Narrative Review Article

Comparison of Solar Energy Storage Methods and Their Implications on Integration with Renewable Energy

Johnson Ye

Kent School, 1 Macedonia Road, Kent, CT 06757, United States

ABSTRACT

Decarbonizing the electrical grid through large-scale implementation of solar energy can address both climate change concerns and the growing global energy demand. While solar energy is abundant, effective storage remains a major challenge due to environmental and integration constraints. If solar energy can be efficiently stored on a large scale, it could provide a sustainable solution to humanity's energy and climate crisis. This article systematically compares six major solar energy storage methods, lithium-ion batteries, redox flow batteries, compressed air energy storage, thermal energy storage, hydrogen energy storage, and pumped-hydro energy storage, to determine which is most suitable for large-scale integration with solar energy systems. For each method, the principles, advantages, disadvantages, and future potential are analyzed to evaluate their feasibility for global application. Pumped-hydro energy storage is shown to be the most promising among the methods discussed.

Keywords: energy storage; solar energy storage; hydrogen energy storage; renewable energy

INTRODUCTION

There's an ample amount of solar energy readily available. However, as of 2023, solar energy only accounted for 5.5% of global energy generation. Most global energy still comes from unsustainable fossil fuels, a leading source of greenhouse-gas emissions (1). Moreover, Sustainable sources of energy need to completely replace fossil fuels, and some of the most promising renewable sources are solar energy and wind energy. To meet future energy demands while mitigating climate change, renewable energy sources such as solar and wind must eventually replace fossil fuels.

A key challenge in achieving this transition is the intermittent nature of solar energy production, which fluctuates based on weather conditions and time of day. Consequently, efficient and scalable energy storage technologies are critical to ensure a stable and continuous power supply. Among various approaches, six major storage technologies have shown significant potential to support large-scale renewable integration, and they are lithium-ion batteries (LIBs), redox flow batteries (RFBs), compressed air energy storage (CAES), thermal energy storage (TES), hydrogen energy storage (HES) and pumped-hydro energy storage (PHES).

This article systematically evaluates and compares these six solar energy storage methods to determine which technology offers the most effective balance of efficiency, reliability, scalability and environmental sustainability for global applications. Each method is analyzed in terms of its working principles, advantages, limitations and long-term feasibility, with the ultimate goal of identifying the most promising option for integrating solar power into future energy systems.

Corresponding author: Johnson Ye, E-mail: yej26@kent-school.edu.

Accepted October 28, 2025
https://doi.org/10.70251/HYJR2348.36132142

ADVANTAGES, CHALLENGES AND EMERGING OPPORTUNITIES OF SOLAR ENERGY STORAGE METHODS

Several popular energy storage methods are reviewed, and their key characteristics are examined. These energy storage methods include:

Lithium-ion Batteries

LIBs are made up of a cathode, an anode, and a membrane that separates the cathode and anode. The space between the cathode and anode is filled with electrolyte solutions that contain lithium ions. To store energy, another form of energy is used to send electrons to the anode; To release energy, electrons flow through a circuit from the anode to the cathode.

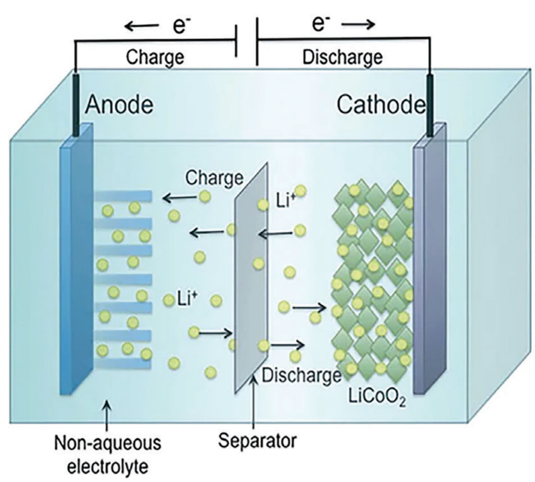

Figure 1. Graphical illustration of the schematics in a lithium battery cell, reproduced from (2).

As shown in Figure 1, a lithium battery cell consists of an anode and a cathode, with a separator in between. During the charge or discharge cycle of the battery, lithium electrolyte moves across the separator while electrons move between the anode and cathode through an electrical circuit. LIBs have high round-trip efficiencies of 85- 90%. In other words, 85-90% of the originally stored energy will be usable after storage. LIBs also have relatively low initial costs at 400 dollars per kilowatt for use of one hour ($ /kWh) with power capacities of 100 MW (3). Considering lifespans, operational costs are around 7-14 dollars per kilowatts for use of one year($/kW-year) or about 2% of the initial costs (4). Although LIBs have relatively long lifespans compared to other batteries, they don't last as long as most large-scale energy storage methods. LIBs have a volumetric energy density of 200-400 watt-hours per liter, far greater than redox flow batteries and other large-scale energy storage methods such as pumped-hydro energy storage (5). As a result, they are often the best choice for mobile applications such as electric vehicles.

LIBs are prone to potential safety issues. LIBs require the integration of safety circuitry as a means of protection against overcharging or excessive discharge. Safety circuitry will add to the cost of LIBs and limit the efficiency of energy storage to some extent. Even with the implementation of safety circuitry, LIBs could still experience safety hazards (6).

