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Review

Improving the Performance of Solar Thermal Energy Storage Systems

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Abstract

In recent times, renewable energy resources have been greatly researched because of the increasing concern to minimize global warming and meet energy demands. Energy storage systems have become useful tools for sustainability and meeting energy needs. Solar energy has proven in recent times to be the primary and most prevalent option due to its environmental friendliness, availability, and minimal pollution. Effective utilization of available energy resources has led to developing new alternative energy devices like the solar thermal energy storage system (STESS) with a solar energy source. Solar thermal energy systems are efficient systems that utilize solar energy to produce thermal and electrical energy. This review aims to give a detailed overview of solar TESS, different TES application systems, and effective methods of increasing the system performance to provide energy during deficient times. The various classifications, basic components, the principle of operation, application areas of STESSs, prospects, and extensive reviews on these aspects have also been discussed in this review. The different factors to be considered geared towards meeting energy demands and increasing the efficiency of solar TES systems have been duly detailed. This review is a single manuscript with a detailed overview of STESS, the principle of operation and components of STESS, thermal energy storage materials, a description of different application systems, and a discussion of factors responsible for improving the system efficiency.

Keywords
Efficiency; global warming; renewable resources; solar energy; STESS

1. Introduction to Solar Thermal Energy Storage Systems (STESS)

Solar energy is essential to sustaining modern-day energy and is a better choice than fossil fuels. The energy obtained from solar radiation undergoes attenuation as shown in Figure 1 and could be utilized in thermal and electrical energy technologies and stored in energy storage devices. To ensure energy sustainability, efficient storage systems should be effectively implemented to minimize heat losses. To effectively utilize the energy; essential factors like increasing peak-to-valley difference and power generation technologies which aid further development of renewable energy technologies should be considered. Solar thermal energy storage system (STESS) generates thermal energy using absorbed solar energy which can be transmitted from the heater to the coolant. It is made up of a solar collector, a control unit with a pump, and a tank for storing hot water [1]. It allows for easier heat storage on a large scale and thermal energy use at deficient times [2]. Water flows through the collectors, gets heated by the sun, and pumped through a heat exchanger for water heating in the storage tank. The solar collector converts solar irradiation to either the thermal energy of the working fluid in solar thermal applications or the electric energy directly in photovoltaic applications [3]. During insufficient solar thermal heat periods, an additional heat exchanger within the boiler is used to heat more water. Solar thermal storage entails accumulating energy collected by a given solar field for subsequent use; either for electricity generation on demand or for use in industrial processes. It acts as a good storage method for thermal energy. Solar TES is cheaper with minimal environmental pollution compared to battery storage. Heat transfer medium (HTM) refers to the fluid or other materials that are useful in transporting thermal energy from the solar receiver to the thermal energy storage (TES) and from TES to the turbine or industrial chamber. TES temperature refers to the amount of stored heat accumulated during the thermal exchange and stored afterward [4]. The heat supplied can be stored using phase change materials (PCM), molten chloride salts, solid particles, ice-slush tanks, advanced alloys, etc. The amount of stored solar thermal energy used depends on the energy demand between daytime and nighttime and seasonal energy demands [5].

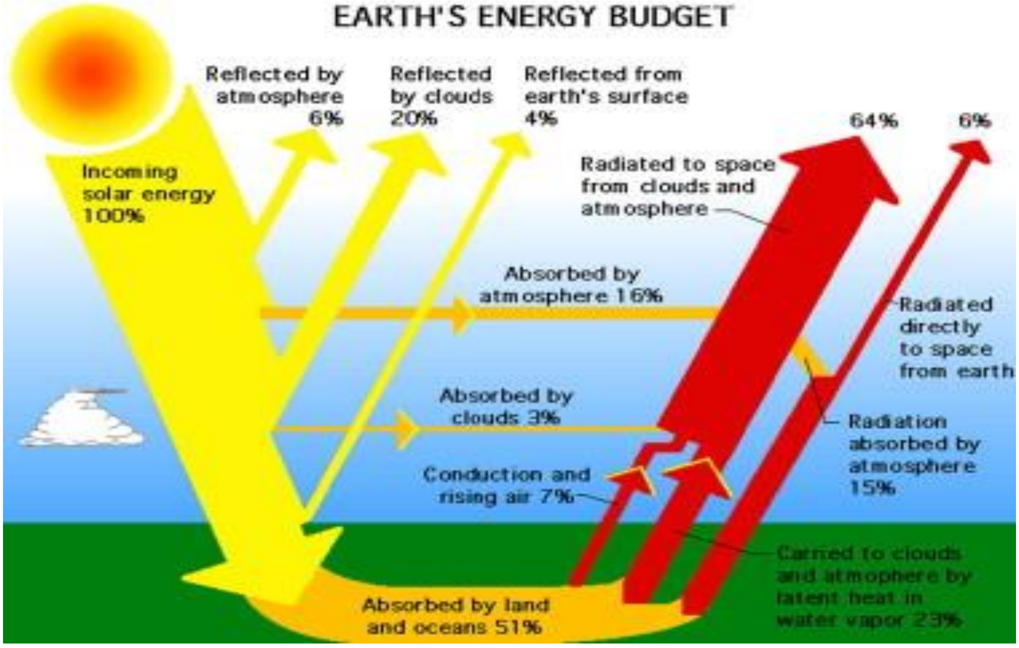

Figure 1 Energy distribution of incident solar radiation [3].

Solar thermal energy has storage forms of sensible heat storage (SHS), latent heat storage system (LHS), or thermochemical heat storage (THS) as outlined in Figure 2. SHS could be in a liquid or solid state and stores thermal energy as the thermal storage media falls or rises [3]. It uses safe, affordable, thermally conductive, and high storage capacity materials like water tanks, molten salt, hot silicon, heat transfer fluids, metal, etc to store thermal energy within temperatures ranging from 200°C to 1200°C. Due to the reliance on the characteristics of the storage media, SHS is constrained by the specific heat capacity of the storage medium.

A latent heat storage (LHS) system involves the phase transition of phase-change materials (PCM) that allows the addition or extraction of heat without obviously altering the temperature of the material [5]. They are safer and have a more reliable thermal energy storage density that can be utilized at medium and low temperatures. PCMs like paraffin waxes, polymers, metal alloys, liquefied air, and gels have high storage capacities, good thermal conductivity, high latent heat, compact storage units, and operate passively. PCMS can store energy diurnally (in the form of ice water and hot water each for cooling and heating) or seasonally (minimizes energy deficiency at periods of absent solar radiation) [6]. They can transit states upon addition or removal of heat. They operate by accumulating heat, storing it, and releasing it at constant temperature conditions. They are useful in regulating heat and optimizing device performance. They can be encapsulated within building surfaces to store thermal energy for cold periods. Some phase change materials undergo photo-activation where solar irradiation controls the performance of the thermal material [6]. Few PCMs suffer poor heat transport mechanisms which makes them less thermally conductive. The amount of PCM added determines the peak temperature that would be made available. PCMs can also be classified into organic (less corrosive, expensive, and prone to flammability), inorganic (less flammable, available, and affordable), and eutectic (low specific heat capacities and low latent heat) materials [7]. LHS systems should be carefully designed (especially during the encapsulation of the PCM) to minimize heat loss. They are also useful for solar thermal utilization and waste heat recovery owing to their thermal energy storage density and thermal stability as it charges and discharges [7]. The increased latent heat of PCMs as they transit from the solid to liquid phase makes them useful materials for thermal energy storage [6]. Kalidasan et al. reviewed trending issues, challenges, and better experimental means of improving solar thermal energy systems [8]. Their review clearly stated phase change materials' environmental benefits and payback period. Thermochemical heat energy storage (TCES) uses reversible exotherm/endotherm chemical reactions through thermochemical materials (TCM) to store large heat capacity, depending on the reactants used. Thermochemical storage (TCS) materials could be organic or inorganic and should be available with increased thermal conductivity, quicker reaction kinetics, more cyclic stability, and high enthalpy of reaction [9]. TCS systems include salt hydrate technology, molecular solar thermal systems, etc. Reversible TCS is responsible for storing and releasing heat during reversible reactions. Metal hydrides exhibit good stable cycles, reversible nature, and increased enthalpies. High-temperature systems can be classified into solid-gas, liquid-gas, and gas-gas categories and exhibit increased energy storage density, wide temperature range, and long-term storage [1]. The reactor design primarily depends on the reaction's nature while the thermal energy source is then transported to the reactant. TCES is very useful for converting, storing, and transporting solar energy. Solar heating systems can be active or passive. Passive solar thermal storage systems are less complicated, affordable, and require fewer components.

