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

Johnson Ye

ABSTRACT

Decarbonizing the electrical grid through the large-scale implementation of solar energy can address both climate change concerns and provide energy for growing global energy needs. While solar energy from the sun is plentiful, capturing and storing solar energy can prove difficult depending on environmental and grid integration factors. If solar energy can be effectively stored at a large scale, then solar energy could be a solution to humanity's energy and climate crises. This article focuses on six different methods of solar energy storage, including pumped-hydro storage, compressed air energy storage, thermal energy storage, redox flow batteries, hydrogen energy storage, and lithium-ion batteries. For each method of energy storage, the principles, advantages, disadvantages, and future potential will be explained and analyzed to evaluate which method is the most promising for integration with solar energy on a global scale. Pumped-hydro energy storage is shown to be the most promising out of the energy storage methods discussed.

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 fossil fuels, which are unsustainable and the leading cause of global warming [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. The biggest obstacle for full integration of renewable energy is its lack of reliability. Different weather conditions cause wind and solar energy to generate more or less energy than global energy demand.

One promising solution to this problem is to store energy. This article will focus on six different methods of solar energy storage with the goal of finding which is most suitable for solar energy storage. For an energy storage method to be successful, it was evaluated on the following criteria: ability to store large quantities of energy, reliability, cost-efficiency, space-efficiency, and energy storage efficiency. The capacity of energy storage is compared based on power rating. Power rating represents the maximum amount of energy that can be discharged. Reliability is compared based on two factors: lifetime and safety level. Cost-efficiency is compared based on operational costs and capital costs. Space efficiency is compared based on volumetric energy density. Finally, the efficiency of energy storage is compared based on round-trip efficiency.

OVERVIEW OF DIFFERENT ENERGY STORAGE METHODS

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

Lithium Ion Batteries

Lithium-ion batteries (LIBs) are made up of a cathode, an anode, and a membrane that separates the cathode and anode. The space in between the cathode and anode is filled up 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.