Another disadvantage of LIBs is that they experience aging and deterioration. A brand-new LIB can usually last between 500-1000 discharge cycles and about 10 years (6). At the end of its lifespan, LIBs also lose 20-30 percent of their original capacity (6). Even when the LIB is not being used, it will still lose functionality over time unless stored in a relatively cool area. Finally, LIBs can only reach a max power rating of up to 100 MW, considerably lower than energy storage methods such as pumped-hydro energy storage, which can reach power ratings of up to 1 gigawatt (5).

Lithium Batteries are a great way to store and transport energy at small scales. In the future, LIBs are expected to get cheaper and safer. In fact, in the next 10 years, LIBs are projected to halve their current price. Furthermore, innovations such as using silicon instead of graphite have the potential to increase its maximum power output (5).

Redox Flow Batteries

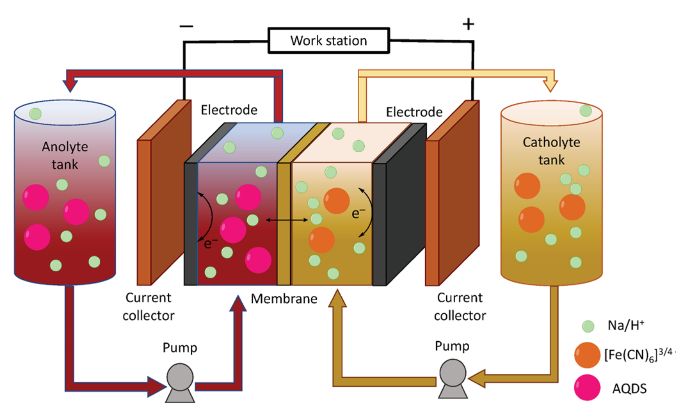

Figure 2. Graphical illustration of a redox flow battery, reproduced from (7).

Figure 2 shows that RFBs contain two tanks of electrolyte solution, similar to a lithium battery. In between these two tanks are cell stacks where electrolytes interact to take on or lose electrons. To generate electricity, chemical bonds that store energy break, which causes electrons to generate a current that flows from the cathode to the anode. One advantage of RFBs is their separation of parameters for energy and power, which gives them a large degree of adjustability. For example, the capacity of the redox flow battery can be adjusted by adjusting the size of the electrolyte tanks. Furthermore, the size of cell stacks can be adjusted to accommodate different power levels. To increase the power level, more cell stacks can be added and connected in series (8). Another advantage of RFBs is their low rate of deterioration, with a lifetime of up to 20 years. Unlike the conventional battery, its storage capacity and round-trip efficiency do not deteriorate. RFBs have relatively low initial costs at 300-400 dollars per kilowatt hour for batteries with power ratings at 100 MW (3). RFBs are also characterized by relatively high round-trip efficiencies of up to 85% (8).

RFBs generally take up much more space than conventional batteries. RFBs typically have low volumetric energy storage densities and require very large tanks with high volume, which limits the use of RFBs for mobile applications such as vehicles(5). Another disadvantage to RFBs is their temperature sensitivity, as RFBs typically require temperatures between 15 degrees Celsius and 35 degrees Celsius to operate efficiently. Lower temperatures cause slower reactions to take place; higher temperatures lead to unstable electrolytes (8). In both cases, the efficiency of RFBs dramatically decreases when they are not within the 15-degree and 35-degree temperature range. RFBs can only reach a maximum power rating of up to 100 MW. Finally, RFBs also have relatively high operational costs at 3 percent of their initial installment costs (3).

Current RFBs are heavily reliant on Vanadium. However, Vanadium is expensive and not commercially available at a large scale for the industrial-scale implementation of redox flow battery energy storage. Current research into RFBs focuses on finding new materials to replace Vanadium that are more effective and widely available. One such alternative to Vanadium is a combination of Zinc and Bromine. However, Bromine and Zinc RFBs only have round-trip efficiencies of up to 70% (8). Bromine-Zinc RFBs are also not as efficient as Vanadium RFBs and tend to have much shorter lifespans. Bromine can also cause hazardous environmental effects when Bromine enters the environment. Although Bromine-Zinc is unlikely to replace Vanadium, there may be better materials that can improve the Vanadium Redox Flow Battery.

Compressed Air Energy Storage

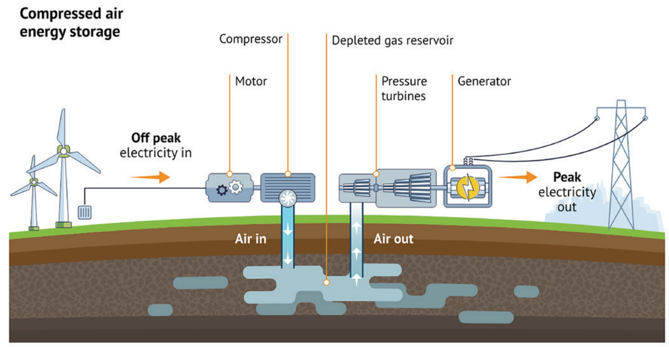

Figure 3. Graphical illustration of a system, reproduced from (9).

