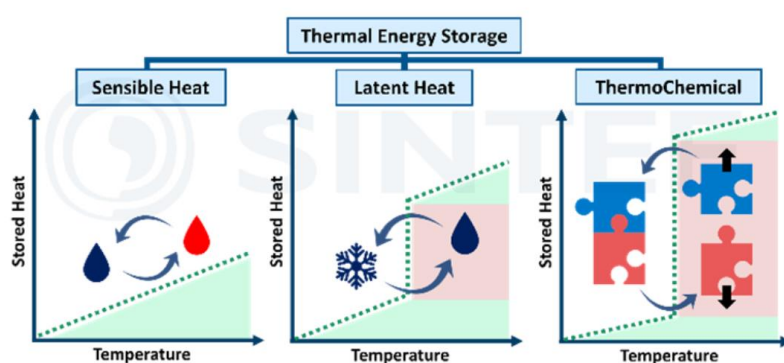


Fig. 3.3 Classification of TES systems and the heat stored with temperature variation.¹⁰

The considerable energy density exhibited by THS systems renders them suitable for applications such as power grid support and seasonal solar thermal energy storage. Furthermore, thermochemical storage (THS) systems exhibit minimal long-term storage losses

¹⁰ <https://blog.sintef.com/sintefenergy/thermochemical-energy-storage-the-next-generation-thermal-batteries/>

due to the chemical potential at which the energy is stored, and the sensible heat of the elements is weak [21].

3.4 Magnetic energy storage

Superconducting magnetic energy storage (SMES) is an energy storage system that stores energy in the form of DC electricity by passing current through the superconductor and stores the energy in the form of a DC magnetic field.

The utilization of magnetic energy storage systems has garnered a lot of interest owing to its potential in boosting the efficiency and durability of power systems, particularly when integrated with renewable energy sources. Superconducting Magnetic Energy Storage (SMES) has been identified as a very promising technology for energy storage due to its ability to provide rapid reaction and achieve high energy density. Furthermore, the implementation of Superconducting Magnetic Energy Storage (SMES) has been suggested as a means of stabilizing power flow in microgrids that incorporate solar generating [26]. Moreover, the significance of Superconducting Magnetic Energy Storage (SMES) in boosting the performance of dynamic systems has been confirmed, highlighting its potential to increase the stability and dependability of power systems [27].

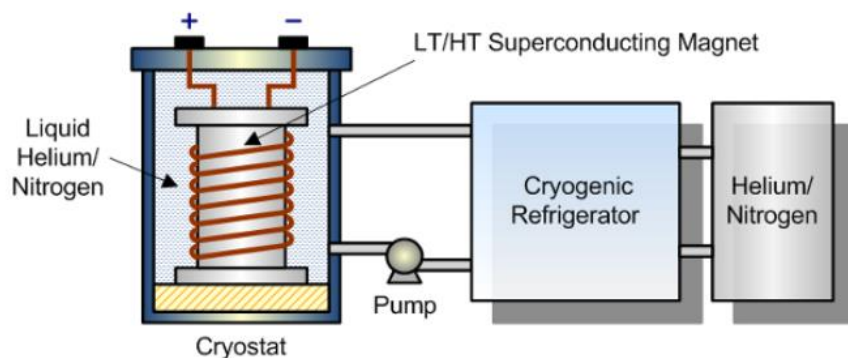


Fig. 3.4 Illustration of an SMES SYSTEM¹¹

¹¹ <http://www.eseslab.com/ESsensePages/SMES-page>

4.0 Methods used

All these storage technologies have distinct characteristics that differentiate them from one another and make them more suitable for specific applications.

This review will be conducted to analyze and compare various technological characteristics. It is important to point out that certain technologies are still in the research phase, so all their characteristics are therefore not yet available. As shown in the table below. Bases for the comparison were the sources [31][32][6][33].

5.0 Result and Discussion

First, the tables for the comparison of the characteristics of storage options follow, then the pro-con analyses of these storage options and the evaluation for two large application fields.