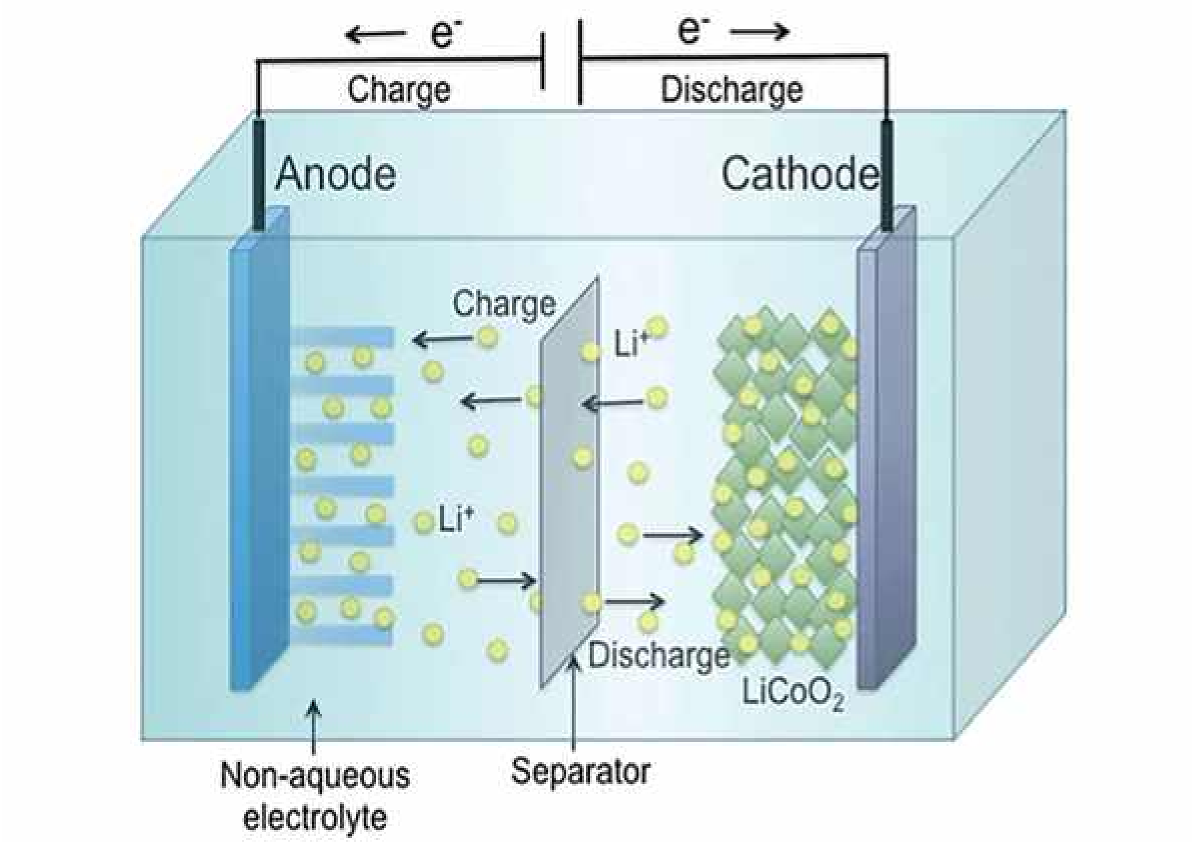

Fig 1: Graphical illustration of the schematics in a lithium battery cell, reproduced from [2].

Advantages:

Lithium-ion batteries have high round-trip efficiencies of 85- 90%. In other words, 85-90% of originally stored energy will be usable after storage. Lithium-ion batteries also have relatively low initial costs at 400 dollars per kilowatt hour for LIBs with power capacities of 100 megawatts [3]. Operational costs are around 7-14 $/kw-year or about 2% of the initial costs[4]. Although LIBs have relatively long lifespans compared to other batteries, LIBs 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.

Disadvantages:

Lithium-ion batteries 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 Lithium-Ion Batteries 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 Megawatts, considerably lower than energy storage methods such as Pumped-Hydro Energy Storage, which can reach power ratings of up to 1 gigawatt[5].

Future Potential:

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

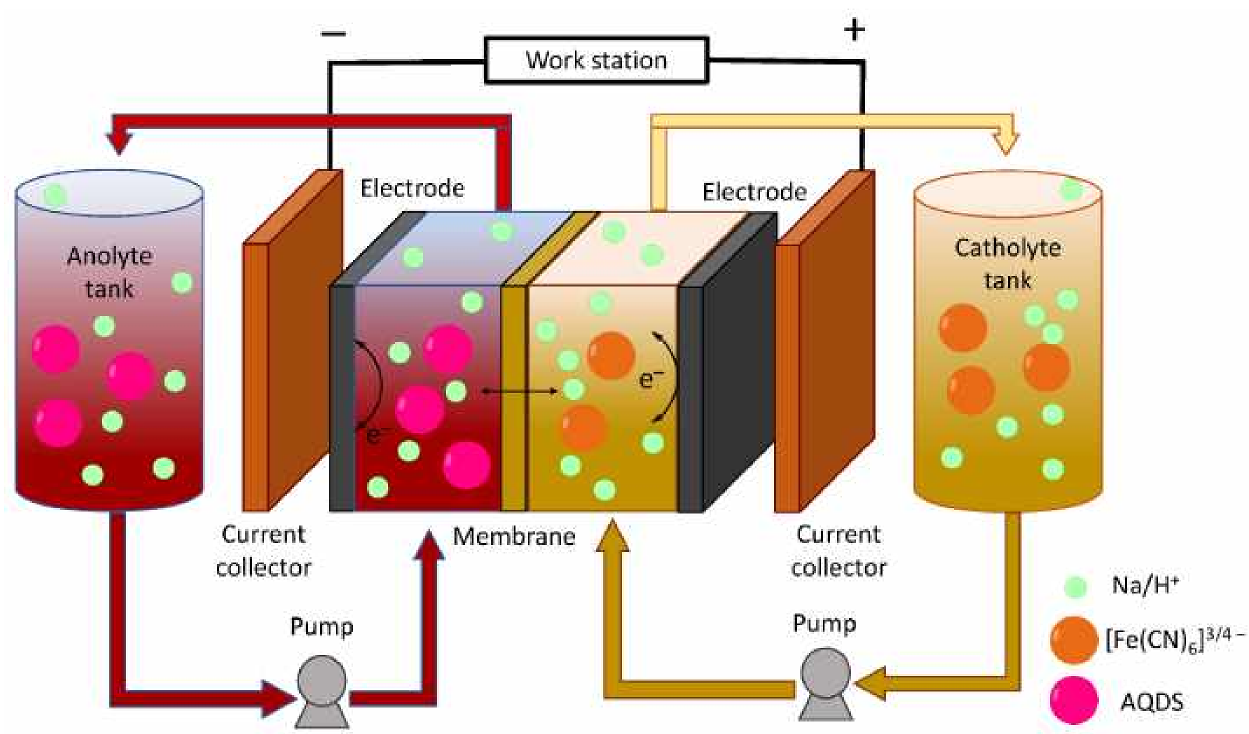

Fig 2: Graphical illustration of a redox flow battery, reproduced from [7].