As shown in Figure 3, energy from sources such as wind turbines is used to power an air compressor. Compressed air is then sent to underground caverns for storage. When energy is needed, compressed air is withdrawn and put into a pressure turbine, which powers a generator that extracts energy from the pressured air and produces electricity. Energy in a CAES system is stored in the form of compressed air in an underground cavity, such as salt caverns. To extract the energy from the compressed gas, the gas is heated, and the expanding gas is fed into a gas turbine to turn an electric generator which produces electricity.

The greatest advantage of CAES is its large storage capacity with power ratings of up to 1 gigawatt. Despite the high upfront costs, CAES facilities are very durable and can last up to 40 years (3). Operational costs are relatively low at 18-22 dollars per kilowatt-year, depending on the energy capacity of the CAES facility (4). Finally, CAES is also useful for long-term energy storage with minimal losses over time.

CAES systems generally have low round-trip efficiencies of 42-55 percent. Although CAES systems can achieve power ratings of up to 1 gigawatt, no plants under operation have been able to manage that much power at this time. For example, the only CAES plant in the United States, as of 2023, is in Alabama and achieved a power rating of only 110 MW (3). Furthermore, CAES also has an extremely high upfront cost of 1,617 dollars per kilowatt hour, which deters potential investors (3). Finally, the location dependency of CAES drastically limits the number of CAES facilities that exist. Four CAES facilities were proposed and built in the US, of which only one in Alabama is currently functional.

Research is currently focused on components of the CAES system, such as hydrogen generators, oxygen/hydrogen compressors, and heat exchangers, to improve round-trip efficiency for CAES(10). New technology is also being developed to reduce the loss of energy due to leakages, such as pressure regulation technologies. Storage media also have the potential to be expanded beyond salt caverns using media such as abandoned pipelines, drained saline aquifers, underwater pressure vessels, and aboveground tanks. These potential improvements in technology could make CAES a much better choice for energy storage in the future (10).

Thermal Energy Storage

There are three main types of TES, sensible heat storage, latent heat storage and thermal chemical energy storage. This article will focus on Sensible Heat Storage and Thermal Chemical Energy Storage (TCES) as a means of comparison. Latent heat storage is still relatively new technology and not ready for large-scale implementation.

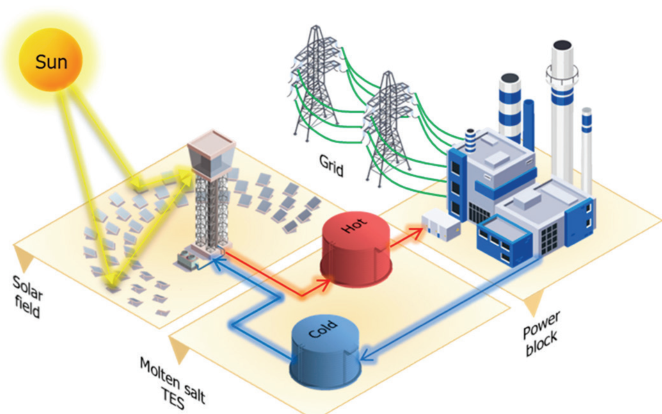

Figure 4. Graphical illustration of a TES system, reproduced from (11).

As shown in Figure 4, solar energy is used to heat molten salt. Molten salt is stored in a storage tank where it retains the heat energy. To convert thermal energy back into usable forms of energy, the heat in molten salt is used to heat up water that, in turn, powers a turbine to produce electricity.

Sensible Heat Storage

Sensible heat storage (SHS) stores energy as a temperature difference in solid or liquid materials such as concrete, rock, sand, or molten salt. The most effective medium of storage is molten salt due to its aptitude for retaining heat. Molten salt is heated in a receiver by concentrating sunlight with heliostats. After being heated, molten salt flows to a hot storage tank that retains most of the heat. To use the stored energy, the molten salt is pumped to a heat exchanger to heat up water. Heated water turns into steam, which in turn powers a turbine to generate electricity.

Sensible heat storage is characterized by a high volumetric energy storage density of up to 210 watt-hours per liter (4). High volumetric energy storage density gives SHS more versatility and opportunities to be used in case-specific scenarios where the location may not be compatible with other energy storage methods. Sensible heat storage can also reach a maximum power rating of up to 150 MW. Although Sensible heat storage has relatively high initial costs, SHS has a long lifetime of up to 30 years (5). Finally, Sensible heat storage is also able to store energy with low losses. For example, Energynest, a concrete-based energy storage plant, can store thermal energy at less than 2% loss per day (12).

SHS has an extremely high initial cost of 1880 $/kWh using molten salt as a storage medium due to the high cost of molten salt and facilities that can maintain specific temperatures. In addition to an extremely high initial cost, SHS also has an extremely high operation and maintenance cost of 53.7 $/kilowatt-year (15). The initial cost, in addition to the high maintenance cost, makes SHS less attractive to potential investors than cheaper alternatives such as batteries. SHS also has an extremely low round-trip efficiency of 44 percent. Furthermore, the most effective medium of storage, molten salt, is not readily available at large quantities. As a result, SHS is unlikely to be compatible with solar energy on a global, industrial scale because it is unable to reach the scale necessary to store large quantities of renewable energy.

