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Thermal Energy Storage in CSP Facilities: A Review of Design Strategies and Economic Considerations

Priyanka Devi[1], Renu Sharma[2], Robin Gupta[3]

[1,3] Department of Physics, Shri Khushal Das University, Hanumangarh, India

[2]Department of Physics, JECRC University, Jaipur, India

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Abstract: This study provides an overview of design methodologies for thermal energy storage systems and examines the key factors in concentrating solar power (CSP) facilities at various levels of hierarchy. A crucial component for enhancing power plant dispatchability is thermal energy storage. While numerous reviews have focused on storage media, few have addressed the design of storage systems and how power plants incorporate them. In addition to analyzing the thermal and energy efficiency of various storage systems integrated into power plants, this research looks at the designs of thermal energy storage systems that have been published in the literature. Additionally, this work summarizes these systems economic components and important published research.

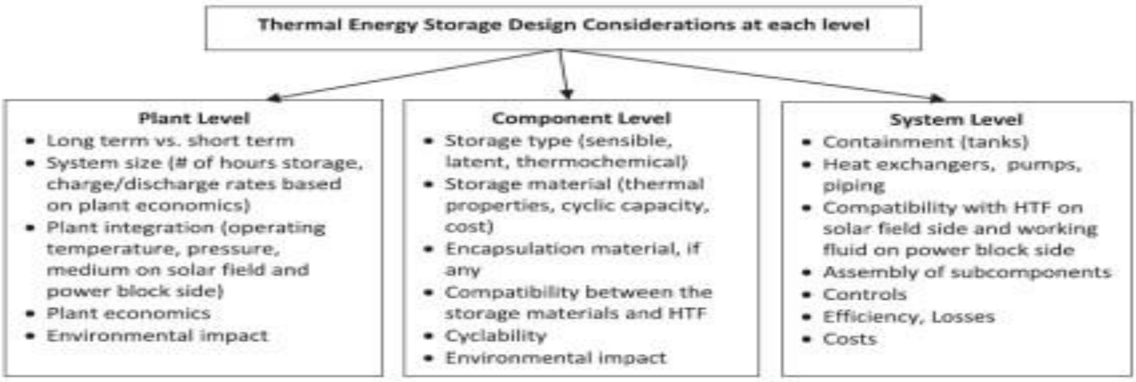
Keywords: TES, PCM, CSP

Concentrating solar power (CSP) plant systems

Concentrated Solar Power (CSP) facilities utilize focused sunlight to heat a specialized fluid, typically referred to as the heat transfer fluid (HTF) produces steam or the vapor of another working fluid.[2] This vapor then powers an engine, like a Stirling engine or steam turbine, in conjunction with a generator to generate energy. The four main CSP technologies are linear Fresnel reflectors, parabolic dish-Stirling engine systems, central receiver towers (also known as power towers), and parabolic troughs. [4] While all these technologies can incorporate thermal storage, dish systems require a unique design to do so. Figure illustrates the elements that make up a CSP plant's three primary sections: the power block, thermal storage, and solar field. The table provides a comparison of the salient features of the different CSP technologies.

Integration of thermal energy storage

1.Cloud cover or adverse weather conditions can induce a transient condition in the turbine generator, which lowers turbine efficiency because of startup losses. While heat transfer fluids (HTFs) give plants some thermal inertia so they can withstand short overcast spells. [9], Large-scale facility experiences suggest that this might not be sufficient to stop turbine shutdown [10]. Implementing Short-term variations in solar insolation can be lessened with the use of a small-capacity storage system.



Peak solar insolation and peak power demand might not coincide. During off-peak hours, like the morning, a TES system can collect energy from the solar field to improve plant dispatchability, and then release energy when demand is at its highest, potentially yielding higher electricity tariffs.