Similar to a conventional battery, redox flow batteries (RFBs) contain two tanks of electrolyte solution. 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.

Advantages:

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 tanks of 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 megawatts [3]. Redox flow batteries are also characterized by relatively high round-trip efficiencies of up to 85%[8].

Disadvantages:

RFBs generally take up much more space than conventional batteries. Redox flow batteries 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 Redox Flow Batteries 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 [9]. In both cases, the efficiency of Redox flow batteries 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 megawatts. Finally, RFBs also have relatively high operational costs at 3 percent of their initial installment costs [3].

Future potential:

Current Redox Flow Batteries 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 redox flow batteries 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 Redox Flow Batteries are also not as efficient as Vanadium Redox Flow Batteries 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 (CAES):

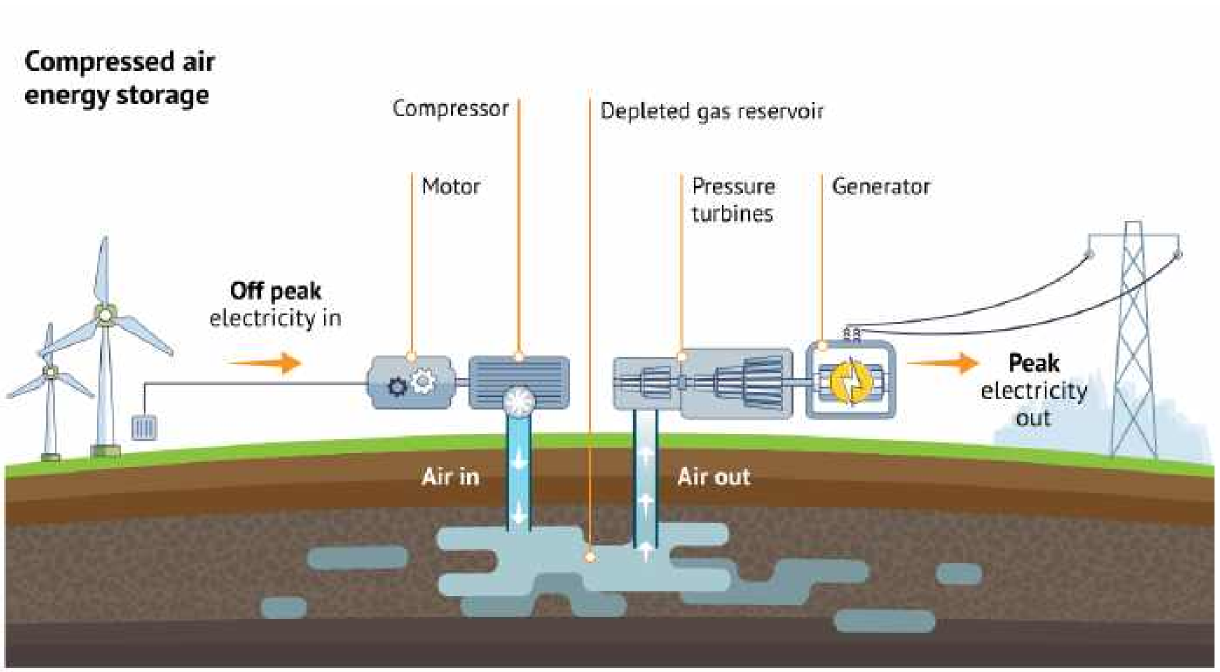

Fig 3: Graphical illustration of a compressed air energy storage system, reproduced from [10].

Energy in a compressed air energy storage (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.

Advantages:

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 [11]. Finally, CAES is also useful for long-term energy storage with minimal losses over time.

Disadvantages:

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 megawatts [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.

Future Potential:

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[12]. New technology is also being developed to reduce the loss of energy due to leakages, such as pressure regulation technologies. Storage media also has 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 [12].