Thermal Chemical Energy Storage (TCES)

To store energy, reactants are separated into products in an endothermic reaction–a reaction that stores heat. To release energy, those products recombine into the reactant in an exothermic reaction–a reaction that releases heat. Similar to Sensible heat storage, the released heat can then be converted into usable forms of energy through processes such as heating water to power a turbine that generates electricity.

One key advantage of TCES is its potential for long-term energy storage. TCES involves storing energy in chemical bonds that don't weaken over time. As a result, it has a very high round-trip efficiency with almost no loss of energy during long-term storage. Another advantage of TCES is its high energy storage density. TCES can reach energy storage densities of up to 10 times that of Sensible heat storage. Finally, TCES also works in a variety of temperatures. Sensible heat storage systems often need to maintain specific temperatures because materials used in sensible heat storage, such as molten salt, become dysfunctional at certain temperature ranges. By contrast, TCES systems can operate at a larger range of temperatures, from 300-1300 degrees Celsius, depending on the type of chemical used (12). This provides more flexibility, which could potentially reduce costs and increase applicability.

One disadvantage of TCES is its low material cyclability, Chemical elements used to store energy decay after use, with some chemicals, such as carbonate, only being able to sustain 10-20 cycles. As a result, these chemicals will need to be replaced often, which leads to high operating costs. Furthermore, current TCES technology cannot be integrated with solar energy generators due to an inability to transform solar energy into chemical bonds(12).

Although TCES is currently not compatible with solar energy, ongoing research focused on promising new mediums of storage is seeking to address this issue, and TCES could one day be used to store solar energy. Finally, TCES has not yet seen industrial-scale implementation. In a study from the DOE that focuses on six promising materials for TCES (Carbonates, Hydroxides, Metal Hydrides, Oxides, Ammonia, and Sulfur), four of them have achieved lab-status implementation, and two have only achieved pilot-status implementation (12).

Current sensible heat storage systems have high capital and operational costs because materials like molten salt require specific temperatures and can be expensive to acquire. The use of solid materials like sand or concrete instead provides an inexpensive, noncorrosive, and less temperature-sensitive alternative. Solid materials can even cost up to 10 times less than liquid materials like molten salt. However, solid materials have a much weaker capacity to retain heat than molten salt. In the future, it is likely that new heat storage mediums that are more cost-efficient and readily available will replace molten salt. TCES is currently a relatively new technology that is not available in large quantities. In the future, as TCES technology becomes more reliable, TCES will likely move beyond lab-status implementation. Characteristics of TCES suggest that it could be useful for storing solar energy.

Hydrogen Energy Storage

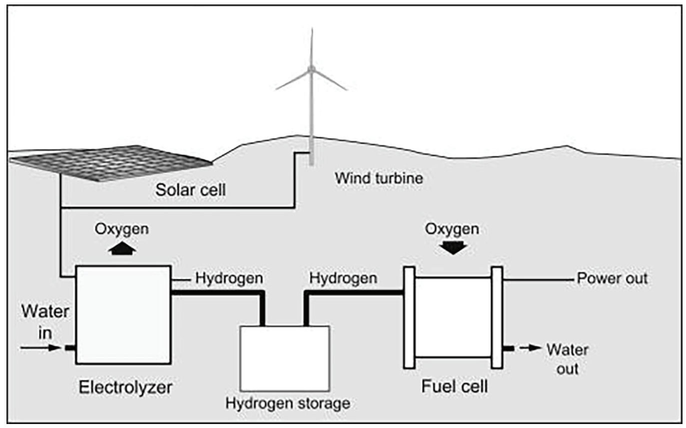

Figure 5. Graphical representation of a hydrogen storage system in a salt cavern, reproduced from (13).

Figure 5 shows that renewable energy sources, such as solar energy, are used to power electrolyzers that separate hydrogen from oxygen in water so that hydrogen can be stored in an underground cavern. To extract the energy, hydrogen gas is used in hydrogen fuel cells, which combine hydrogen molecules with oxygen in the air through an electrochemical process that produces electricity. Hydrogen can be generated from electrochemical processes such as electrolysis using surplus solar energy. Hydrogen is then stored in aboveground tanks or underground areas such as salt caverns. When energy is needed, stored hydrogen is converted back into usable forms of energy through fuel cells. Hydrogen can be stored in high-pressure gas tanks, cryogenic liquid tanks, gas pipelines, salt caverns, metal hydrides, and liquid organic hydrogen carriers. Of all these methods of hydrogen storage, only salt caverns can store hydrogen at a large scale (salt caverns can store up to 8 million kilograms of hydrogen (14). All other forms of hydrogen storage only have storage capacities ranging from 20 kg to 15,000 kg of hydrogen (14). For comparison, this article will focus on salt caverns as the primary hydrogen storage method because they can store energy on a large enough scale to be compatible with renewable energy.

HES surpasses all other energy storage methods in its capacity. HES can discharge up to 5 gigawatts of power (14). This means that current large-scale installation of hydrogen storage can discharge up to 5GW of power. However, this does not necessarily reflect the limits on what the overall power scale of hydrogen storage technology can achieve, as the scale of the installation can be dependent on the size of a natural geological cavern used to store hydrogen underground. Furthermore, hydrogen also has an extremely high volumetric energy density of 600 watt-hours per liter (5). Finally, even though HES has a low round-trip efficiency, HES is useful for long-term storage because there is no energy loss over time. Paired with renewable energy sources such as solar energy, HES can be an extremely attractive option because it can collect large amounts of energy during off-peak periods and store it for long periods of time until periods of high energy demand.

