SolarPACES 2023, 29th International Conference on Concentrating Solar Power, Thermal, and Chemical Energy Systems

Analysis and Simulation of CSP and Hybridized Systems

https://doi.org/10.52825/solarpaces.v2i.780

Published: 03 Feb. 2025

Towards a More Efficient Design on High Temperature Concentrating Solar Power Plant With Cascaded Thermal Energy Storage

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Abstract. This work proposes a novel concentrating solar power (CSP) plant configuration aiming at a high operation temperature of 1000°C. The thermal energy storage system (TES) would be the focus of this research by modifying it and proposing four configurations to enhance the overall efficiency of high-temperature solar power towers. The objective is to identify the most thermodynamically efficient designs by analyzing the literature on the different components and comparing them to a reference base case of a conventional 100 MWe solar power tower plant (2-tank molten salt TES) operating at 565°C. The proposition consists of a Brayton/Rankine combined cycle with a double cascade TES. In the proposed cascade TES, the primary unit consists of a high-temperature air/ceramic packed-bed thermocline operating at 1000°C, while the secondary unit is a single molten salt tank used as sensible heat. The secondary TES is used as a heat sink during charge, improving efficiency and reducing the size of the air/ceramic-packed bed by extracting the thermocline out of the tank. Excess energy stored in the secondary TES is utilized for preheating during discharge. The methodology incorporates evaluating various combinations of solar block, TES, and power block integration. Combinations are selected from a comprehensive literature review. The study focuses on night-time operations. Further analysis of the cost-benefit of the designs would be required to compare the overall energy production and furthermore the LCOE.

Keywords: CSP, High-Temperature Configuration, Dual TES in Cascade

1. Introduction

Due to its energy storage capability, the energy transition requires the deployment of large utility-scale solar projects, including CSP technology. Remarkably, by 2022, over 25 CSP projects have been commissioned in the thriving regions of the Middle East and China [1]. Phase IV of the latest megaprojects on solar energy includes a solar a 100 MW_e solar power tower and 600MWe of parabolic trough recently started operation at the Mohammed bin Rashid Al Maktoum Solar Park in Dubai, UAE, which achieved the lowest levelized cost of energy LCOE in history, USD0.073/kWh Solar power tower technology is becoming state-of-the-art in CSP plants, thus, the study of operation at higher temperatures is a priority. This study proposes four configurations to operate a 100MW$_e$ Solar Tower Plant at a higher temperature than the standard 565°C of the commercial molten salt configuration.

2. Literature Review

CSP systems, including parabolic trough and central receivers, operate at temperatures ranging from 20-400°C and 300-1000°C, respectively. However, these systems, particularly central receivers, often operate at temperatures much lower due to limitations of the HTF [2]. For example, when using molten salt, solar towers are limited to operate at 565°C, reducing the thermodynamic cycle's conversion efficiency [2]. In practice, the actual operational temperatures for these systems are often lower than their technical capabilities. The current storage technology for solar tower CSP plants is known as "two tanks molten salts storage" [3]. Despite being a mature and effective technology, it has several drawbacks. As the freezing temperature of the salt, particularly nitrated-based commonly used in CSP, is around 230°C and its maximum operating temperature is below 600°C due to decomposition and corrosion, its storage capacity is limited [4].

Next generation solar power tower is expected to use a Brayton cycle in the power block and operate in the range of 700°C to 1000°C. Conventional nitrate salts limit the operational temperature to 600°C [3]. While chloride salts could reach higher temperatures at 800°C, they are highly corrosive at this temperature level [5]. Therefore, gases and/or particles such as ceramics are the only immediate viable heat transfer media (HTM) options for high-temperature applications beyond 800°C, enabling higher theoretical efficiency [6]. At high temperatures, particle receivers and air/ceramic packed beds as thermal energy storage (TES), also called thermocline, as it consists of separating hot fluid from cold fluid, thanks to clever use of buoyancy forces, are considered. In a high-temperature thermocline system for TES, ceramics are used as filler, and air as HTF [2].

The thermocline system TES leverages the concept of thermoclines, distinct temperature layers within a medium, to boost energy efficiency and power generation flexibility. This system employs a stratified thermal storage medium with a vertical temperature gradient featuring a high-temperature region at the top and a lower-temperature region below, maintained through precise heat transfer, thus presenting several drawbacks [4]. As the thermocline thickness is rarely infinitesimal, the temperature at the storage outlet tends to increase long before the storage is fully charged, proved experimentally by [2]. Depending on the elements downstream of the storage (i.e., circulating fans), the charge is stopped when the outlet temperature reaches a threshold value. As a result, the thermocline TES contains a "dead volume", which lowers the utilization ratio of the storage. To solve this issue and optimize the packed-bed TES utilization, a secondary thermocline TES is proposed in cascade to the packed-bed and used as a heat sink, enabling larger extraction of the packed-bed's thermocline.