Thermal Energy Storage

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

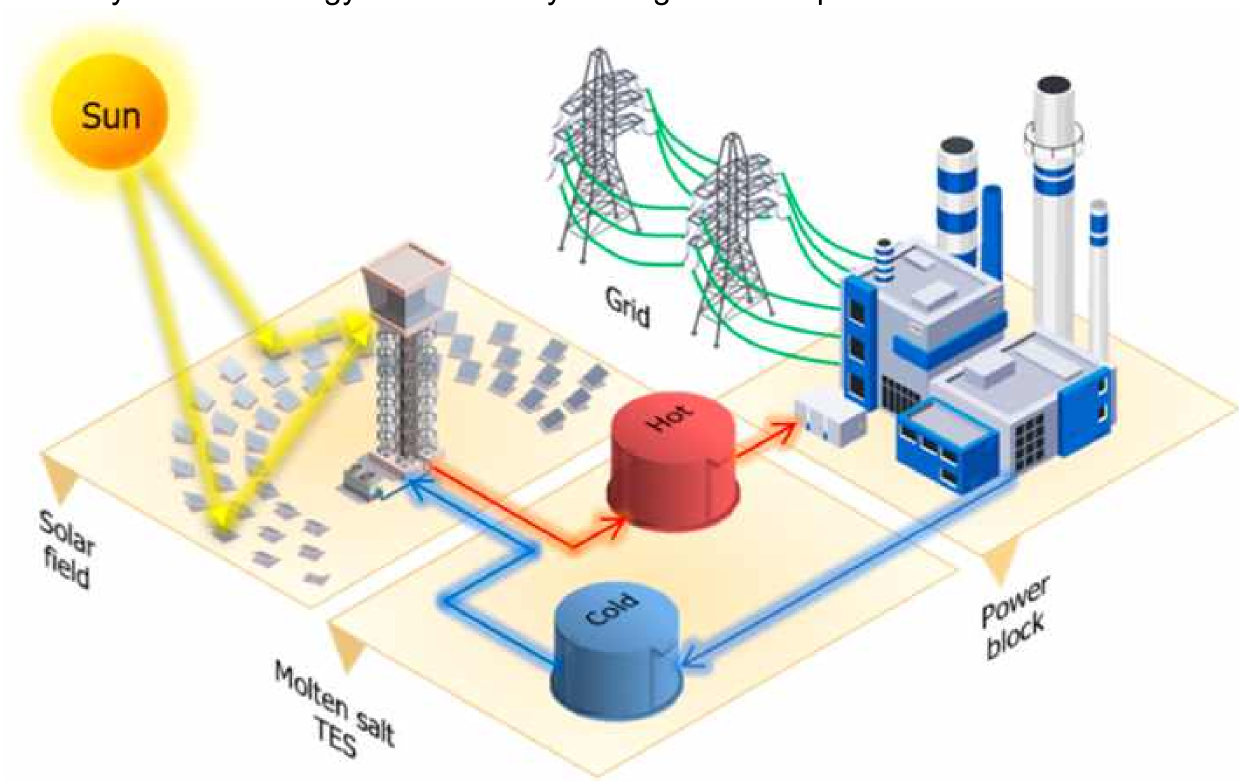

Fig 4: Graphical illustration of a thermal energy storage system, reproduced from [13].

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 to spot 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.

Advantages:

Sensible heat storage is characterized by a high volumetric energy storage density of up to 210 watt-hours per liter [11]. 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 megawatts. 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 [14].

Disadvantages:

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 make 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 up water to power a turbine that generates electricity.

Advantages

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 [14]. This provides more flexibility, which could potentially reduce costs and increase applicability.

Disadvantages

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[14].

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 [14].