5.1 Characteristics of energy storage options

Table 1 Characteristics of mechanical energy storage options

Energy storage technology	Energy Efficiency (%)	cost	Discharge time	Self-discharge per day	Energy Density (Wh/kg)	cycle life	Power rating (MW)
- Flywheel	- 95	-	- Milli-seconds-15min	- 100%	- 100-130	- >125,000	- 0-1
- PHES	- 65-80	- \$1700-\$5100/kW	- 1-24h+	- Very small	- 0.3	- 75years	- 100-5000
- CAES	- 50	-	- 1-24h+	- small	- 10-30	- 40years	- 5-400

Table 2 Characteristics of electrochemical storage options

Energy storage technology	Energy Efficiency (%)	cost	Discharge time	Self-discharge per day	Energy Density (Wh/kg)	cycle life	Power rating (MW)
- Lead acid	- >70	-	- Seconds-hours	- 0.1-0.3%	-	-	- 0-20
- Lithium ion	- ~90	- \$2500-\$3900/kW	- Minutes-hours	- 0.1-0.3%	-	-	- 0-100kW
- Sulphur Sodium	- 75-90	-	-	-	-	-	-

- Redox flow	- 82	-	- Seconds-hours	- small	-	-	- 30kW-3MW
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Table 3 Characteristics of electrical storage options

Energy storage technology	Energy Efficiency (%)	cost	Discharge time	Self-discharge per day	Energy Density (Wh/kg)	cycle life	Power rating (MW)
- Super-capacitor	95				<50	10k – 100k	
- SMES	- >95	- 1000-10000 \$/kWh	- Milli-seconds to minutes	- Very high	- 20 MW/hr	- 20+ years	- 20-40MW - [46]

Table 4 Characteristics of Power to Gas storage options

Energy storage technology	Energy Efficiency (%)	cost	Discharge time	Self-discharge per day	Energy Density (Wh/kg)	cycle life	Power rating (MW)
- Hydrogen fuel cells	-	-	- Seconds-24h+	- Almost zero	-	-	- 0-50MW

Table 5 Characteristics of thermal storage options

Energy storage technology	Energy Efficiency (%)	cost	Discharge time	Self-discharge per day	Energy Density (Wh/kg)	cycle life	Power rating (MW)
- Thermal (thermo-chemical)	- 80-90	-	- hours	-	-	- 30 years	- 150 MW

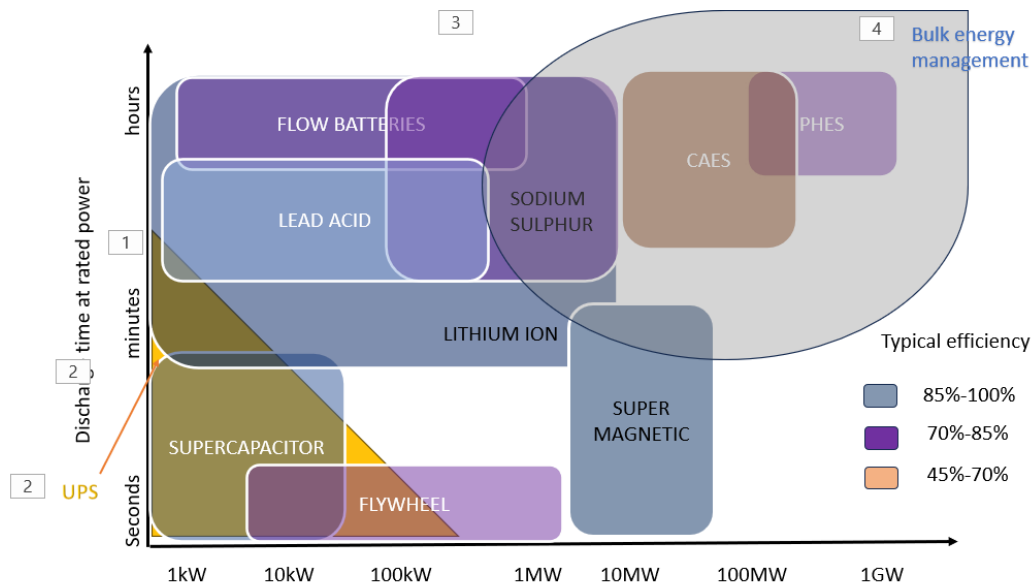


Fig. 5.1 Energetic properties and usage fields of storage options [own compilation]