A power plant's capacity factor is a performance indicator that contrasts the amount of net electricity delivered with the amount of energy it might have generated during the same time period if it had operated continuously at full power. Solar power plants without storage have very low capacity factors due to limited daily solar energy availability.[7] A plant can function with a TES system when sunlight is unavailable, and if large enough, enables 24-hour operation. As illustrated table 1 shows that the capacity factor, or solar fraction, can rise from a normal 25 to 28% to as high as 43% after seven hours of storage. Compared to plants without storage, storage systems for this use would need a bigger solar field.[1]A thermal energy storage (TES) system needs to work in tandem with the power block and solar field. Comprehensive three subsystems' models are frequently combined in simulations to forecast and enhance the operational strategy and efficiency of concentrated solar power (CSP) plants [10].Thermal efficiency can be increased by operational measures, which will raise the plant's electrical production and increase its economic value [9].To make well-informed choices about thermal storage integration and CSP investments, it's crucial to assess the trade-offs between annual electrical output, extra capital expenses, the power's time-of-use value, and the

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levelized cost of electricity (LCOE).[6] Consequently, examining CSP's technical and financial aspects is essential.[6] CSP systems use traditional thermodynamic power cycles, the operating temperature has a major impact on the power block efficiency.[1] The annual direct normal insolation (MWh/m2) available, the annual solar field collection efficiency, thermal losses, and net power cycle efficiency, as well as storage efficiency when appropriate, all affect how much electricity a plant produces. [13,16]. Solar collector field Efficiency can be defined as the ratio of incident solar energy to usable thermal energy collected.[8] The ratio of net power output to heat input is known as power cycle efficiency. The efficiency of a TES unit can be described in a number of ways based on the type of storage. This will be discussed in the section that deals with TES unit design concerns.[4]

Design considerations with storage

Incorporating Power plant integration of Thermal Energy Storage (TES) designs may necessitate additional considerations and optimization. For instance, in The maximum temperature of the HTF in parabolic trough power plants is determined by the solar field during daytime operation.[7] However, when discharging at night, the HTF's peak temperature differs, potentially causing less heat transfer and the production of steam at lower temperatures.[7] In order to solve this problem, steam pressure can be lowered, decreasing water saturation temperature and consequently enhancing heat transfer and steam production rates. These variations must be factored in when calculating the cycle's efficiency.[6]

PCMs can also be macro- or microencapsulated to improve their capacity for heat transfer. Encapsulated PCMs have several benefits, including a larger heat transfer surface, less PCM's environmental reactivity and its capacity to control variations in the storage material's volume as phase transition takes place. Packing bed systems can make use of microencapsulated PCMs.[5] The most popular techniques for microencapsulation include:

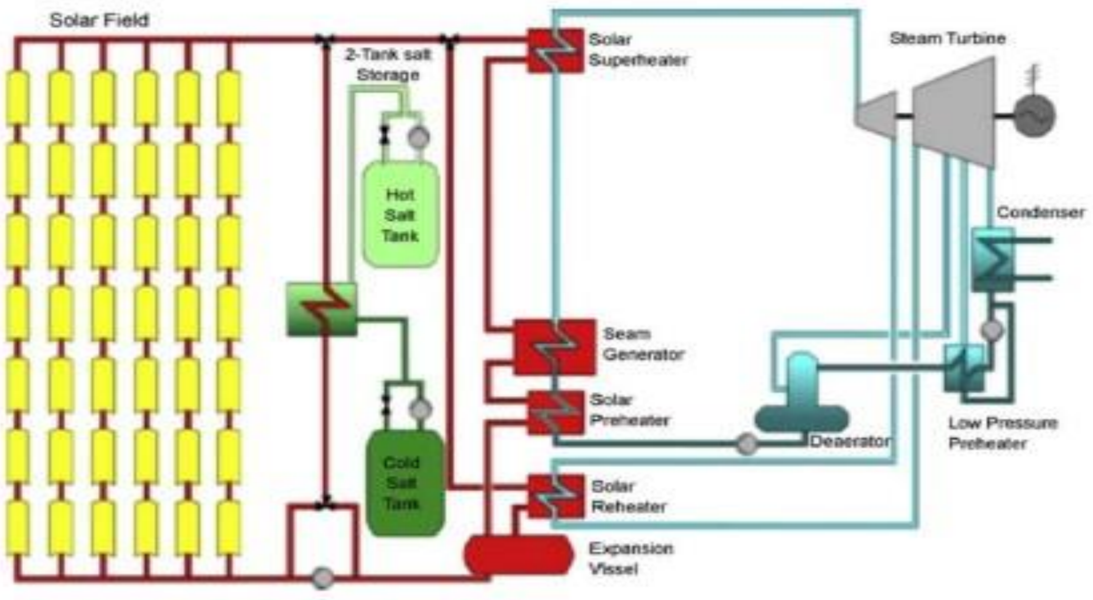
Physical techniques include:

- pan coating,
- air-suspension coating,
- centrifugal extrusion,
- vibrational nozzle,
- spray drying and congealing (vi) fluid bed coating.