3. Methodology

The methodology comprises three steps: 1) identify all possible combinations for the proposed design and generate their process diagram; 2) select the most suitable configurations to be modeled and compared with support of literature review 3) compare results and discuss.

4. Configuration Identification and Selection

The main system for the configuration requires a solar power plant as energy input for the TES during the charge and the energy input to the power block is defined by the TES during the discharge as shown in *Figure 1*.

Figure 1. *Configuration Identification Diagram*

4.1 Solar Power Plant

The components of the solar tower power plant are the heliostat field, the tower, and the central receiver. Compared to solar dish stirling and parabolic concentrating photovoltaic, solar tower is compatible with thermal energy storage due to its temperature range, energy dispatchability, high efficiency and scalability [7]. Also, the advantage compared to linear fresnel and parabolic trough is the ability to reach higher temperatures (higher theoretical yield). As state-of-the-art moves towards night operation to coordinate energy production with other renewable technologies such as solar and wind, sizes and shapes of the heliostat field and solar tower are becoming standardized (100 and 200MWe) because it allows plants to have round-clock solar production, as seen in the new project developments announced by 2023 [1]. PV is efficient, with very low LCOE for daytime production. CSP is more expensive, but it can more easily integrate storage and be used to produce electricity once the sunsets. Thus, this work assumes a radial heliostat field layout and a tower of 195m (average height of operating ST of 100MWe), operating only at night, to be considered for the proposed configuration of high-temperature central. As per the central receivers, they can be tubular, volumetric, small particle, falling film, or particles as presented in *Table 1*. However, as this research focuses on packed bed TES, only tubular and volumetric central receivers have been considered for the study. The type of receiver defines the relationship between the receiver and the storage system, defining a closed or open loop of the air used as the heat transfer fluid of the thermocline system.

Table 1. *Review of receivers toward solar tower configuration selection*

Receiver Type	**Gas** **(Outlet Temperature / Thermal Efficiency)**	**Liquid** **(Outlet Temperature / Thermal Efficiency)**	**Solid** **(Outlet Temperature / Thermal Efficiency)**
Tubular • External • Cavity • Billboard • Cylindrical	>800°C 80-90% (theoretical) [8] 40% (prototype) [9]	>600°C 80-90% [10]	NA
Volumetric	>700°C 50-60% [11],[12][15]	NA	NA
Small/Falling Particle • Direct Indirect	>700°C 80-90% (theoretical) [6]	>600°C 80-90% (experimental) [6] 94% (theoretical) [13]	>800°C 80-90% (simulation) 50% prototype [14], [15]

After the analysis, the tubular external receiver is selected for the proposed configuration.

4.2 Power Block

The power block will be considering a Brayton/Rankine combined cycle of due to targeted operating temperature and the high efficiency of these cycles, as the literature review shows in *Table 2*.

Table 2. *Review of power cycles for solar tower configuration selection*

Power Block	Types	Efficiency	Notes for CSP applications
Steam-based cycles	Rankine	37–42%	Typically, limited up to 400°C for oil and 600°C for molten salt HTF and usual gross thermal efficiency of 37% to 42% [16].
Steam-based cycles	Water-Ammonia Power Cycle (Kalina Cycle)	40-53%	A mixture of water and ammonia as the working fluid, operates with a higher thermal efficiency compared to traditional Rankine cycles due to the ability of the Kalina Cycle to better match the temperature glide of heat addition and rejection processes [17].
Gas-based cycles	Brayton	42-45%	Brayton can operate at temperatures exceeding 1000°C and uses gas as the working fluid with gross thermal efficiencies of 42 to 45% [18].
Gas-based cycles	Combined Brayton Cycle	49.8%	Supercritical steam cycles have the potential to achieve higher thermal efficiencies but require more power for the compression stage [19]. Also, fluidized bed systems involve suspending solid particles within a fluid medium, allowing for rapid heat transfer and storage, thus improving system performance [2].
Gas-based cycles	SCO_2	50%	Gases serve as high-temperature fluids (HTFs) in these advanced storage technologies, offering advantages such as high heat transfer rates and thermal stability, as for the thermocline systems [20].

After the analysis, the combined cycle is selected for the proposed configuration.