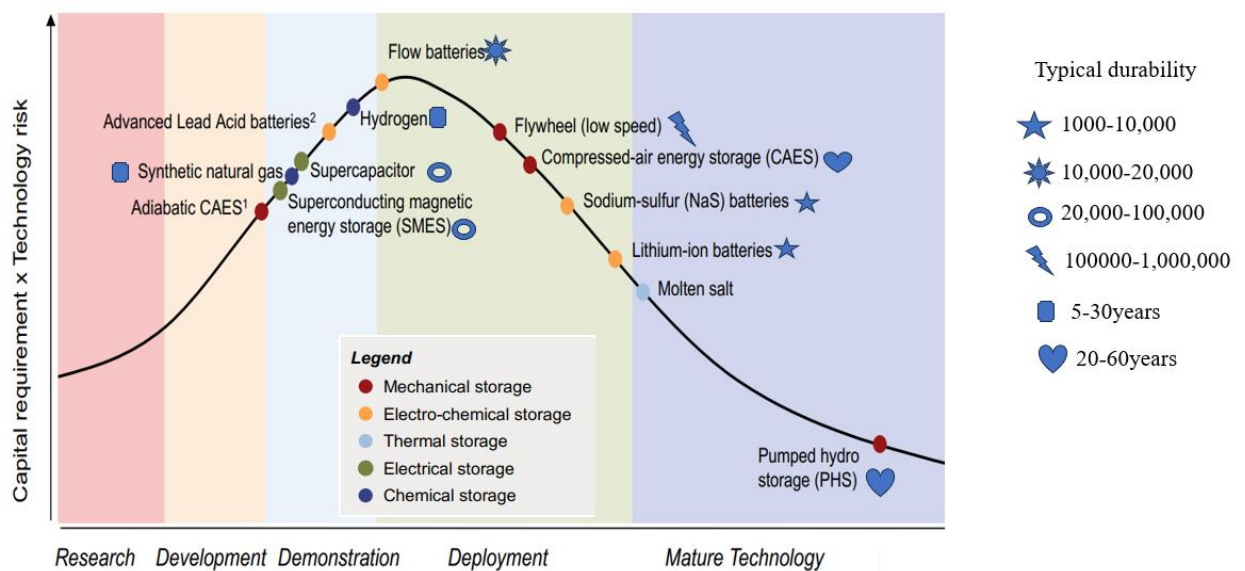


Fig. 5.2 Maturity and durability of storage technologies

5.2 Pro-Con Analysis of mechanical energy storage options

Table 6 Pro-Con Analysis of mechanical energy storage options

Technologies	Pros	Cons
Flywheel	- Effective for load levelling and shifting. - Low maintenance - High energy density - Fast response time [34]	- Not suitable for long term energy storage - Need for permanent magnet in the rotor. - Deep discharge cannot be achieved [35]
PHES	- - Large scale storage - - low operating cost - - long lifetime - - water supply and flood control	- -geographical challenge - -high startup cost - -energy losses - -impact on water quality in the environment [36]
CAES	- -better air quality - -reduced maintenance cost - -increased energy savings [37]	- -low efficiency - -slow response time

Table 7 Pro-Con Analysis of electrochemical storage options

Technologies	Pros	Cons
Lithium ion	- - Can be made smaller and lighter - -high energy density - -low self-discharge rate	- -Thermal runaway - - Rare element
Lead acid	- -wide availability - -deep discharge capability - -suitable for off-grid application	- -No maintenance - -cheap and easy to manufacture - -Good performance at high and low temperatures
Sodium sulfur	- -commercially available - -high energy density	- -Shuttle effect - - High operating temperature
Redox flow	- -long lifecycle - -suitable for large scale storage	- -Limited life cycle - -high maintenance requirements - -low energy density

Table 8 Pro-Con Analysis of electrical storage options

Technologies	Pros	Cons
Supercapacitors	- high rate of charge and discharge - improved safety, low toxic materials - low cost per cycle - fast response time - long lifespan [38]	- high self-discharge - cannot be singly implemented, except in series connection to other capacitors - low energy storage capacity
SMES	- High efficiency - Fast response time - Near-zero losses - High power Full discharge	- High cost of operation