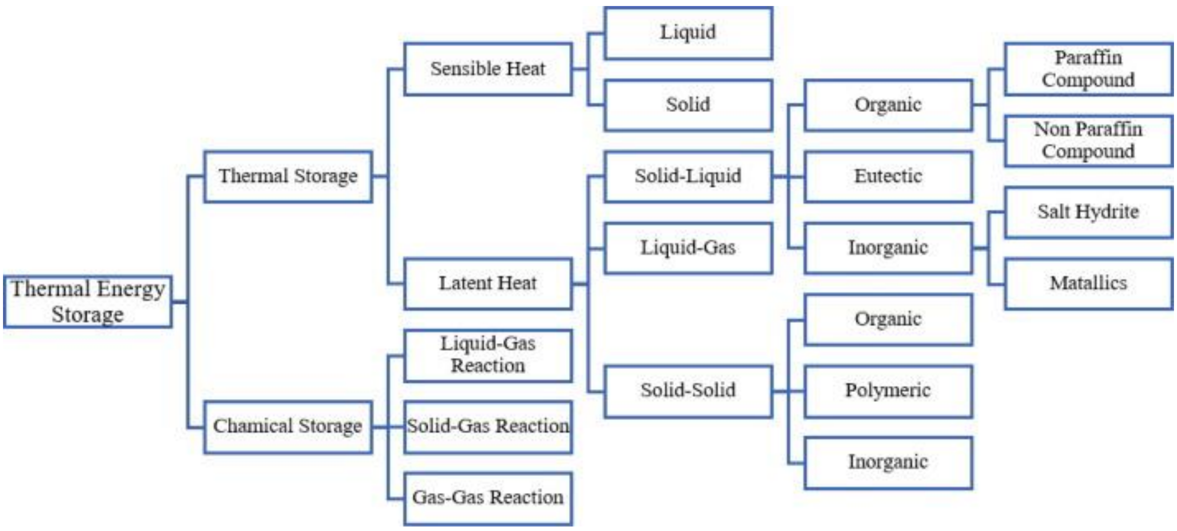

Figure 2 Classifications of thermal energy storage [10].

This review has successfully given an overview, of the basic components, and principles of operation of solar thermal energy storage systems. Application areas and factors to be considered for improving the performance of STESSs have been discussed. This review has also detailed performance improvement strategies of several STES devices, previous reports of solar thermal storage systems, prospects, and recommendations for solar thermal energy storage systems. These concepts in this single manuscript distinguish it from previously reported works.

2. Basic Components and Operation of Solar Thermal Systems (STSs)

The solar energy gets transformed into various forms and channeled for various applications upon solar irradiation on the solar collector, as seen in Figure 3. The major components of STSs include a collector, pipes, controller, tank, water feeds, boiler, and pump. They have highly performing mechanisms of increasing power conversion efficiency and energy storage density. An automated solar thermal controller operates the solar thermal system. The collector is the major solar thermal component. It is usually installed on rooftops. It has specially coated reinforced glass pipes that capture solar radiation, transforming it into thermal energy [11]. The control is automated as the collector temperature rises more than the storage tank temperature. The pump switches on and transports the heated transfer fluid to the thermal water tank. The pipes which carry heat transfer fluids are encapsulated within the insulator to minimize thermal loss. The thermal transport fluids in the pipes are fluids or other materials used to transport heat from the solar receiver to the thermal energy storage and from TES to the turbine [12]. They include liquids and molten nitrate salts made of eco-friendly antifreeze and circulated through the collector and hot water tank. Proper treatment of the boiler feedwater helps to preserve the boiler efficiency, steam quality, and equipment uptime.

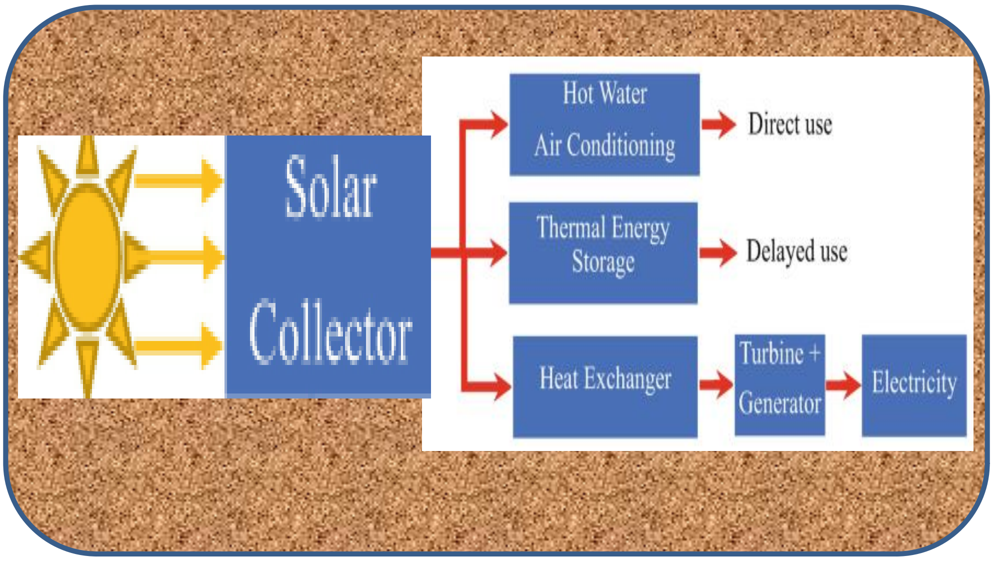

Figure 3 A schematic of the working pathway for solar thermal energy systems.