HES has extremely high capital costs. Electrolyzers used to generate stored hydrogen are the first of three capital costs for HES at 850 USD per kilowatt for alkaline electrolyzer systems (15). The lowest achievable production cost for hydrogen is 4.7 dollars per kilogram. Thirty kilograms of hydrogen can be used to produce 1 WM hour of energy, which translates to a cost of 0.14 dollars per kilowatt hour of energy stored (15).

In addition to the capital cost of electrolyzer systems is the capital cost for hydrogen storage facilities. Aboveground storage facilities cost 8000 dollars per kilowatt-hour, while underground facilities cost 1000 dollars per kilowatt-hour. This difference in cost results from the high expense necessary to create a suitable man-made storage structure for hydrogen. Underground facilities, by contrast, utilize natural features such as caverns, which dramatically reduce costs. Although underground storage facilities are much more economically feasible for large-scale storage, underground storage facilities also come with a location constraint. Finally, fuel cells to convert hydrogen back into energy cost an additional 3000 dollars per kilowatt-hour (14). Operation and maintenance costs are at 28.5 $/kW-year (14). HES is also characterized by a round-trip efficiency of only 40 percent due to energy losses in electrolysis, storage, and fuel cells.

Pumped-hydro Energy Storage

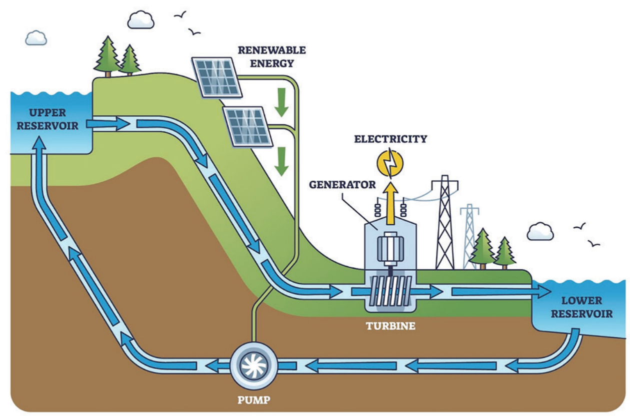

Figure 6. Graphical illustration of the working principle in a pumped hydropower storage system diagram reproduced from (16).

Figure 6 shows how renewable energy is used to power a pump that pumps water from a lower reservoir to a higher reservoir, storing gravitational energy. When energy is needed, water flows back down to the lower reservoir to power a turbine that generates electricity. PHES systems operate by leveraging the gravitational potential energy difference between two reservoirs at different elevations. Water is pumped from the low to the high reservoir to store excess energy, and energy is recovered by running stored water downstream through electric turbines

PHES facilities have long lifetimes of 50-60 years. Furthermore, PHES systems can also achieve extremely high round-trip efficiencies of 70-85 percent. PHES is a form of large-scale energy storage, with power ratings of up to 1 gigawatt (14). Operational costs are about 1 percent of the initial cost at 16 dollars per kilowatt hour (11). PHES is also extremely reliable and safe to operate. These advantages make PHES a good choice for large-scale energy storage.

The biggest disadvantage of PHES is its high initial investment cost. PHES facilities have an initial cost of 1633 USD per kilowatt hour of energy storage capacity (3). Facilities need to be built at specific locations that may take anywhere from 3-5 years for construction. High investment costs are only worth it in the long term, which can deter investors who want a quick return on investment. An article on PHES facilities in the US researched 6 different PHES facilities, of which they lasted an average of 10 years. Most of these facilities closed down due to market uncertainties (17). PHES is also very harmful to the environment. Most PHES facilities involve dams built in the middle of rivers that disrupt the ecosystem to a large degree. These further limits the locations that PHES facilities can be built in, as these facilities often require approval from the government due to environmental repercussions.

As of 2010, 36 permits had been issued for PHES facilities in the United States. Of the 36 permits issued, less than a quarter of them relied on dams. 29 are of a closed-loop and off-stream design to mitigate environmental impacts. PHES technology is improving in favor of using underground reservoirs and closed-loop designs.

At the moment, PHES can be extremely harmful to the environment. However, recent innovative case-specific approaches to PHES facilities may have several advantages that make it feasible. For example, a proposed PHES project in Mulqueeney Ranch, California, proposes to use recycled wastewater as the source of energy storage (17). This is not only more environmentally friendly but could also improve the environment through its operation, as the pumping process has the potential to aerate the water. This innovative approach to PHES can not only supply energy efficiently to these facilities but also mitigate the negative environmental impact from these facilities.

DISCUSSION

Key metrics across technologies are summarized in Table 1. In Table 1, the author has ranked the order of importance as follows: maximum power rating, capital costs, lifetime, round-trip efficiency, operational costs, and volumetric energy density. The next most important factor, capital cost, determines the economic practicality of each energy storage method. The last four metrics, lifetime, round-trip efficiency, operational costs, and volumetric energy density, determine the operational effectiveness of an energy storage method.