Table 9 Pro-Con Analysis of Power to Gas storage options

Technologies	Pros	Cons
Hydrogen fuel cells	- hydrogen is readily available - high energy density - almost zero emission - long usage time [39]	- hydrogen extraction - high cost - highly flammable [39]
Super magnetic energy storage (SMES)	-	- High cost of operation

Table 10 Pro-Con Analysis of thermal storage options

Technologies	Pros	Cons
Latent heat storage	- high energy density - low storage temperature range - little pressure change of heat storage [40]	- limited storage capacity - low thermal conductivity
Sensible heat storage	- cost effective e.g., water tank storage or underground storage systems - simpler design compared to latent heat storage [41]	- lower energy density - limited temperature range - reduced efficiency if using solely SHS [41]
Thermochemical storage	- energy can be utilized as it is created [42] - negligible thermal losses - long term storage	- frequent maintenance and monitoring [42] - complex system structure [43] - material compatibility and corrosion [44]

5.3 Applications

5.3.1 Small scale applications (household and small businesses)

The daily consumption patterns of residential households exhibit a range of fluctuations. Typically, there are two distinct periods of high consumption observed: one occurring in the morning between the hours of 6 and 8, and another taking place in the evening at approximately 20 hours. The observed peak largely arises because of the population's active working period. During the morning peak, there is a notable surge in household demand as individuals wake and engage in various chores, such as showering, cooking breakfast, and preparing for their daily work or educational commitments. Likewise, the evening peak manifests because of individuals' reentry into their residences following their daily engagements, resulting in an upsurge in energy consumption for activities such as meal preparation, use of electronic devices, in addition to using grid electricity, a hybrid system can be used to better control usage. The implementation of a hybrid system supports the integration of renewable energy sources, such as solar power, thereby enabling a reduction of energy consumption derived from the grid. With the utilization of solar energy during daylight hours, homeowners and small business owners can minimize their dependence on conventional electricity sources and potentially decrease their overall energy expenses. Furthermore, the capacity to effectively oversee and track consumption patterns via a hybrid system offers significant data for enhancing energy utilization and generating well-informed decisions regarding future energy investments.

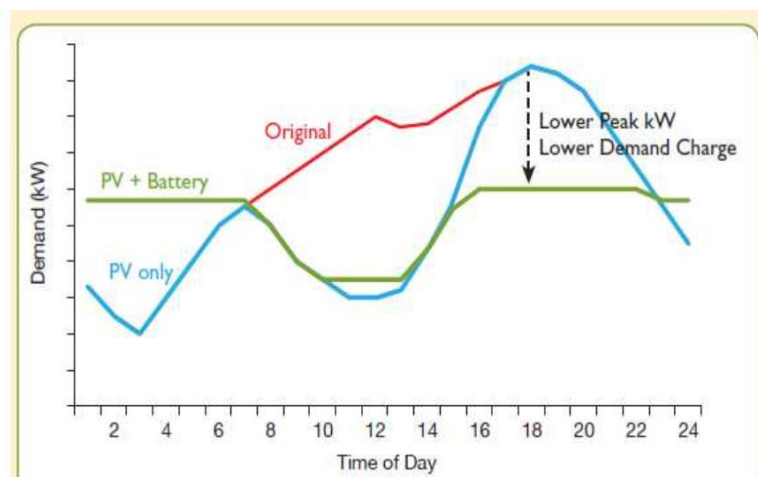


Fig. 5.3.1 Peak demand reduction with PV system and battery storage¹²

¹² <https://www.solarpowerworldonline.com/2013/02/solar-white-paper-peak-demand-reduction-using-battery-storage>

5.3.2 Large scale (industrial and commercial)

To assess the influence of storage on commercial and industrial applications, it is imperative to consider the specific daily consumption profile being targeted. This profile can vary significantly depending on the nature of the application in question. It can be proposed that the highest level of consumption in commercial and service buildings occurs throughout the period of 9:00 AM to 7:00 PM. In the context of various industries, it is important to note that the peak consumption levels may vary, depending on the specific industry in question. There are those that engage in a continuous work schedule of 24 hours per day, 7 days per week, while others adhere to a more conventional work schedule of 9 hours from 9 am to 6 pm, 5 days per week.