Kim et al. generated fuel from carbon dioxide using STE systems while adopting solar-chemical energy conversion [13]. They obtained a configuration that effectively splits carbon dioxide and water to reduce the cost of utilities and get a 6.4% rate at interest. Tian and Zhao reviewed the use of solar collectors for solar thermal applications [3]. Their review focused on diverse heat transport-enhancing methods, solar-tracking mechanisms, and advancements in the applications of solar thermal devices. STES systems have also been modeled to enhance energy efficiency in ceramic plants [14]. Solar TESS has been technically assessed based on their design, development, and factors affecting the storage systems [15, 16]. They were able to determine the optimum tuning parameter that affects the rate of heat demand-supply chain. Otanicar, Phelan, and Golden studied the optical features of liquids that are useful absorbers in solar TES [17]. They achieved this by developing an experimental technique to determine the extinction and refractive indices of the liquids. Amongst the liquids, the water showed better absorption features at 13% and could be potentially applied in solar thermal collectors. Kumar, Hasanuzzaman, and Rahim have properly discussed the advancements, design, and prospects in solar thermal energy technologies. Ahmad, Reynolds, and Rezgui predicted a model for detecting faults, diagnosing, and determining the performance of STES [18]. The different tree-based models were compared in terms of their cost, correctness, and stability with the random forest model showing useful potential for use in solar thermal collectors. Oró, Chiu, Martin, and Cabeza studied numerical models of packed-bed TES and discovered that forced convection is a major influencing factor compared to free convection [19].

3. Application Areas of Solar Thermal Storage Systems (STSS)

The applications of STSSs are increasingly gaining attention owing to the high performance of solar thermal systems, improved energy storage density, and high energy conversion efficiency [20]. The solar collector absorbs solar irradiation as heat and gets transported to the working fluid as outlined in Table 1 [3]. Solar thermal applications encompass solar collectors (concentrating or non-concentrating collectors) and thermal energy storage components [21]. Concentrating collectors have a better concentration ratio, higher temperatures of the working fluid, and better thermodynamic efficiency than non-concentrating collectors [3]. Solar collectors are required to be optically active with high thermal absorption while thermal storage systems should have increased thermal storage density, a great rate of heat transfer, and excellent durability over the long term [22]. The heat transported by the working fluid is useful in reducing large energy bills in residential and commercial settings. It is most beneficial to buildings with huge energy needs, expensive heaters, and for biomedical applications. The stored thermal energy is useful for passive solar heating, ventilation, air conditioning, and cooling via a vapor absorption refrigeration system [23]. Developing a cost-effective commercial solar thermal power plant integrated with solar collectors is feasible and achievable [23].

3.1 Concentrated Solar Power Plants (CSPPs)

Concentrated solar power (CSP) plants are utility-scale plants that efficiently obtain electricity from incident solar radiation using solar heat concentrating mirrors [24]. Such plants use parabolic dishes, troughs, and solar tower power plants. The mirrors channel the solar radiation on receivers containing the heat transport fluid for generating heat. It is a useful renewable energy system used to generate electricity because it provides dispatchable electricity. Nitrate salts serve as the heat transport medium responsible for delivering heat energy. Using TES increases the reliability of CSPPs during periods of weak solar irradiance. It helps to store the heat transfer fluid either as direct or indirect storage for use at a later time [25]. It allows the CSP to produce electricity at night and on periods when energy is insufficient using heat engines based on Brayton, Rankine, and Stirling cycles [20]. Energy can be stored mechanically, thermally, or electrically in the plant. The solar thermal energy medium can be a cascade-type PCM storage or molten salt TES [5]. The molten salt TES systems are thermally stable with low viscous nature, high heat conduction, and non-toxic nature and serve as an indirect storage system that can discharge at regulated conditions [26]. It maintains high cycle efficiency and is usually incorporated with parabolic trough and tower systems. Thermal energy storage adopts latent heat change of materials in storing the solar heat energy in a power plant. In designing collector solar plants with TES capacity, the solar multiple (SM) value should exceed one [27]. The CSP setup can also include an air-cooled condenser to increase plant performance. For optimization, the power conversion efficiency is relevant in accounting for thermal losses in the system. Coupled TES technology with CSP plants yields better temperature control and higher operating temperatures of the coupled system [20]. Integrating TESS into concentrated solar power increases the energy-storing capacity which encourages sustainability.

Pérez-Higueras and Fernández extensively discussed the basics, engineering methods, and optimum design of concentrator power plants [28]. Bakos and Antoniades introduced the use of elastic films in designing dish solar collectors with primary and secondary mirrors [29]. They obtained a nominal power of 10 MW and an estimated annual production of about 11 GWh. Ahmadi et al. critically proved the economic benefits of concentrator solar plants regarding national return and their suitability in generating power [30]. Ghodbane et al. numerically investigated solar collectors to determine the local concentration ratio, efficiency, shading effects, and optical losses [31]. 77.22% efficiency and 116.3 ratios for the local concentration were obtained for the collector. Santos et al. thermodynamically evaluated the effect of coupling the organic Rankine cycle onto solar concentrators [32]. They obtained efficient devices that can convert solar energy into electricity. To improve the performance of solar concentrators, Wang et al. developed a new double-stage dish concentrator that would allow the mirrors to overlap and minimize excessive shading effects [33]. The novel concentrator which had a compact mirror structure was able to reduce the size of the receiver. A comparative analysis of solar concentrators aided by natural gas was modeled by Siva Reddy, Kaushik, and Tyagi using an analytic energetic model [34]. They observed that the device would heat water and generate steam.They observed that the device would heat water and generating steam. Increased solar concentration has been shown by Zeitouny to negatively impact the efficiency and photovoltaic performance of solar power systems [35]. Africa has also suffered national and economic setbacks from the electricity deficit [36]. However, concentrator solar plants have good potential for boosting electricity in South and North Africa [37-39].

3.2 Compressed Air Energy Storage (CAES)

This medium-scale and large-scale energy-storing technology minimizes unstable renewable energy output and increases the utilization rate [4]. During a period of energy deficiency, energy gets stored by compressing air in an air-tight space under high pressure. CAES comprises combustion chambers, compressors, expanders, compressed air storage, and motors/generators as shown in Figure 4. While storing energy; air goes into the compressor from the atmosphere, undergoes compression to high-pressure air, and is preserved in the compressed air storage. As heat is released, the stored air goes through the combustion chamber, gains more temperature and pressure, enters the expansion chamber, and releases electricity as output. Heat loss is encountered when the exhaust is channeled directly into the environment. The solar thermal energy storage in CAES is responsible for cooling the heated compressed air during the energy storage phase. It is a good way of resolving setbacks associated with CAES [4]. TES setup has heat exchangers for compression and expansion, a thermal energy storage medium, and a heat accumulator that serves as the medium storage [4]. The compressed air heat can be transferred in the thermal exchanger using a gas-liquid or gas-solid heat transport through the medium. The heat removal factor as a major determinant of system efficiency is the ratio between the absorbed heat from the solar collector to the highest thermal energy available [40]. It is obtained based on the thermal and physical characteristics of the moving fluids and influences the performance of the solar thermal collector.