The maximum power rating is ranked as the most important factor, as it indicates the scale of the energy storage system and ensures that an energy storage method has the necessary capacity required to support large-scale energy storage. Moreover, for the application of grid-scale energy storage systems coupled to renewable energy systems, a high-power rating will ensure that it can store the excess energy output of a large-scale renewable energy production plant. Generally, a power rating of 1 GW or more indicates a scale large enough for application to grid-scale solar energy systems. Storage methods such as HES with a large power rating reflect not only that HES has the capacity to supply power to a large number of applications at once but also indicate it has a high energy storage capacity, as a high-power rating can only be maintained if there is an ample amount of energy stored. While HES has the highest power rating, up to 5 times that of PHES and CAES, PHES and CAES also have high enough power ratings for them to be useful for storing solar energy. For example, 1 gigawatt is enough to power 750,000 homes (18). Furthermore, RFBs and LIBs are typically smaller-scale energy storage systems. They are more useful for small-scale applications, such as homes or in vehicles, rather than as the main energy storage source at a photovoltaic power station.

The capital costs are the second most important metric because they determine the real-world economic practicality of each storage method. A high capital cost could prohibit the widespread adoption of an energy storage method, as a large upfront investment

Table 1. Comparison of six metrics for each of the discussed solar energy storage methods (4, 5, 12, 14, & 15)

	Max Power Rating (MW)	Round-trip Efficiency (%)	Lifetime (years)	Operational Costs ($/kW-year)	Capital Costs ($/kWh)	Volumetric Energy Density (watt-hour per liter)
PHES	1000	70-85%	60	18	1633	0.2-2
CAES	1000	42-55%	40	18-22	1617	2-6
TES (SHS Molten Salt)	150	44%	30	53.7	1880	70-210
RFB	100	85%	20	7-16	300-400	20-70
LIBs	100	85-90%	10	7-14	400	200-400
HES	5000	40%	50	28.5	1000-8000	600

would be needed to start construction of the energy storage system, posing a large barrier to adoption. The importance of the system lifetime is secondary to the capital costs because a long lifetime could balance out high capital costs to some extent. Therefore, system lifetime can further influence the practicality of an energy storage method after consideration of capital costs. PHES has an initial capital cost of 1633 $/kWh. PHES facilities have a lifetime of 60 years. This translates to a capital cost of 27.2 $/kWh-year of operation. In comparison, CAES has a capital cost of 1617 $/kWh and can last for 40 years. This represents a capital cost of 40.4 $/kWh-year, which is significantly greater than PHES. Hydrogen storage has an initial capital cost of 1000 $/kWh for underground storage and 8000 $/kWh for above-ground storage. Underground storage is only available at specific locations and is not widely available. For large-scale implementation of hydrogen storage, above-ground storage, which is highly capital-intensive, will likely need to be used. In addition to the capital cost of hydrogen storage is the capital cost of fuel cells and electrolyzers, which power the chemical reactions that store energy in hydrogen. Electrolyzers and fuel cells add 3850 $/kWh to the capital cost of hydrogen. Even with underground storage, the capital cost is still very high at 4850 $/kWh. This converts to 97 $/kWh-year of operation. This is significantly higher than CAES and PHES.

In terms of system lifetime, PHES also stands out on top. PHES has a lifetime of 60 years, which is more than the lifetime of hydrogen (50 years) and CAES (40 years). Hydrogen, CAES, and PHES all have lifetimes far greater than RFBs and LIBs, which only have lifetimes of 20 years and 10 years, respectively. Lifetime is a significant factor of consideration because the longer the lifetime, the more reliable a source of energy will be for long-term storage. Long lifetimes indicate less frequency of replacement, which decreases the overall costs. RFBs have an initial capital cost of only 300-400 $/kWh. They can be used for 20 years, which converts to 15-20 $/kWh per year of use. This is the least capital-intensive method of energy storage, being over 30 percent cheaper than PHES. Finally, LIBs have capital costs of 400 $/kWh and can last for 10 years. This translates to a cost of 40 $/kWh per year of use. This puts LIBs in the middle of the spectrum at similar costs to CAES.

Round-trip efficiency is ranked fourth since it accounts for the operational effectiveness of each energy storage method. The operational effectiveness poses fewer barriers to entry compared to the upfront practicality of an energy storage system. This is because the operational effectiveness only matters after a system is determined to be practical enough to be implemented upfront. Round-trip efficiency determines the overall efficiency of the energy flow through a storage device and accounts for the loss of energy in that process. This could affect the efficiency of the operation to a large extent, and therefore, it is the most important metric regarding the operational effectiveness of an energy system. In terms of round-trip efficiency, RFBs and LIBs surpass all the other energy storage methods. However, round-trip efficiency is not as important as other factors, such as costs or power rating. During periods of excess sunlight, more energy will likely be produced than can be stored. Furthermore, solar power has the potential to generate far more energy than humanity needs. As a result, the energy lost through storage, as measured by round-trip efficiency, is not as significant. For the large-scale energy storage methods, PHES has the highest round-trip efficiency of 70-85%. This is significantly higher than CAES and hydrogen storage, which can only reach half of their round-trip efficiency. PHES not only has similar round-trip efficiencies to the batteries but also has a much higher power rating than the batteries.