Future Potential

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

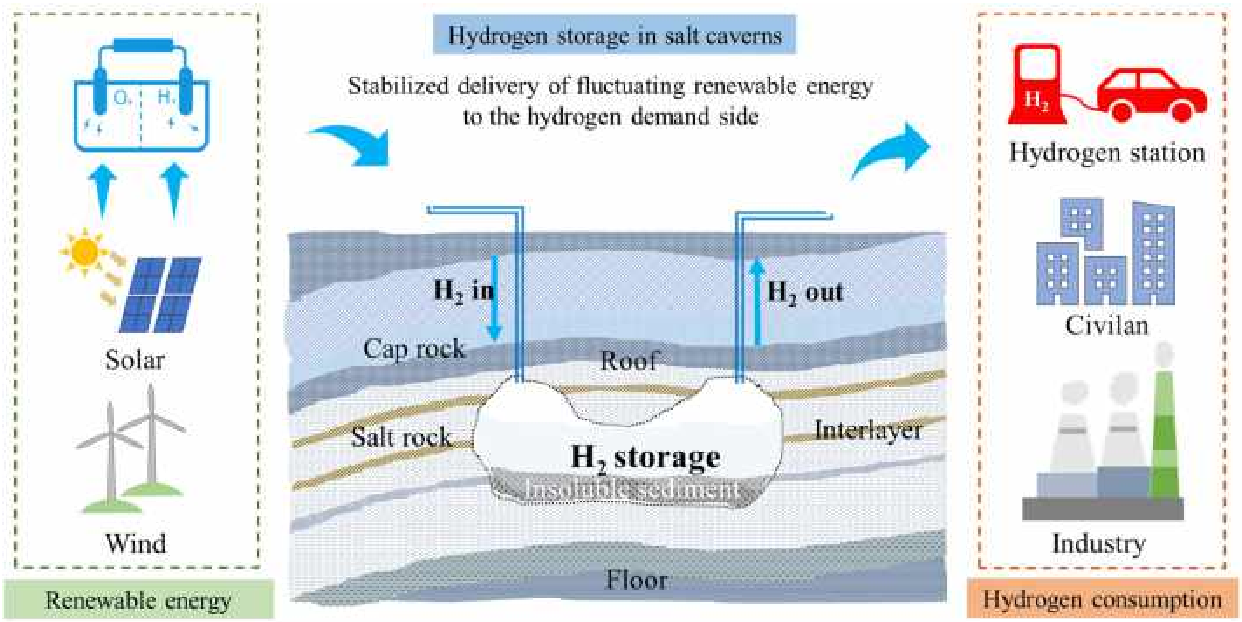

Figure 5: Graphical representation of a hydrogen storage system in a salt cavern, illustrating hydrogen produced from renewable energy being stored within a geological site. Diagram reproduced from [16].

Principles

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)[17. All other forms of hydrogen storage only have storage capacities ranging from 20 kg to 15,000 kg of hydrogen [17]. 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.

Advantages

Hydrogen energy storage (HES) surpasses all other energy storage methods in its capacity. Hydrogen Energy Storage can discharge up to 5 gigawatts of power [17]. Furthermore, hydrogen also has an extremely high volumetric energy density of 600 watt-hours per liter [18]. Finally, even though HES has a low round-trip efficiency, hydrogen energy storage is useful for long-term storage because there is no energy loss over time. Paired with renewable energy sources such as solar energy, hydrogen energy storage 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.

Disadvantages

Hydrogen energy storage has extremely high capital costs. Electrolyzers used to generate stored hydrogen are the first of three capital costs for hydrogen energy storage at 850 USD per kilowatt for alkaline electrolyzer systems[19]. The lowest achievable production cost for hydrogen is 4.7 dollars per kilogram. Thirty kilograms of hydrogen can be used to produce 1 megawatt hour of energy, which translates to a cost of 0.14 dollars per kilowatt hour of energy stored [19].

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. Underground storage facilities are much more economically feasible for large-scale storage. However, underground storage facilities only work in specific locations. Finally, fuel cells to convert hydrogen back into energy cost an additional 3000 dollars per kilowatt-hour [20]. Operation and maintenance costs are at 28.5 $/kw-year [20]. Hydrogen energy storage 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