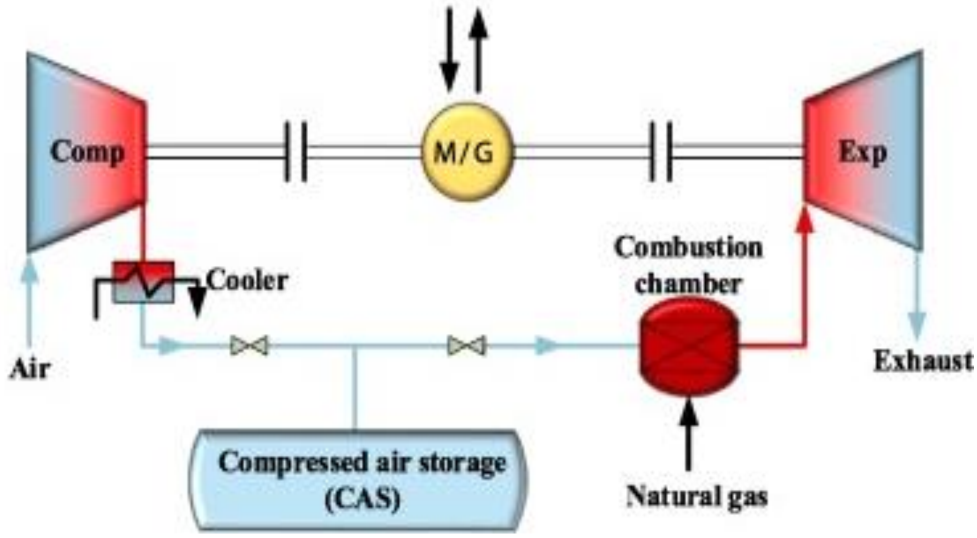

Figure 4 Schematic of the operation of CAES systems [4].

Lund and Salgi studied the essence of incorporating CAES into future energy technologies [41]. Their observation revealed a potentially feasible technology for the present and future markets. But, Wolf, Span, and Yan reviewed the basic principles and achievements of compressed air energy storage systems to enhance the system's understanding and efficiency [42]. The value of CAES was investigated by optimizing the use in market reserves [43]. The dispatch strategy is envisaged to be independent of the variables adopted in the design process. Different CAES configurations have been analyzed based on their sensitivities and using an energy balance [44]. The polytropic adiabatic device structure yielded 60% efficiency and depends on the extent of demand. Wang et al. experimentally studied CAES devices incorporated with water as thermal energy storage [45]. A roundtrip efficiency of 22.6% and the highest power of 430 kW was obtained for the developed system. Wolf and Budt developed an adiabatic CAES that would perform under low-temperature conditions [46]. Their results confirmed that the temperature of the stored compressed heat did not affect the roundtrip efficiency of the system.

3.3 Parabolic-Type Collector Power Plants (PCPPs)

Parabolic type collectors encompass parabolic dish collectors and parabolic trough collectors. Parabolic dish collectors (PDCs) have an arrangement of parabolic dish-shaped mirrors for focusing solar energy on a fluid-carrying receiver placed at the focal point of the dish mirrors [3]. The heat transfer fluid gets heated to working temperatures and pressures for electricity generation. PDC solar-thermal systems exhibit minimal initial losses and can be modulated for scale-up and increased optical efficiency. Parabolic trough collectors (PTCs) use mirrors with curvatures to concentrate sunlight onto a receiver depending on the trough size [27]. PTCs are scalable and have higher tracking accuracy. The functional components of the plant system include the solar field collector system, power block, and TES material. The PTC focuses the solar radiation on a receiver while the receiver tube carries the heat transfer fluid for heat absorption. A two-tank TES system is incorporated in storing the heat energy and allows the power block to operate continuously during sunlight-deficient periods [27]. For PTCPPs, choosing a heat transfer fluid is crucial as it plays a major role in facilitating maximum performance at a minimal cost. A Nonlinear Genetic algorithm is a good way of enhancing the performance and storage capability of PTC solar thermal power plants [27]. It is an optimization approach that determines the system efficiency using parameters like the plant performance, capacity factor, and levelized energy cost. Studies have shown that increased solar radiation, improved heat gain, and minimized heat loss contribute to better PTCPP efficiency [47, 48].

Lecuona et al. proposed an affordable solar cooker made of phase change materials for effectively storing heat and for potential use in parabolic power systems [49]. A one-dimensional model was used to perform the cooker's efficiency during hot seasons and predict the usage for three-course meals. A Bragg bottom-type parabolic collector having a spatial layout was proposed by Hao et al. to investigate their wave amplification characteristics [50]. This device layout yielded better performance with an optimum collection angle of 82 to 115 degrees. A copper tube coated with aluminum was incorporated in developing a parabolic-type solar water heating system [51]. They obtained a mass flow rate of 2.5 kg per minute and a thermal efficiency of 31.85%. Kouche and Gallego numerically simulated parabolic trough collectors using parameters that depend on temperature [52]. Their model was based on nonlinear partial differential equations and could give useful information on plant efficiency.

3.4 Solar-Powered Heaters

Solar-powered systems involve systems used in heating surrounding using air or water medium. Air and water are useful media that are efficient and earth-abundant. Integrating TES with solar air heaters is an efficient way of solar energy storage for heating the air before and after sunset. This energy storage system works significantly in regions with a great temperature difference throughout the day. This energy demand and supply imbalance could be reasonably met using an efficient device for storing energy. Packed beds are useful for storing heat as warm air flows in solar air heaters by transmitting the air heat from the topmost to the bottom of the bed. These packed beds are affordable, easy to manufacture, and used in tandem with solar air heaters [53]. Proper insulation of the packed bed allows energy to be trapped as the temperature of the solid material increases. The energy stored as latent heat, chemical energy, or sensible heat can be retrieved by transporting cold air from the bottom of the bed to the top. The packed beds can undergo temperature complementation to increase the energy storage density, enhances stability, and improve the system performance [54]. Water heaters powered by solar energy have the bottom of the heaters filled with phase change materials for thermal energy storage [6]. Solar cookers also utilize solar energy in heating food and sanitizing food. Here, the incident solar light focuses the reflecting surface onto the narrow cooking area to generate heat. The more solar radiation on the reflector, the more thermal energy stored.

Chauhan et al. designed a transparent solar air heater where the heating source was an aluminum plate [55]. The heat source proved efficient and a 101% temperature increase was recorded for the heated air. Solar heaters were combined with heat and power systems for heat generation and electricity production [56]. Wang et al. proposed a solar-powered heater for heating water up to 90 degrees Celsius [57]. A heat storage unit was coupled with a solar thermal collector in a dynamic model proposed by Lamrani et al. [58]. They observed increasing thermal power and storage density as the water was replaced with phase-change materials.

3.5 Pumped Thermal Energy Storage System (PTESS)

PTESSs are efficient energy storage technologies with increased energy densities, and capacity, affordable, and do not need a special installation site [59]. It is useful for storing heat in hot and cold storage systems as it charges and converts to electric current after discharge. It has a power block allows it to function as a heat pump and a TES device has high and low thermal storage units [54]. PTES has high efficiency for storing heat and adopts a left-running thermal cycling pattern. A breakdown of the TES materials and their classifications is shown in Figure 5. Heat is pumped from the low to the high-temperature storage during charging via a reverse power cycle [60]. As it discharges, it converts the heat stored to electric current via a power cycle. PTES systems use thermodynamic cycles like Rankine and Brayton-Joule modes [59]. Rankine mode occurs when the electricity demand exceeds than the energy produced, causing the Carnot battery to generate power from thermal storage. For the Rankine cycle; thermal energy is generated during charging through a heat pump cycle while the heat stored is used to generate electric current [54]. Brayton-based PTES system acts as a Brayton heat pump as it charges while it acts as a heat engine during discharging phase. Releasing thermal energy appropriately from heat storage can enhance the stable nature of the working fluid while discharge and thus, increase the system efficacy [59]. PTES works within certain pressure limits such that the working fluid would not be directly heated and increased pressure in the thermal reservoir could be reduced. To improve roundtrip efficiency, Wang et al. proposed thermally integrating PTESS with a system that distributes natural gas [61]. Integrating PTES systems with concentrator solar plants eliminates capacity limits and increases the system efficiency by evaluating the compressor pressure ratio and the outlet temperatures of the water coolers. For PTES-CSP configuration, the highest temperature is independent of the outlet temperature and more sensitive to varying operating conditions [59]. Performance indices should be estimated on the assumption that the system is filled with the thermal energy storage material as it discharges, negligible TES thermal losses, and assume constant temperature within the storage vessels [59]. This performance index helps to determine the system's efficiency and evaluate its performance as the design conditions are varied.