Chemical techniques include:

- interfacial polymerization,
- in situ polymerization,
- matrix polymerization
- solvent evaporation.

It is still needed to research whether these techniques can be used to materials that are heated to high temperatures. Additionally, electroplating has been utilized to store and reuse waste heat from industrial processes at high temperatures, as well as to encapsulate metal PCMs with nickel. [1]



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Concentrating solar power commercial plants and thermal energy storage systems

2.1.Key technology for CSP There are four types of STE technology: tower, parabolic, linear Fresnel, and parabolic trough.[9] They can be categorized as follows based on how they concentrate the sun's beams and the position of the receiver: tower and dishParabolic trough and linear Fresnel systems, in which the mirror tracks the sun along one axis (line focus), and dish systems, in which the mirror tracks the sun along two axes (point focus).[9] The receiver is stationary in linear Fresnel and tower systems, but moveable in parabolic trough and dish systems. The sun's energy is focused onto a receiver tube that goes through a parabolically curved trough-shaped reflector along the collector's inner side in parabolic trough technology.[2]

	Current trough	Current tower
Maturity	High, commercially proven	Medium, recently commercially proven
Key technology providers	Abengoa Solar, Sener Group, TSK-Flagsol, Acciona, ACS-Cobra.	Abengoa Solar, BrightSource Energy, Solar Reserve, eSolar, Torresol
Typical plant capacity [MWe]	100	50–100
Operating temperature of solar field [°C]	290–390	290–565
Plant peak efficiency [%]	14–20	23–35
Annual average conversion efficiency [%]	13–15	14–18
Collector concentration [suns]	70–80	> 1000
Power block cycle	Superheated steam Rankine	Saturated steam Rankine Superheated steam Rankine
Power block fluid conditions	steam @380 °C/100 bar	steam @540 °C/100–160 bar
Power cycle efficiency [%]	37.7	41.6
Heat transfer fluid	Synthetic oil, water/steam (DSG), molten salt (demo), air (demo)	Water/steam (DSG), molten salt, air (demo)
Annual capacity factor [%]	20–25 without TES 40–53 with 6 h TES	40–45 with 6–7.5 h TES 65–80 with 12–15 h TES
Storage system	Indirect 2-tank Molten Salt storage	Direct 2-tank Molten Salt storage, Steam Accumulator
Storage temperature range [°C]	293–393	290–565 for Molten Salt storage 120–330 for Steam Accumulators
Capital cost [US$/kW][a]	4700–7300 (without TES, OECD countries) 3100–4050 (without TES, non-OECD countries) 6400–10700 (with TES)	6400–10700 (with TES)
LCOE [US$/kWh]	0.26–0.37 (without TES) 0.22–0.34 (with TES)	0.2–0.29 (with 6–7.5 h TES) 0.17–0.24 (with 12–15 h TES)
Cooling method	Wet	Wet, dry
Suitable for air cooling	Low to good	Good
Water requirement [m3/MWh]	3 (wet cooling) 0.4–1.7 (hybrid cooling) 0.3 (dry cooling)	1.8–2.8 (wet cooling) 0.3–1 (hybrid cooling) 0.3 (dry cooling)

A HTF, usually synthetic oil travels down the tube along the trough collector after being heated by the energy concentrated in the receiver tube. Next, a conventional steam generator-turbine uses the heated HTF to produce power. Additionally, existing coal-fired facilities or mixed cycles can be merged with parabolic trough technology [2]. By directing a solar power tower uses many massive sun-tracking mirrors, often called heliostats, to direct sunlight onto a receiver at the top of the tower, to turn sunlight into electricity [2]. These solar rays heat the HTF that enters the receiver, which is frequently steam or melted salts. Power is then produced by using the heated HTF in a conventional steam generator and turbine.[3]