Operational costs also affect the practicality of an energy storage type. However, operational costs tend to be much lower than the upfront capital costs, and investment can happen over time. As a result, it is a metric of comparison for operational effectiveness and poses a lesser barrier to adoption compared to the capital costs. Operational costs are not prioritized as high as round-trip efficiency because the energy lost through storage is far more costly than the operational costs. PHES has operational costs of 18 $/kW-year while CAES has operational costs of 18-22$/kW-year. RFBs have operational costs of 7-16 $/kW-year. LIBs have operational costs of 7-14 $/kW-year. HES has operational costs of 28.5 $/kW-year. Hydrogen has the highest operational costs. Operational costs for batteries are also lower than operational costs for PHES and CAES. However, operational costs are not as important as initial capital costs because they make up only a small percentage of total costs.

Finally, the least important metric is volumetric energy density because volumetric energy density is only a factor necessary for consideration in areas with limited space. However, grid-scale renewable energy facilities usually have ample space nearby and are affected to a much smaller extent by low volumetric energy densities. HES has the highest volumetric energy density at 600 watt-hours per liter, followed by LIBs and TES. RFBs, CAES, and PHES have far lower volumetric energy densities, with PHES being the lowest at 0.2-2 watt-hours per liter.

When comparing the different energy storage methods with the considered evaluation metrics, PHES appears to be the most promising energy storage method. In terms of maximum power rating, PHES comes second only to HES, with the former achieving a power rating of 1 Gigawatt and the latter achieving a power rating of 5 Gigawatts at the current large-scale installation. However, as hydrogen technology matures, the power rating of hydrogen can further exceed PHES, making it even more attractive in terms of power capacity.

HES also has significantly lower round-trip efficiency than PHES. In terms of round-trip efficiency, RFBs, LIBs, and TES all surpass PHES, achieving round-trip efficiencies of 80-90 percent. However, PHES has a round-trip efficiency of 70-85 percent, which is not significantly less than that of RFBs, LIBs, and TES. PHES's high power rating and ability to store large quantities of energy more than make up for a minor difference in round-trip efficiency. In terms of system lifetime, PHES has the longest out of all energy storage methods. In terms of capital costs, PHES has a cost of 1633 $/kWh, which is similar to CAES but much more than small-scale energy storage methods such as LIBs, RFBs, and TES, which all have initial costs under 400 $/kWh. However, LIBs, RFBs, and TES all have significantly shorter lifetimes. PHES has a capital levelized over its lifetime similar to RFBs, and lower than TES and LIBs. Finally, the only factor in which PHES performs significantly weaker than the other storage methods is volumetric energy density. PHES has the lowest volumetric energy density out of all the storage methods discussed at 0.2-2 watt-hours per liter. For integration with solar energy, this is not a significant disadvantage because space is often readily available near large, rural solar arrays.

In summary, PHES is shown to be the most promising energy storage method for large-scale after considering all the comparison metrics. It has great performance characteristics in the categories of maximum power rating, lifetime, and round-trip efficiency. Even though PHES has the lowest volumetric energy density and a high initial capital cost, the advantages of its maximum power rating, lifetime, and round-trip efficiency outweigh its drawbacks. Furthermore, when factoring in the long lifetime of PHES, the capital costs can be amortized over its lifetime, making it the second cheapest among all energy storage methods. In other words, the extremely long lifetime of PHES makes up for its high capital costs in terms of economic considerations. The extremely low volumetric energy density of PHES is also not a major disadvantage for grid-scale integration with solar energy because solar energy facilities are generally located in rural areas with ample space available and can be installed at a location where large water bodies exist. Although PHES has the strongest technical performance, excelling in the most important metrics for consideration, PHES may be prone to other drawbacks, such as location constraints, government regulations, and environmental concerns. Although PHES can only function in locations with bodies of water capable of acting as an upper and lower reservoir, other large-scale energy storage methods also have similar location constraints. For example, CAES and HES require underground caverns to store hydrogen or compressed air. Location constraints may be unavoidable, and in different settings, the best option may be to choose the large-scale energy storage method that works best with the geography of the location, whether it be HES, CAES, or PHES. Another potential issue with the implementation of PHES is environmental concerns. PHES can be extremely harmful to ecosystems. As a result, governments often impose policies to protect these ecosystems that could further limit the locations where PHES systems may operate. However, recent innovative approaches to PHES are increasingly relying on closed-loop systems of underground reservoirs, which are much less sensitive to environmental policies. In the end, although PHES is the most prevalent energy storage method in terms of technical performance, due to location constraints in all large-scale energy storage systems. At locations where PHES does not work effectively, CAES and HES can be stronger alternatives in those cases.