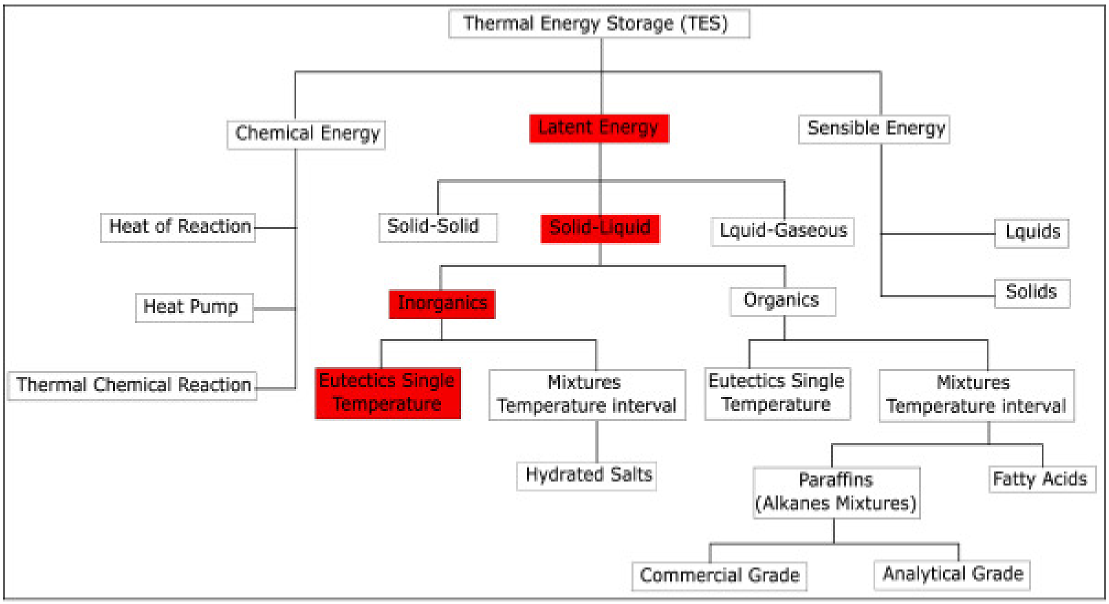

Figure 5 Classification of thermal energy storage materials [24].

White, Parks, and Markides discussed the thermodynamic properties of PTES like energy density, power density, and efficiency for roundtrip [62]. Upon further analysis of parameters influencing the efficiency, the system was susceptible to compression and expansion irreversibility. Dumont and Lemort reported that PTES performs excellently at low air temperatures, high waste heat , and low lift heat pumps [63]. Davenne and Peters simulated a model capable of a roundtrip efficiency of over 50% and having large-scale application areas [64]. A new PTES integrated with thermal heat storage was proposed by Frate, Antonelli, and Desideri and simulated under steady-state conditions [65]. Integrating the thermal system raised the efficiency above 100%. roundtrip efficiency of over 50%, increased energy density, and higher sensitivities for the PTES system were obtained by Blanquiceth et al. [66].

3.6 Solar-Aided Power Generation (SAPG)

SAPG technology is an effective technology that integrates solar thermal energy into coal-fired power plants [67]. It uses solar radiation to produce an electric current (as compared to concentrator solar plants) and minimizes fuel consumption [2]. Here, solar thermal energy is a good substitute for extracting steam for preheating feed water in a regenerative Rankine system. The solar field collects solar radiation and is moved by the HTF which keeps preheating the feedwater via a heat exchanger. The stored extraction steam continuously expands in the turbine for generating power. The rate of flow of the HTF is regulated by the oil pump in the solar field and the amount of heat released changes with solar radiation. A change in the solar field output determines the power generated, especially when operating in the power boost mode. An advantage of SAPG is using extraction steam in preheating the feedwater during insufficient heat times in the absence of TES, thus avoiding the high cost associated with TES [68]. So the SAPG can operate continuously even at periods of low solar energy as seen in the works reported by Huang [2], and Hong [69]. Proper regulation of TES integrated into a SAPG plant yields increased efficiency and performance improvement [68]. Several studies have revealed the affordability and better efficiency of SAPG technology. Hu et al. utilized solar thermal energy as a substitute heater in the extraction steam of a regenerative Rankin power station [67]. Huang et al. investigated a 330 MW SAPG plant model to explain the impact of fluctuating radiation on the system performance [67]. To maximize the performance of a SAPG plant, incorporating a direct air-cooled condenser in power-boosting mode as illustrated in Figure 6 is recommended [68]. Regarding the amount of load required, the power-boosting mode requires that the power produced rises with the steam's flow rate while the fuel consumption rate reduces with the generator's capacity. Introducing solar heat in this mode changes the exhaust steam flow and turbine exit pressure.