Classification

There are two types of TES designs for high temperature both active and passive solar power plants are available. Heat is transferred into the storage material by forced convection, and the storage medium itself passes through a heat exchanger, its primary characteristic.[1] You can use this heat exchanger as a solar receiver or as a steam generator. Direct and indirect systems are two categories of active systems. In passive storage systems, which are usually dual medium storage systems, the heat transfer fluid merely passes through the thermal storage system to charge and discharge a solid substance.[3] while charging, the heat transfer fluid transfers energy from the energy source to the storage medium; while discharging, it gets energy from the storage. Below is a description of these active systems.[1] In an active direct system, the heat transfer fluid functions as both the storage medium and the heat transfer fluid. This means that for a material to be both an effective a suitable storage medium and a heat transfer fluid, it needs to possess certain qualities.[1] Steam accumulators and molten salt systems are examples of commercial active direct thermal energy storage devices. The direct heat transfer fluid is immediately stored in a hot tank in a two-tank storage arrangement for usage on cloudy or nighttime days. Before being pumped and heated once more, the other tank receives the cooled heat transfer fluid, also known as the cold tank. The requirement for expensive heat exchangers is eliminated when the HTF and storage material are both steam or molten salt.[3] Molten salts are used as a heat transfer fluid in an active direct molten salt TES system used in a standard solar tower installation is depicted in the process flow schematic. Pressurized tanks called steam accumulators can store extra steam generated by the receiver and then release it to power the turbine.[3]A steam tower plant using active direct steam accumulation thermal energy storage technology is shown in the process flow diagram. This plant layout currently uses a two tank molten salt system.[3] A heat exchanger transfers the HTF's energy to a secondary fluid, usually molten salts, which is then kept in storage tanks for later use. A heat exchanger is necessary to move the energy from the heat transfer fluid that circulates in the solar field to the second medium that serves as the storage medium in an active indirect system, which uses a second medium to store the thermal energy.[8] Furthermore, steam or molten salts allow the solar field to be operated at higher temperatures than the current heat transfer fluids commonly used in parabolic trough oil plants, which are limited by the decomposition temperature of synthetic oil.[6] The plant's performance can be improved and The electricity's levelized cost (LCOE) can be decreased thanks to all of these factors. When employing using molten salt as a fluid for heat transmission, Kearney argues that it only makes financial sense to incorporate thermal energy storage in solar installations.[2]

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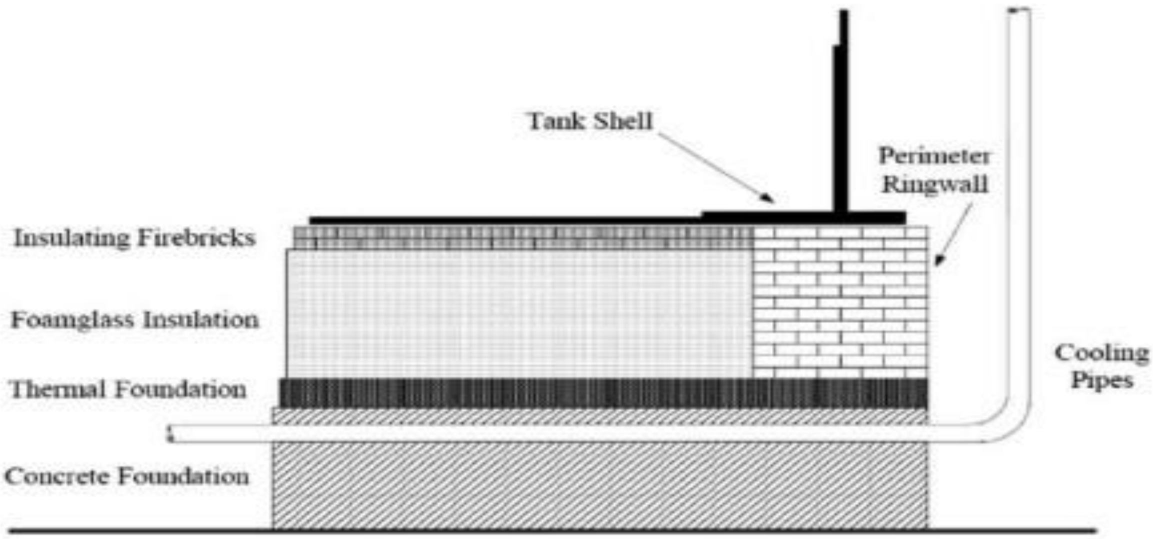
Indirect Technique for storing thermal energy using molten salts