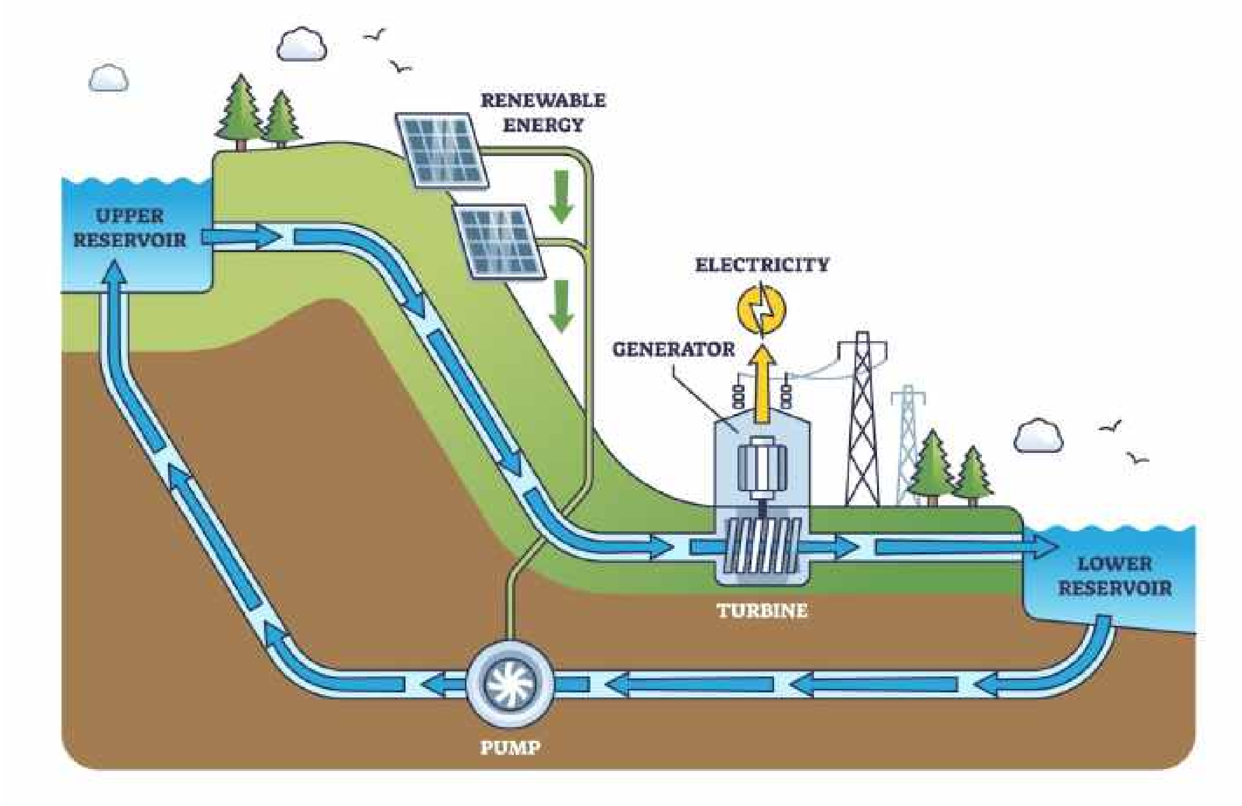

Fig 6: Graphical illustration of the working principle in a pumped hydropower storage system, diagram reproduced from [21].

Pumped-hydro energy storage (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

Advantages

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 [17]. Operational costs are about 1 percent of the initial cost at 16 dollars per kilowatt hour [22]. PHES is also extremely reliable and safe to operate. These advantages make PHES a good choice for large-scale energy storage.

Disadvantages

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 [23]. 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. This further limits the locations that PHES facilities can be built in, as these facilities often require approval from the government due to environmental repercussions.

Future potential

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 [23]. 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

	Max Power Rating (watts)	Round-trip Efficiency (%)	Lifetime (years)	Operational Costs ($/kW-time)	Capital Costs ($/kWh)	Volumetric Energy Density (watt-hour per liter)
PHES	1 GW	70-85%	60 years	18 $/kW-year	1633 $/kWh	0.2-2
CAES	1 GW	42-55%	40 years	18-22 $/kW-year	1617 $/kWh	2-6
Thermal (SHS Molten Salt)	150 MW	44%	30 years	53.7 $/kw-year	1880 $/kWh	70-210
Redox Flow Battery	100 MW	85%	20 years	7-16 $/kW-year	300-400 $/kWh	20-70
Lithium-Ion Battery	100 MW	85-90%	10 years	7-14 $/kw-year	400 $/kWh	200-400
Hydrogen	5 GW	40%	50 years	28.5$/kW-year	1000-8000 $/kWh	600

Table 1: Comparison of six metrics for each of the discussed solar energy storage methods [11, 14, 17, 18 & 19]

Hydrogen energy storage has the highest power rating. Although Hydrogen energy storage can reach power ratings of 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 [24].

Furthermore, redox flow batteries and lithium-ion batteries 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.

In terms of round-trip efficiency, redox flow batteries and lithium-ion batteries 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.

In terms of 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 redox flow batteries and lithium ion batteries, 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.

In connection with initial capital costs, PHES also stands out on top. 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 per 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 per 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 per year of operation. This is significantly higher than CAES and PHES.

Redox flow batteries 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, lithium-ion batteries 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 Lithium-Ion Batteries in the middle of the spectrum at similar costs to CAES.