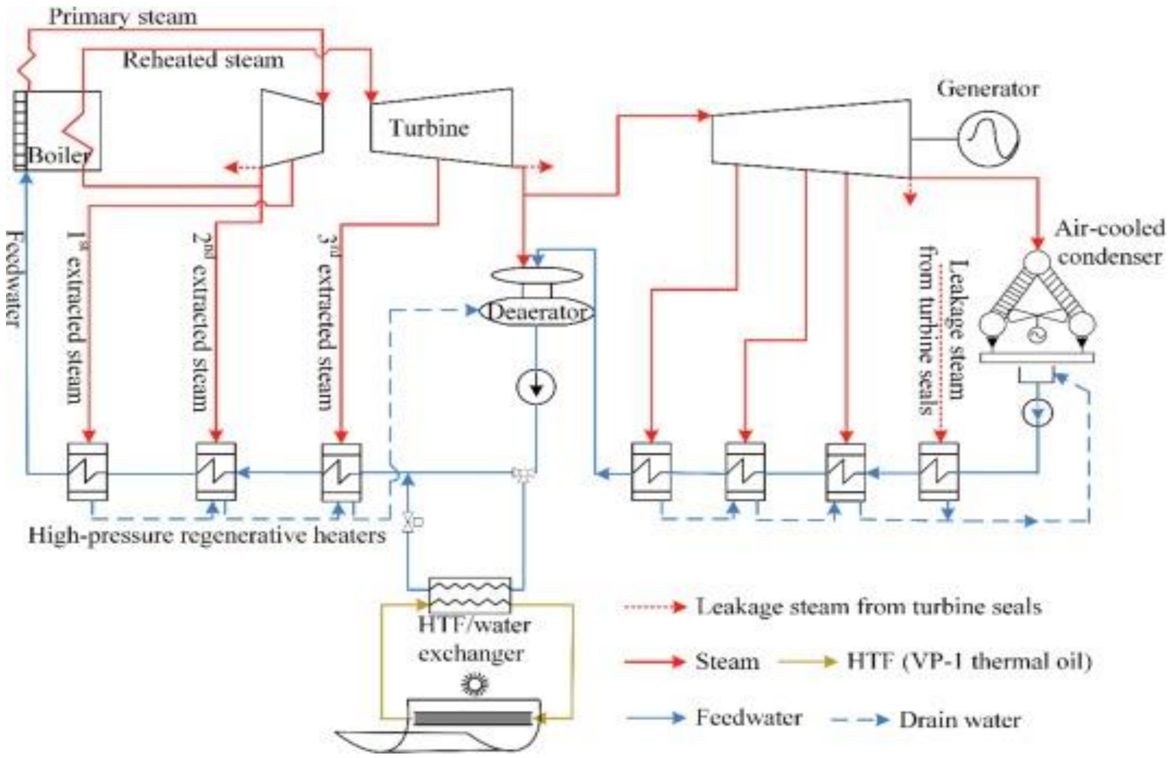

Figure 6 Schematic representation of a SAPG plant directly connected with an air-cooled condenser [68].

3.7 Salt Gradient Solar Pond (SGSP)

This refers to an artificial water body like a lake or pond that can absorb and store the incident solar irradiation as a sensible heat [70]. It has adiabatic walls and an open cavity filled with a saline solution. This technology works as a function of the salt gradient and is desirable because it is affordable, simple to operate, and has good thermal retention. It can economically store heat for longer periods. SGSP is divided into upper, lower, and non-convective zones which act as insulating zone, thermal storage units, and solar collectors respectively [71]. The performance of the SGSP system depends on the geometrical shape chosen, design pattern, zone thickness, and type of thermal storage material used. Circular geometry has been shown to exhibit better thermal retention as compared to square and rectangular-shaped geometries [70]. The salt acts as the thermal storage medium whose rate of thermal extraction affects the device's efficiency. The state of the pond is influenced by the kind of salt used and the salt concentration. To boost the salt performance and curtail heat loss, enhancers like gels, phase change materials, and floating rings can be integrated into the setup [70]. Although this technology suffers from thermal instability over time, they have the potential to power stand-alone grids thermally and electrically. SGSP finds vast application in solar distillation, electricity production, and industrial activities.

Zangrando detailed the procedure for establishing salt gradient solar ponds in a published review [72]. The process begins by partly filling the aquatic body with highly saline brine and pumping fresh water through a solution-immersed diffuser. This procedure is simple, affordable, and requires less maintenance. Rghif, Zeghmati, and Bahraoui adopted double-diffusive convection in modeling SGSP to understand the heat retention rate [73]. Their model revealed that the thermal efficiency of the device is independent of the Soret effect, but depends on the Dufour effect. Dufour and Soret effects on the convection pattern of the ponds have been numerically analyzed [71, 74]. Their results showed that increasing the Dufour coefficient enhances thermal transport and minimizes heat loss [75]. The effect of integrating phase change materials on SGSP has been studied and revealed increased thermal losses upon the addition of PCMs [76]. The stability of the pond was experimentally studied to find dynamic methods of enhancing heat transport [77]. Experimental findings on the effect of double-diffusive convection on the calculation time were compared to numerical analysis with the numerical model giving more accurate thermal behaviors and a small error percentage [78]. The transient property of SGSP in the Mediterranean region has been investigated to prove that thermal energy is stored as sensible heat [79].

The different thermal energy storage systems have been compared regarding the numerical methods adopted, heat transfer fluid used, and advantages and disadvantages as outlined in Table 1.

Table 1 Comparative Analysis of the different thermal storage systems [80-85].

STESS	Numerical Models	Heat transfer fluid	Advantages	Disadvantages
Concentrated solar plants	1-D thermophysical model	Water, air, molten salts	Easy operation, electricity generation, provides a secure energy grid	Expensive, promotes deforestation, and requires large areas of land to operate.
Compressed air energy storage	3-D CFD	Air	Easy optimization, energy delivery, quick startup time	Low roundtrip efficiency, long response time, complex mode of operation
Parabolic-type collector power plants	Optical heat transfer & Thermofluidynamic model	Thermal oil, water, liquid sodium, molten salts	Good for stationary installation, able to trap direct & diffuse solar radiation, vast application areas, easy to fabricate and operate	Requires solar trackers, requires intense sunlight
Solar air heaters	Transient 2-D laminar model	Air, Mixture of water and anti-freeze/propylene glycol	No carbon dioxide emissions, reduced consumption of fossil fuels	Expensive, larger volumes of air due to the low air density, low thermal capacity of air
Pumped thermal energy storage	Dynamic simulation model	Hot molten salt, cryogenic liquid	Independent of location, long life expectancies, less environmental footprint, less expensive	Energy is lost in round-trip inefficiencies, complexities, requires additional infrastructures
Solar-aided power generation	Dynamic numerical model	Water, air	Requires renewable energy source, Abundant and efficient source,	High start-up costs, slow rate of recharging, low

			reduced greenhouse gas emissions	efficiency, unreliable solar radiation
Salt gradient solar ponds	1-D numerical DDT technique	Molten salt	Good harvesters of thermal energy, increased power efficiency	High environmental concerns and large-scale requirements

4. Factors to Consider Towards the Performance Improvement of STESS

4.1 Design of the Heat Exchanger

For heat exchanger design, the collectors are usually grouped according to the medium of removing heat using water or air. Water exhibits high thermal capacity and great optical characteristics. A tube configuration should be incorporated while designing the heat exchanger to make the discharge tube more effective due to the reduced thermal conductivity of the phase change material [86]. The absorber plate should be coated black for increased heat absorption. The absorbed heat must be transferred to the working fluids as fast as possible to reduce overheating [87]. Heat removal plates should be incorporated to cool the system to a particular temperature for higher efficiency and utilization in low-temperature systems like adsorption cooling systems and domestic hot water production [88]. Selective surfaces are made of a thin layer at the top that has high absorption to radiations with shorter wavelengths that are transparent to thermal radiations of longer wavelengths, and a thin layer at the bottom with more reflectance and less emittance to radiations of long wavelengths. The glazing cover should be coated with anti-reflectors to minimize losses and increase efficiency [3]. A fin design and highly porous metal matrix could also be used to increase the performance of PCM tanks [89, 90]. The recuperator can be coupled with the heat exchanger to increase the separation rate of the hot fluid from the cold fluid as it passes the partition plate and transfers thermal energy [4]. The recuperator has a simple structure with effective heat exchange mechanisms that enhance the performance of the heat exchanger. Porous insertions into a double-passage solar collector [91] as seen in Figure 7 and oscillating flow have been investigated to improve heat transfer [92, 93]. Francia also discovered that inserting a transparent honeycomb in the airspace between the absorber and the glazing is very useful for minimizing the loss of heat and increasing the thermal performance of a collector [94].