A Rankine steam turbine/generator cycle, an oil parabolic trough solar plant consists of a large field of parabolic trough collectors, a heat transfer fluid/steam generating system.[4] As is the case with nearly all of the parabolic trough solar plants currently under development, Systems for optional thermal storage may also be included.[7] The two-tank of molten salts is a perfect fit for this technology since it completely suits the thermally sensible behavior of the thermal oil already in use. Since, within this temperature range, thermal oil operating temperatures, nitrate molten salts are efficient and functional. are typically between 290°C and 390°C.[9] The preheater, evaporator, superheater, and reheater are typically included in the power cycle that this system uses. Common savings achieved with this technology range from 37% to 37%, depending on cycle design.[2]

	Solar salt	Hitec	Hitec XL
Composition [by weight]	60% $NaNO3$ 40% $KNO3$	7% $NaNO3$ 53% $KNO3$ 40% $NaNO2$	45% $KNO3$ 7% $NaNO2$ 48% $Ca(NaNO3)2$
Melting point [°C]	220	142	120
Maximum operation temperature [°C]	585	450–538	480–505
Specific heat [J/kg °C] @ 300 °C	1495	1560	1447
Density [kg/m3] @300 °C	1899	1860	1992
Viscosity [cp] @300 °C	3.26	3.16	6.37
Cost [$/kg]	1.30	1.93	1.66



Optimization procedure for TES tanks Using the previously described heat transfer analysis, the thermal variation and HTF exit temperatures from a particular size TES system may be determined.[3] However, for the TES system to be incorporated into the power plant, the tanks must be of a certain capacity. The amount of storage space needed, operational temperatures, operating time, and the thermal performance of the TES system itself will all affect this. Fig.

illustrates an easy-to-use technique.[2] In addition to thermal analysis, which can offer heat losses and temperature variations, structural analysis is essential for system design since it establishes the tank's ideal safe dimensions.[2]

When developing TES tanks, It is necessary to consider the following factors:

- Stress on the tanks as a result of the system's thermal gradients
- Pressure inside the tank as a result of storage media
- Setting aside room for the heat transfer fluid or storage material to expand thermally
- The solid media's thermal expansion in the event of a thermocline with packed bed systems or filler material
- If encapsulated PCMs are utilized as a storage medium, thermal stress will occur inside the enclosed shell.
- The tank's dimensions and form
- The tanks' maximum permitted height, determined by the structural analysis and manufacturing feasibility.

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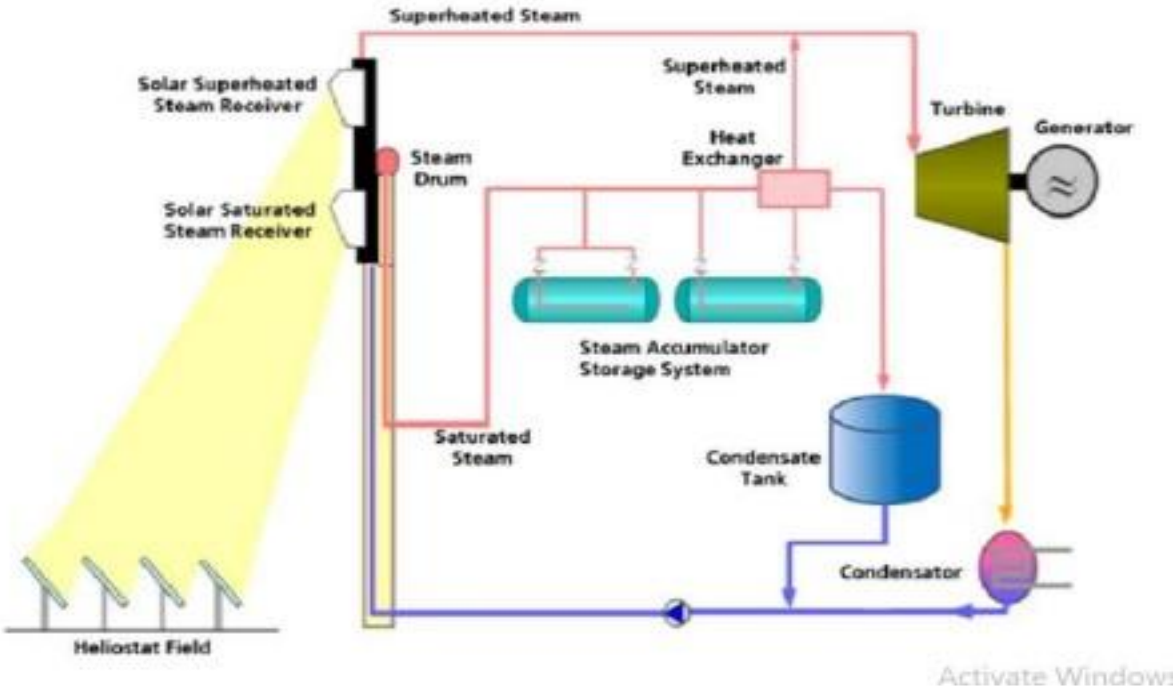
Salomoni et al. [250] analyze a below-grade cone-shaped two-tank molten salt heat storage system that uses a novel high-performance concrete for foundation and structure.[2] They use a fixed heat source of 100 °C to the interior concrete surface using a finite element (FE) model to simulate the entire domain.[5] They also consider and evaluate durability of concrete in regard to extended heat loads and the relationship between the hot tank and the earth.[6]