LIMITATIONS

This study is a review paper with the purpose of providing insight into potentially promising forms of energy storage for large-scale applications. The results do not by any means indicate that PHES is the best form of energy storage in all hypothetical cases but rather suggest that PHES can be a promising option. To reach a conclusive result favoring one form of energy storage, a real-world feasibility study and evaluation are necessary for each specific case of application. Furthermore, not all factors were taken into account. Rather, metrics shared amongst several energy storage methods useful for comparison were the focus of this study. For example, factors such as energy capacity, geographic limitations, policy limitations, and gravimetric energy density were not used for comparison due to a lack of data and were specific to a particular geographical location and application. These factors can be significant, especially regarding PHES. For example, PHES requires very specific geographical conditions to create a gravitation potential difference within a water body for the hydro-power dam to be built. If such a geographical condition does not exist, manual modification of the landscape may be required to create such geological characteristics. This manual modification of the landscape can incur high costs and make PHES more expensive than the data suggests. Furthermore, policy is also not considered as a factor, as the scope of this paper limits only the comparison on the technical performance / typical capital expenditure and operation expenditure of these technologies as reported from various sources. Government fiscal policy such as tax incentives, subsidies, or policies that incur environmental restrictions, can play a big role in affecting the cost-effectiveness and feasibility of these storage options, which can affect the conclusion of this study.

CONCLUSION

In this article, six energy storage methods–including PHES, CAES, TES, RFB, HES, and LIBs–were compared to determine which method is the most strategic for large-scale, solar energy storage. PHES stands out as the most promising due to its high round-trip efficiency, high power rating, and long lifetime. As humanity moves towards a future of renewable energy, PHES is especially crucial during times of excess energy production, peak demand, and grid instability. To further transition society to renewable energy sources, we must utilize systems such as PHES where applicable and continue to innovate, develop, and deploy these systems to facilitate the wider adoption of renewable energy storage.

However, this article does not consider other deciding factors such as geographic limitations, energy capacity, gravimetric energy density, and government policies. Furthermore, this paper also does not include real-life testing that is necessary to conclude with certainty. In the future, for a more comprehensive review, additional data such as gravimetric energy density and maximum energy capacity of different energy storage methods should be gathered, since both are factors that may influence the results. In addition, it is also important to consider factors that affect each energy storage method in the real world, such as geographic limitations and government policies. Finally, in order to draw definite conclusions on the most promising energy storage method, each energy storage method should also be evaluated and tested in the real world, as theoretical conclusions may deviate from realistic operating conditions.

CONFLICTS OF INTERESTS

The author declares that there are no conflicts of interest related to this work.

REFERENCES

1. Solar PV. Available from: https://www.iea.org/energy-system/renewables/solar-pv(accessed on 2025-9-3)
2. What is lithium ion battery how do lithium ion batteries work? Available from: https://www.tycorun.com/blogs/news/what-is-lithium-ion-battery-how-do-lithium-ion-batteries-work (accessed on 2025-7-14)
3. Baxter R, *et al*. Energy Storage System Pricing. *DOE ESHB*. 25 (25): 1-22.
4. Mongird K, *et al*. An Evaluation of Energy Storage Cost and Performance Characteristics. *Energies*. 2020; 13 (13): 1-21. https://doi.org/10.3390/en13133307
5. Zablocki A, *et al*. Fact Sheet Energy Storage. *EESI*. 2019; 1 (1): 1-10.
6. Sabu Thomas, Oumarou Savadogo, Amadou Belal Gueye, Hanna J. Maria. Nanostructured Lithium-ion Battery Materials: Synthesis, Characterization, and Applications. *Elsevier*. 0443133387: 47-64
7. Asenjo-Pascual J, *et al*. Understanding Aqueous Organic Redox Flow Batteries: A Guided Experimental Tour from Components Characterization to Final Assembly. *MDPI*. 2022; 1 (1): 1. https://doi.org/10.3390/batteries8100193
8. Vítězslav N, *et al*. Redox flow batteries as the means for energy storage. *Journal of Energy Storage*. 2017; 13 (13): 1-5. https://doi.org/10.1016/j.est.2017.07.028
9. Compressed Air Energy Storage. Available from: Available from https://www.energyencyclopedia.com/en/free-downloads/images (accessed on 2025-10-20)
10. Ahmed S, *et al*. Technology Strategy Assessment.

Energy Earthshots US DOE. 1 (1): 1-28.
11. Prieto C, *et al*. Molten Salts Tanks Thermal Energy Storage: Aspects to Consider during Design. *MDPI*. 2023; 1 (1): 1-4. https://doi.org/10.3390/en17010022
12. Ho C, *et al*. CHAPTER 12 THERMAL ENERGY STORAGE TECHNOLOGIES., US DOE. 1 (1): 1-21.
13. Energy storage technologies and real life applications – A state of the art review. Available from https://www.sciencedirect.com/topics/engineering/hydrogen-energy-storage(Accessed on 2025-10-20).
14. Headley A, *et al*. Chapter 11 Hydrogen Energy Storage. *DOE ESHB*. 1 (1): 1-23.
15. Armstrong R, *et al*. The Future of Energy Storage. *MIT*. 2022; 1 (1): 1-80.
16. What is pumped hydro storage, and how does it work? Available from: https://blog.yesenergy.com/yeblog/what-is-pumped-hydro-storage-and-how-does-it-work (accessed on 2025-7-14)
17. Yang C, *et al*. Opportunities and barriers to PHES in the United States. *Renewable and Sustainable Energy Reviews.* 2011; 15 (1): 839-844. https://doi.org/10.1016/j.rser.2010.09.020
18. Gigawatt: The Solar Energy Term You Should Know About. Available From: https://www.cnet.com/home/solar/gigawatt-the-solar-energy-term-you-should-know-about/ (Accessed on 2025-7-14)