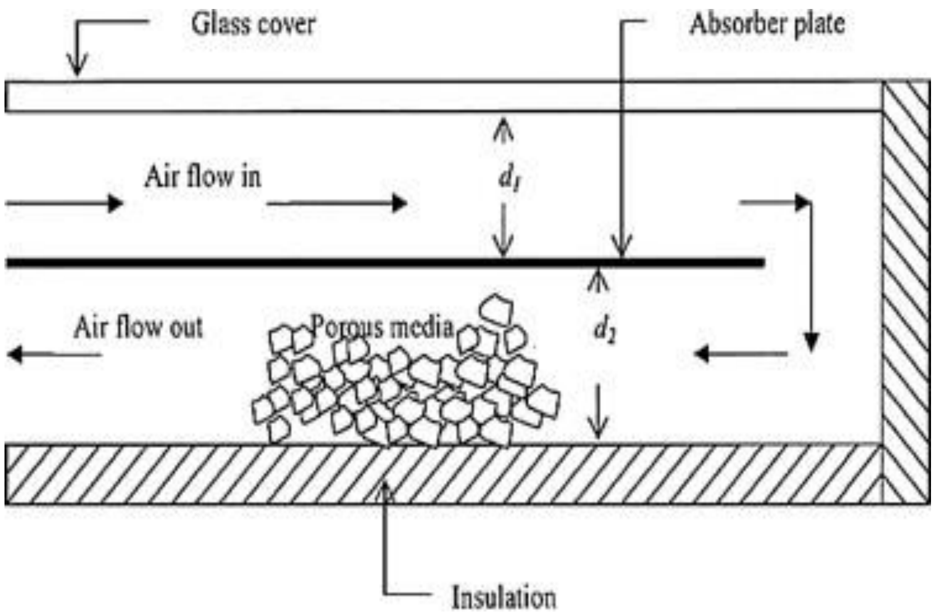

Figure 7 Porous insertion in the second channel of a double-passage solar collector [91].

4.2 Choice of Storage Medium

The choice of transfer exchange storage is crucial in determining the energy system's output. TES technology has limitations like difficult maintenance processes, low thermal energy quality, and storage processes [4]. The TES technique should be optimized and high-grade technologies developed to resolve these limitations. Packed bed phase change material tanks can be an alternative to molten salts [95]. Molten salts suffer limitations in terms of the cost and volume needed for effective heat transport. A PCM configuration in a cascade system as illustrated in Figure 8 has the PCM sandwiched between the heat transfer fluid (HTF) pipes for proper heat transfer. It is useful in increasing the heat transfer rate during the phase change, increasing exergy efficiency, and creating quicker charge-discharge mechanisms [96]. The heat exchangers are arranged in parallel and series patterns to influence the outlet temperatures, flow rate, and system performance. Every PCM has a given melting temperature that gets classified into a series-arranged bucket called a cascade. The dimensions of the system are determined by the thermal properties of the PCMs [5]. Packed bed TESS adopts thermal storage using affordable solid fillers in a heat storage tank. Different latent-sensible storage tanks can be used in a cascade storage system to enhance the power efficiency of the generation plant [97]. Hybrid cuprous oxide nanofluid synthesized through a two-step approach has recorded a 21% increase in thermal conductivity, better performance, and high thermal-optical efficiency [40]. These nanofluids are formed from the combination of the moving fluids of nanoparticle size and are crucial in improving the collector efficiency at elevated temperatures.

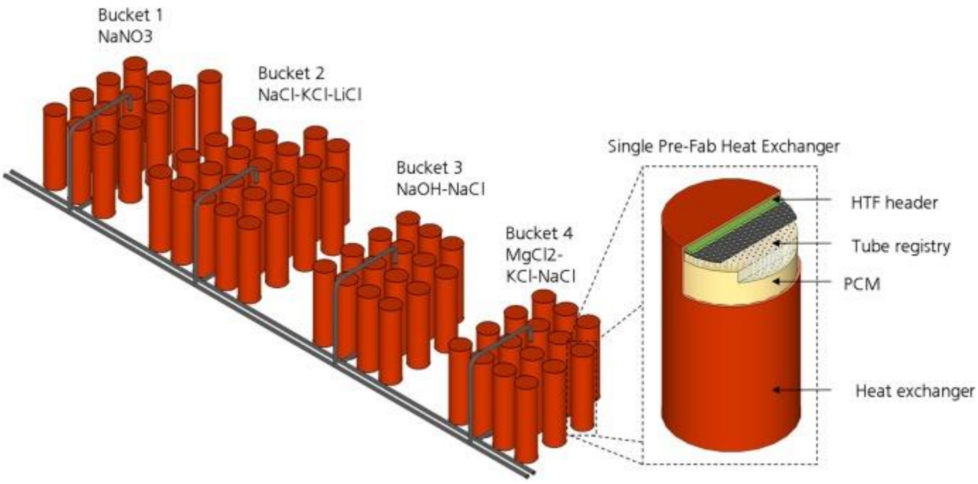

Figure 8 A setup of the PCM cascade and a pre-heated heat exchanger [5].

4.3 Baseline Configuration

Baseline configuration gives the product configuration upon production, which can only be changed using control procedures. Choosing an affordable indirect two-tank molten salt has been shown in Figure 9 to improve the performance of storage systems [5]. The area, absorber, emissivity, and tilt angle of the baseline should be carefully accounted for to improve solar collectors' performance. To store hot fluid in the liquid phase at the subsurface, the hydrostatic pressure should be sufficient to regulate the fluid (water) [98]. The proper configuration of the thermal well determines the thermal characteristics needed in fluid regulation. The thermal wells should be operated in a push-pull mode and useful in storing heat obtained from the solar collectors. The hot wells get pulled as the cold wells are pushed, and vice versa. This technique allows the fluid to provide pressure as it flows in the thermal storage system and recovery modes.

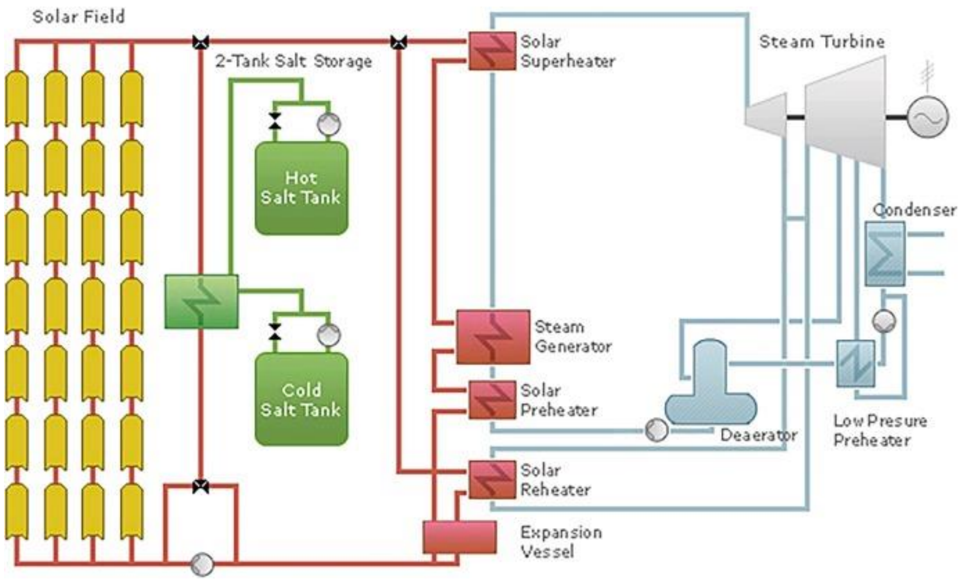

Figure 9 Baseline configuration having an indirect two-tank molten salt TES [5].