Steam accumulator storage

The most popular Molten salt is a thermal energy storage medium.

However, water can also be used as a storage medium in so-called Direct Steam Generation (DSG) facilities, a fluid for heat transfer.[10] DSG is a more environmentally friendly technology that increases total plant efficiency by doing away with the requirement for intermediary heat transfer fluids. There is no need for a heat exchanger because the turbine receives the steam produced in the receiver directly.[9] It does away with the steam/molten salt generator or the train of oil/water heat exchangers. The present nitrate molten salts in solar tower power plants have a maximum operating temperature of 565°C, and the upper limit of the maximum through solar field temperature (up to 400°C) imposed by thermal oil degradation vanish thanks to technology.[10]



Steam accumulators are the sole commercial DSG plant TES solution. Based on the Ruth accumulator system, an active direct storage device is a steam accumulator. device that stores steam in accumulator tanks at high pressure.[1] Those pieces of equipment are not antiquated artifacts. In fact, for many years, storage systems have been (and continue to be) used in power plants and the process industries to balance steam generation and demand. Over more than 60 years, a 50 MW power plant with 67 MWh of storage capacity was run on the Berlin Island Grid using steam accumulators.[3] Steam accumulators are utilized in a variety of industries, including nuclear power plants, food processing, equipment for product testing, industrial and hospital sterilizing, and biotechnology.[1]

Only two commercial tower plants—Abengoa constructed PS10 and PS20, which are located in Spain, that use steam accumulator thermal energy storage were operational as of January 2016[6]. In addition to becoming the world's first two commercial solar towers, they also served as the catalyst for the direct steam technology's launch in 2007 and 2009, respectively.[5] Saturated steam technology is used in CSP towers of the first generation (Fig. 10). The PS10 and PS20 are covered by this plan.[4]

At 50% turbine workload, the PS10 storage system (Fig. 20) can function for 50 minutes on average, or 20 MWh of storage capacity [6]. Four tanks make up the system, and each tank is operated in turn according to its charge level. Steam is created in the receiver during plant operation and then transported to the turbine, where it grows to provide mechanical work and electricity. The steam accumulators are used to store extra steam for later use.[4] When energy is needed to cover a brief period, saturated water energy will be recovered at variable pressure up to the lowest pressure allowed to run the turbine.[4]

Cost analysis for TES comparison

Comparing the costs of the two commercial technologies for storing thermal energy in STE plants that are currently on the market is the goal of this study. [9] To assess the economic comparison of the ideas presented in this study, thorough performance and cost assessments were carried out. The results of the economic analysis are displayed for a Rankine cycle with different plant configurations, storage concepts, and sizes.