To achieve balance, it is necessary to incorporate a hybrid system consisting of photovoltaic panels and batteries, especially hydrogen fuel cells mostly because of its high efficiency, low emission, and large storage capacity. In the context of an industrial application, the contracted power of 100 kW for example, the power supply in question would remain uninterrupted for a duration of 24 hours, concerning industries that work during nighttime or those who operate from 9-18hours. In the latter case, there would be an additional residual usage of around 6 kW. Residual consumption covers some equipment that stays active throughout the night.

In the scenario of an industry operating continuously, a suitable strategy would involve the implementation of a hybrid system that combines direct energy consumption with the utilization of photovoltaic panels. This system would not only facilitate the direct utilization of energy but also incorporate battery storage capabilities. The batteries would experience discharge throughout the night period, specifically between the hours of 16:00 and 24:00. During off-peak hours, particularly between 0:00 and 7:00, it is preferable to use the grid as the cost of energy currently frame is somewhat lower.

The optimal method for commercial solar energy storage is the utilization of pumped hydro storage. The technology exhibits a notably efficient method for storing energy at a substantial scale, possesses a prolonged lifespan, and demonstrates the capability to retain energy stored over extended periods, potentially spanning several decades. Furthermore, pumped hydroelectric storage systems possess the capacity to promptly adapt to fluctuations in energy demand, rendering them exceptionally versatile and dependable for commercial utilization. Moreover, this technology exhibits an environmentally conscious characteristic as it does not

generate any gas emissions while in operation, so making a valuable contribution towards the attainment of a sustainable energy future.

The next example makes it clear where pumped hydroelectric storage systems stand in comparison to other ways to store energy. PHS systems in the USA made up 93% of utility-scale storage power capacity and over 99% of electrical energy storage in 2019. They were responsible for 553 GWh of energy storage. When all utility-scale energy storage projects, like batteries, flywheels, solar thermal with energy storage, and natural gas with compressed air energy storage, were added together by the end of 2019, they only added up to 1.6 GW of power capacity and 1.75 GWh of energy storage capacity. In terms of power capacity and energy storage capacity, these numbers show how important pumped hydroelectric storage systems are in the United States [45].

6.0 Conclusion/Summary

Having compared and evaluated these technologies considering things like power rating, storage capacity, frequency of charging and discharging, efficiency, reaction time, area of application and every limitation that affect the amount of power and energy needed.

The PV system makes the most energy when it is in direct sunlight. Because of this, not all systems of storage can be used in this way.

We looked at everything that makes up the different storage methods and how much they cost. In the end, we decided that conventional and flow batteries are the most efficient ones for a PV system.

Lead acid, NaS, Li-ion, and redox flow batteries are all types of regular batteries. Most of the time, lead acid batteries are used in fixed jobs and PV systems. Even though lithium batteries have a lot of promise, they are still very expensive. Because they have a high specific energy, they can only be used in small-scale uses, mostly on mobile devices.

For flywheels, the cost of the installation is lower, but the cost per unit of energy capacity is high. The prices for pumped hydro, compressed air, and batteries are more even, but the prices for batteries vary a lot for every fixed amount of power.

Pumped hydro storage (PHS) utilizes two vertically separated water bodies. Low-cost electricity is used to push water from the lower to the higher reservoir using a pump and turbine

or reversible pump turbine. In times of high demand, it functions as a hydro power plant, releasing water to power turbines and generating electricity.

Efficiency averages 70%–85%. Most losses occur in the pumping and turbine stages, which are 92% efficient, and to a lesser level in transformers, motors, generators, and shaft lines. Typically, pumped hydro storage systems may attain maximum power load within minutes, with reaction times in seconds. The traditionally suitable site is adversely affected by PHES' high elevation differences across reservoirs. Although underground reservoirs are under investigation to prevent this issue.

Pumped hydro is the most mature energy storage technology, followed by CAES. Pumped hydro is the greatest grid energy storage method globally and has been used for decades. However, CAES has multiple active facilities worldwide and is a reliable and efficient energy storage system.

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