4.4 Heat Transfer Fluid (HTF) Used

Ideally, heat transfer fluids (HTFs) have high boiling points, low melting points, increased heat conduction, low vapor pressure at elevated temperatures, low viscosity, less corrosion with metal containers, and heat storage capacity [27]. HTFs like water, oil, and air are nanofluids with higher thermal conductivities. Heat transfer enhancement materials like metal foams and graphite composites can also be incorporated to improve the performance of HTFs [3]. Molten-salt-based HTFs are suitable for high-temperature systems because they have high boiling points, lower melting points, and are thermally stable. Several heat transfer enhancement technologies like incorporating high-thermally conductive enhancers and cascaded storage should be used [3]. Some thermally conductive materials including metal beads, metal fins, carbon materials, and metal powders have also recorded increased heat transfer mechanisms as outlined in Table 2 [99]. Metal foams with continuous metal matrices, ultra-light isotropic structures, and high thermal conductivities can also improve the system's efficiency [100]. Gasia et al. added fins to a thermal storage system having water as the heat transfer fluid and obtained better performance and increased thermal conductivity [101]. To enhance the heat transfer mechanism; the melting temperature of the phase change material should be manipulated and the PCMs should be encapsulated to provide a larger specific surface area for more heat transfer [7].

Table 2 Several thermal conductivity enhancements in phase change materials [102].

Enhancement	Technique	Constraints
Fins and extended surfaces	Improving the thermal transport area	The increase in total weight, cost, and properties of the PCM are not changed.
PCM-embedded porous matrices	Improving thermal transport area, creating a heat transport chain, and enhancing the heat conduction of PCMs	Costly porous material, reduction in storage capacity, more weight
Dispersing highly conductive particles within the PCM	Increasing thermal conductivity of PCM by the materials with high thermal conductivity.	Sedimentation of more conductive particles may appear, particles hardly form a heat transport network.
PCM micro-encapsulation	Improving the thermal transport area	Expensive, reduction of mass per unit volume of PCM
Multiple PCM Technique	Improving temperature gradient	Restrictive adaptation and irrelevant in varying situations

4.5 Technical and Environmental Impact

Another key factor in ensuring the technical feasibility of STESS is the system's excellent technological and environmental effects. To make it more technically feasible; a high thermal storage volume is necessary to lessen the system volume and improve performance, an effective thermal transport rate should exist between the thermal storage and its medium for good heat absorption, and the storage material should be chemically and mechanically stable to minimize degradation [3]. Environmental factors like the strategy for operation, the maximum load required, and integration into a power plant should serve as criteria for environmental friendliness. Other technical properties of the system like reversible charging and discharging processes, heat losses, simplicity, etc, should be considered for improving the system's performance.

4.6 Prospects and Recommendations

To consider solar thermal energy storage systems for prospects; factors like the power conversion efficiency, system output, usage potentials, economic impact, environmental effect, energy consumption rate, maintenance, and production costs should be looked into [103]. The role of solar thermal energy systems in meeting future thermal energy needs is a very good prospect to consider before installing these systems. This is necessary to ease over-dependence on non-renewable resources and supply heat at scarce periods. Installing more thermal systems powered by solar energy could raise socio-economic costs and encourage green technologies [104]. Another future perspective would be to develop hybrid systems [105], smart grids, and transformers that would make integrating the thermal energy storage systems a better pathway towards increasing the system efficiency [106]. Inserts like vortex generators, baffles, and twisted tapes can be incorporated into solar TES to enhance system efficiency [107].

Future work should focus on creating educative platforms to increase knowledge on the importance of solar thermal systems and useful parameters for improving performance. The economic and social impacts of installing this system should not be neglected. Prospects should aim towards integrating solar thermal plants into industrial setups for better commercialization [103]. Thermal systems should be installed around the globe, especially in regions where the ambient temperature is very hot and sunny [108]. New materials should be developed to fabricate multijunction tandem thermal devices with the potential for improved thermal efficiencies and applicability in concentrator photovoltaic systems [106]. Solar-to-thermal converters should be developed with minimal breakdowns, durability, and affordability. Future applications of nanomaterials as photocatalysts should be better explored to improve the efficiency of the working fluid [109]. Continuous research and extensive modeling into building more efficient and affordable thermal systems should be highly encouraged [110, 111]. Existing limitations to the expansion of STES systems should be looked into and resolved [112]. Policy regulations and scale-up methodologies like trade removal, investment schemes, fiscal systems, etc., should be adopted to promote solar TES systems [113]. In developing the power industry, the generator and renewable energy capacity should be accounted for. To resolve issues associated with TES technology, in-depth research, and more efficient materials should be explored to improve the performance of STRESS. To sustain the development and utilization of solar thermal energy; various solar thermal storage materials and systems with better efficiencies should be explored.

5. Conclusions

This review has successfully detailed general information, mode of operation, application areas, factors to consider towards performance improvement, recommendations, and prospects of solar thermal energy storage systems. The quest to reduce fossil fuel dependence is an important reality that should be looked into through the effective utilization of renewable energy resources. Solar thermal energy storage technology, compared to other energy technologies has exhibited a long life cycle, affordability, high energy storage efficiency, and large storage capacity. Developing this energy storage technology can solve continuity defects, encourage large-scale utility, and minimize unstable power output. The thermal energy stored upon solar irradiation is useful for heating and cooling applications with wider technological advancement. Improvements in TES and heat transfer fluids should be good options for enhancing the system's performance.

This review has successfully discussed an overview, basic components, and principle of operation of solar thermal energy storage systems. Factors to consider like heat design exchanger, choice of storage medium, baseline configuration, heat transfer fluid, and technical and environmental impacts are useful for improving the performance of STESSs. STSSs are successfully utilized in concentrated solar plants, compressed air energy storage, parabolic-type collector power plants, solar air heaters, pumped thermal energy storage, solar-aided power generation, and salt-gradient solar ponds. These energy storage systems have shown good performance levels that are useful for carrying out designated tasks in the different systems. The results obtained and reviews discussed have attributed the high-performance levels of the systems to their efficient energy conversion, heat transfer fluids, storage medium, and the design of the heat exchanger.

Acronyms

STESS	Solar thermal energy storage system
STSS	Solar thermal storage system

TES	thermal energy system
TESS	Thermal energy storage system
HTM/HTF	Heat transfer medium/fluid
PCM	Phase change material
SHS	Sensible heat storage
LHS	Latent heat storage
THS	Thermochemical heat storage
TCM	Thermochemical material
TCES	Thermochemical heat energy storage
TCS	Thermochemical storage
STS	Solar thermal system
STE	Solar thermal energy
CSP	Concentrated solar power
CAES	Compressed air energy storage
PCPP	Parabolic-type collector power plant
PDC	Parabolic dish collector
PTC	Parabolic trough collector
PTCPP	Parabolic trough collector power plant
PTESS	Pumped Thermal Energy Storage System
SAPG	Solar-aided power generation
SGSP	Salt gradient solar pond
CFD	Computational fluid dynamics
DDT	Definite difference technique

Author Contributions

Agnes C. Nkele: Conceptualization, Manuscript draft. Imosobomeh L. Ikhioya: Proofreading. Chinedu P. Chime: Proofreading. Fabian I. Ezema: Supervision, Correspondence.

Competing Interests

The authors have declared that no competing interests exist.

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