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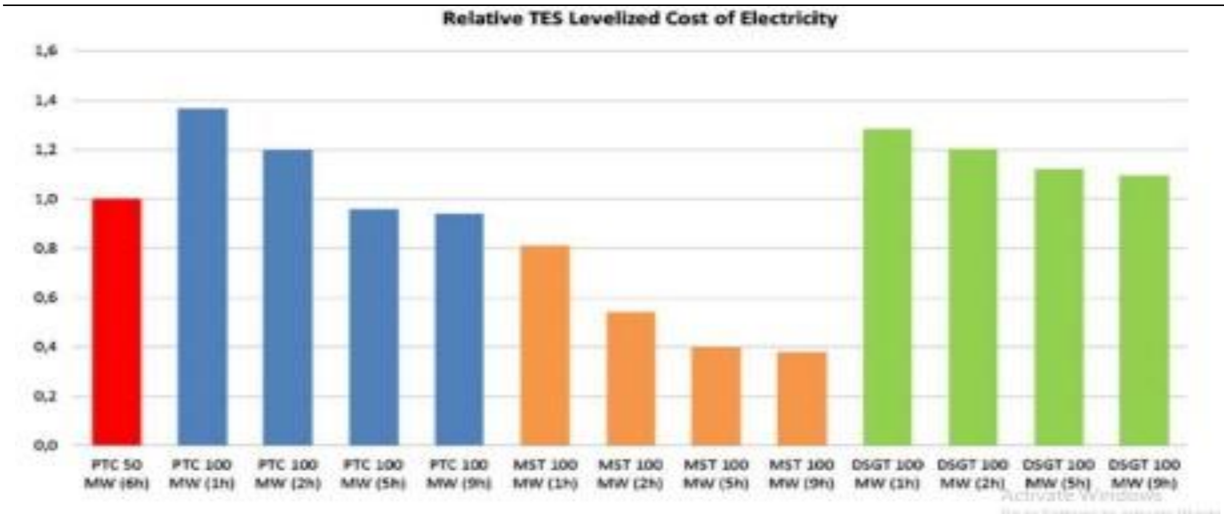

The design of the storage system for the three facilities examined in this study was based on the following key presumptions:

- The plant produces the same electrical gross output, which is equivalent to 100 MWe.
- In 1 h, 2 h, 5 h, and 9 h, the same storage capacity is assumed in terms of discharging hours at equal full nominal conditions.

At least from the perspective of operational conditions, it is assumed that the power cycle is similar. At 540°C and 130 bar, a subcritical Rankine turbine powers the direct steam power cycle and the molten salt tower.[8] The steam accumulators' output in the direct steam tower example varies between the turbine's assumed minimum working pressure of 2 bar and its maximum operating pressure of 130 bar. Conversely, the power cycle operating conditions for the parabolic trough plant with synthetic oil and molten salt storage are established by a subcritical Rankine turbine operating at 380°C and 100 pressure.[9]

The following factors will be taken into account when calculating the storage cost for direct steam storage with steam accumulators:

- tanks for pressure vessels;
- foundations;
- superheating heat exchanger
- piping and mechanical erection
- electrical and I & Storage medium are insignificant because they are not regarded as water.

The following are taken into consideration for molten salt two tank

storage:

- molten salt storage tanks (which include, among other things, hot storage tanks, cold storage tanks, and molten salt pumps)
- molten salt medium inventory
- molten salt melting system
- mechanical and piping erection
- electrical and I & C; and (vi) civil works.

The price of both hot and cold storage tanks includes foundation and insulation. The oil-to-salt heat exchanger is a component of the equipment item for the parabolic trough plant. [10]

Conclusion

Based on a thorough analysis of the literature, a summary of there are thermal energy storage devices available that are appropriate for concentrating solar power facilities. There includes discussion of the cutting-edge design approaches and storage concepts employed by different scholars. More study is required to enhance the economics and thermal performance of these systems, despite the fact that solar power plants might be made practicable by all three basic types of storage media: thermochemical, latent, and sensitive.

Given the present trend of rising temperatures, current thermal storage research efforts concentrate on creating by 2020, new technologies could reduce the cost of thermal storage from its present LCOE of 5¢/kWh to 1¢/kWh.

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Advanced manufacturing techniques and nano-based technologies are being used in recent advances to accomplish this. When designing storage systems, researchers are placing a strong emphasis on energetic efficiency. Combining various forms of storage may be a low-cost way to help power plants reach the necessary efficiency.

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