The final factor for consideration is operational costs. PHES and CAES both have operational costs of 16 $/kWh. Redox Flow Batteries have operational costs of 10 $/kWh. Lithium-ion batteries have operational costs of 8 $/kWh. Hydrogen energy storage has operational costs of 0.008 $/kWh. Hydrogen energy storage has operation costs significantly lower than all the other energy storage methods. Operational costs for batteries are lower than operational costs for PHES and CAES, as well. However, operational costs are not as important as initial capital costs because they make up at most 1-2% of total costs. Although hydrogen energy storage has the lowest operational costs, it also has the highest capital costs.

Thus, PHES appears to be the most promising energy storage method. In terms of maximum power rating, PHES comes second only to hydrogen energy storage, with the former achieving a power rating of 1 Gigawatt and the latter achieving a power rating of 5 Gigawatts. Although hydrogen energy storage has a maximum power rating five times that of PHES, hydrogen energy storage can be up to five times as expensive as PHES in terms of initial costs.

Hydrogen energy storage also has a 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.

For integration with solar energy, power rating and maximum energy capacity are far more important than round-trip efficiency because solar energy is readily available in large quantities. Compared to other large-scale energy storage methods such as CAES and hydrogen storage, PHES has a much higher round-trip efficiency. CAES and Hydrogen Storage both have round-trip efficiencies of roughly half of PHES.

In terms of lifetime, PHES has the longest out of all the 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 cost 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 the purposes of integration with solar energy, this is not a significant disadvantage because space is often readily available near large, rural solar arrays.

In summary, PHES performs extremely well 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, for the purposes of integration with solar energy, factors like Maximum Power Rating, Lifetime, and Round-Trip Efficiency matter significantly more than volumetric energy density and initial capital cost. Solar Energy Facilities are usually found in rural areas with ample space. These facilities are also generally subsidized by the government with an ample amount of funding. Meanwhile, maximum Power Rating, Lifetime, and Round-Trip Efficiency are more important for this specific use case because these characteristics characterize an energy storage method's efficiency and capacity.

LIMITATIONS

One potential limitation of this study is inaccuracies in the data for some metrics of comparison. Some data points are given as a range rather than a specific number. Another potential limitation of this study is a lack of real-life testing. Even though the data suggests PHES is the most promising, PHES may not work as well as the data suggests in the real world, where more uncertainties exist. One final limitation is a lack of metrics for comparison. In this study, only six metrics were compared. However, there are many more metrics, such as energy capacity and gravimetric energy density, with not enough data available for comparison.

CONCLUSION

In this article, six energy storage methods–iincluding pumped-hydro storage, compressed air energy storage, thermal energy storage, redox flow battery, hydrogen energy storage, and lithium-ion batteries–were compared to determine which method is the most strategic for large-scale, solar energy storage. Pumped-Hydro 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 a promising method of solar energy storage, especially crucial during times of excess energy production, peak demand, and grid instability. In order 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 for wider adoption of renewable energy storage.

REFERENCES

[1] “Solar,” IEA. Accessed: Sept. 03, 2025. [Online]. Available: https://www.iea.org/energy-system/renewables/solar-pv

[2] Tycorun, “What is lithium ion battery how do lithium ion batteries work？,” Tycorun Batteries. Accessed: July 14, 2025. [Online]. Available: https://www.tycorun.com/blogs/news/what-is-lithium-ion-battery-how-do-lithium-ion-batteries-work

[3] R. Baxter, “CHAPTER 25 ENERGY STORAGE SYSTEM PRICING”.

[4] K. Mongird *et al.*, “An Evaluation of Energy Storage Cost and Performance Characteristics,” *Energies*, vol. 13, no. 13, Art. no. 13, Jan. 2020, doi: 10.3390/en13133307.

[5] “Fact Sheet | Energy Storage (2019) | White Papers | EESI.” Accessed: July 13, 2025. [Online]. Available: https://www.eesi.org/papers/view/energy-storage-2019

[6] M. I. Khan, R. Gilani, J. Hafeez, R. Ayoub, I. Zahoor, and G. Saira, “Chapter 3 - Advantages and disadvantages of lithium-ion batteries,” in *Nanostructured Lithium-ion Battery Materials*, S. Thomas, A. B. Gueye, O. Savadogo, and H. J. Maria, Eds., in Micro and Nano Technologies. , Elsevier, 2025, pp. 47–64. doi: 10.1016/B978-0-443-13338-1.00017-4.

[7] J. Asenjo-Pascual, I. Salmeron-Sanchez, J. R. Avilés-Moreno, P. Mauleón, P. Mazur, and P. Ocón, “Understanding Aqueous Organic Redox Flow Batteries: A Guided Experimental Tour from Components Characterization to Final Assembly,” *Batteries*, vol. 8, no. 10, Art. no. 10, Oct. 2022, doi: 10.3390/batteries8100193.

[8] P. Vanýsek and V. Novák, “Redox flow batteries as the means for energy storage,” *J. Energy Storage*, vol. 13, pp. 435–441, Oct. 2017, doi: 10.1016/j.est.2017.07.028.

[9] P. Vanýsek and V. Novák, “Redox flow batteries as the means for energy storage,” *J. Energy Storage*, vol. 13, pp. 435–441, Oct. 2017, doi: 10.1016/j.est.2017.07.028.

[10] E. Encyclopedia, “Compressed air energy storage - Glossary - Energy Encyclopedia.” Accessed: July 14, 2025. [Online]. Available: https://www.energyencyclopedia.com/en/glossary/compressed-air-energy-storage

[11] K. Mongird, V. Viswanathan, J. Alam, C. Vartanian, V. Sprenkle, and R. Baxter, “2020 Grid Energy Storage Technology Cost and Performance Assessment,” 2020.

[12] S. Ahmed, D. Flowers, and P. Balducci, “Technology Strategy Assessment - Compressed Air Energy Storage,” Department of Energy, July 2023. [Online]. Available: https://www.energy.gov/sites/default/files/2023-07/Technology%20Strategy%20Assessment%20-%20Compressed%20Air%20Energy%20Storage_0.pdf

[13] C. Prieto, A. Blindu, L. F. Cabeza, J. Valverde, and G. García, “Molten Salts Tanks

Thermal Energy Storage: Aspects to Consider during Design," *Energies*, vol. 17, no. 1, Art. no. 1, Jan. 2024, doi: 10.3390/en17010022.

[14] C. K. Ho and A. Ambrosini, "CHAPTER 12 THERMAL ENERGY STORAGE TECHNOLOGIES," *Therm. Energy Storage*.

[15] W. H. Balliet, L. McLaughlin, Z. Ma, and K. Glusenkamp, "Technology Strategy Assessment - Thermal Energy Storage," Department of Energy, July 2023. [Online]. Available: https://www.energy.gov/sites/default/files/2023-07/Technology%20Strategy%20Assessment%20-%20Thermal%20Energy%20Storage.pdf

[16] X. Liu *et al.*, "Offshore Wind Power—Seawater Electrolysis—Salt Cavern Hydrogen Storage Coupling System: Potential and Challenges," *Energies*, vol. 18, no. 1, Art. no. 1, Jan. 2025, doi: 10.3390/en18010169.

[17] A. J. Headley, "CHAPTER 11 HYDROGEN ENERGY STORAGE," Sandia National Laboratories, Mar. 2022. [Online]. Available: https://www.sandia.gov/app/uploads/sites/163/2022/03/ESHB_Ch11_Hydrogen_Headley.pdf

[18] "Fact Sheet | Energy Storage (2019) | White Papers | EESI." Accessed: July 14, 2025. [Online]. Available: https://www.eesi.org/papers/view/energy-storage-2019

[19] R. Armstrong and Y. Chiang, "The Future Of Energy Storage," MIT, Cambridge, 2022.

[20] A. J. Headley, "CHAPTER 11 HYDROGEN ENERGY STORAGE".

[21] "What Is Pumped Hydro Storage, and How Does It Work?" Accessed: July 14, 2025. [Online]. Available: https://blog.yesenergy.com/yeblog/what-is-pumped-hydro-storage-and-how-does-it-work

[22] H. R. C. Directors, "NREL includes pumped storage in 2022 electricity technology baseline report," Factor This™. Accessed: July 14, 2025. [Online]. Available: https://www.renewableenergyworld.com/energy-storage/pumped-storage/nrel-includes-pumped-storage-in-2022-electricity-technology-baseline-report/

[23] C.-J. Yang and R. B. Jackson, "Opportunities and barriers to pumped-hydro energy storage in the United States," *Renew. Sustain. Energy Rev.*, vol. 15, no. 1, pp. 839–844, Jan. 2011, doi: 10.1016/j.rser.2010.09.020.

[24] "Gigawatt: The Solar Energy Term You Should Know About - CNET." Accessed: July 14, 2025. [Online]. Available: https://www.cnet.com/home/solar/gigawatt-the-solar-energy-term-you-should-know-about/