4.3 Thermal Energy Storage

After the literature review summarized in Table 2, the thermocline system is selected as the main study configuration. High-temperature TES in packed beds has a well-established track record in steel and glass manufacturing and materials are relevant to the application. While large-scale packed bed TES for power generation is not yet prevalent, several test facilities, pilots, and demonstration plants actively explore this potential, e.g., Siemens Gamesa Renewable Energy's (SGRE) electric thermal energy storage plant in Hamburg [21]. Also, cowpeas stoves and glass furnace regenerators are typically structure beds, however they do not utilize packed beds. The work presents the use of an air-ceramic packed bed as configuration A. The Molten salts will be considered for the secondary storage system in configuration B, C and D

5. Results

The two proposed designs of a thermocline as a TES and the two cascade TES of a high-temperature air/ceramic packed-bed thermocline system and molten salt single tank to increase energy efficiency in CSP solar power tower are presented in Figures 2 to 5, respectively. The systems are presented in their charge and discharge phases. Heat is transferred from the solar tower to the TES during charge, and the discharge drives the power block. It is considered a night operation, shaping the charge and discharge phase into a 6-hour charge and 18-hour discharge ideally. The designs differ on receiver types, heat transfer fluids, TES systems and configurations, and heat exchangers. The left side of the diagram (green) represents the charge of each system, and on the right side (purple), the discharging process is represented. The connection to the receiver or power cycle defines an open or closed loop.

Configuration A includes a single tank for a high-temperature thermocline system with an air/ceramic packed bed. The work suggests using ceramics of different shapes made from a post-industrial ceramic material commercially known as Cofalit, a configuration that has not been modeled before. The charge and the discharge phase are direct through the thermocline system as the receiver is considered a cavity receiver with a closed air loop as shown in *Figure 2*. The limitation of the outlet temperature of the thermocline system is imposed by the operational temperature of pumping equipment, which has been assumed to be 400°C. The discharge powers the energy block directly. The inlet temperature of the thermocline during the discharge is the compressed air utilized in the Bryton cycle estimated to be 320°C.

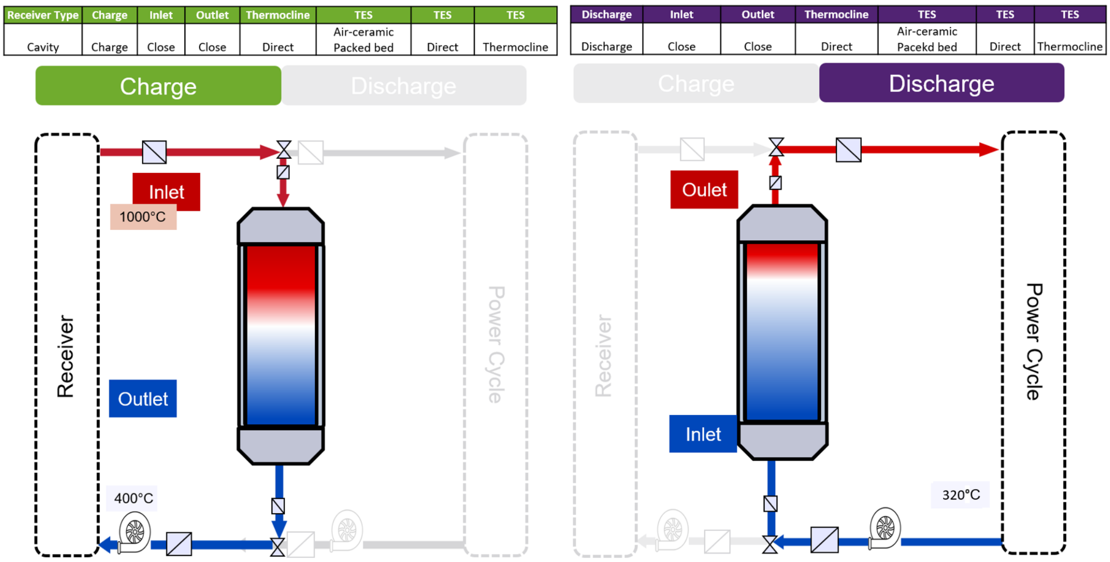

Figure 2. *Configuration (A) TES of high temperature operation of an air/ceramic packed bed connected to the central receiver of solar tower power plant during the charge phase and to the power block of a combined cycle (Bryton-Rankine) during the discharge.*

Configuration B considers a thermocline and a single homogeneous molten salt tank, the thermocline being heated in a closed loop by the receiver while the molten salt tank is heated by a heat exchanger at the outlet of the thermocline storage (*Figure 3*). Although these two systems are well known in the industry, the novelty of this work is combining them to extract the thermal gradient from the thermocline storage during the charge phase and allow extra energy storage in the secondary tank. During the discharge, the heat exchanger of the molten salt will act as a preheating system for the thermocline. The temperature of the molten salt will be restricted to 565°C. The inlet temperature of the molten salt heat exchanger during the discharge is the compressed air utilized in the Bryton cycle estimated to be 320°C.

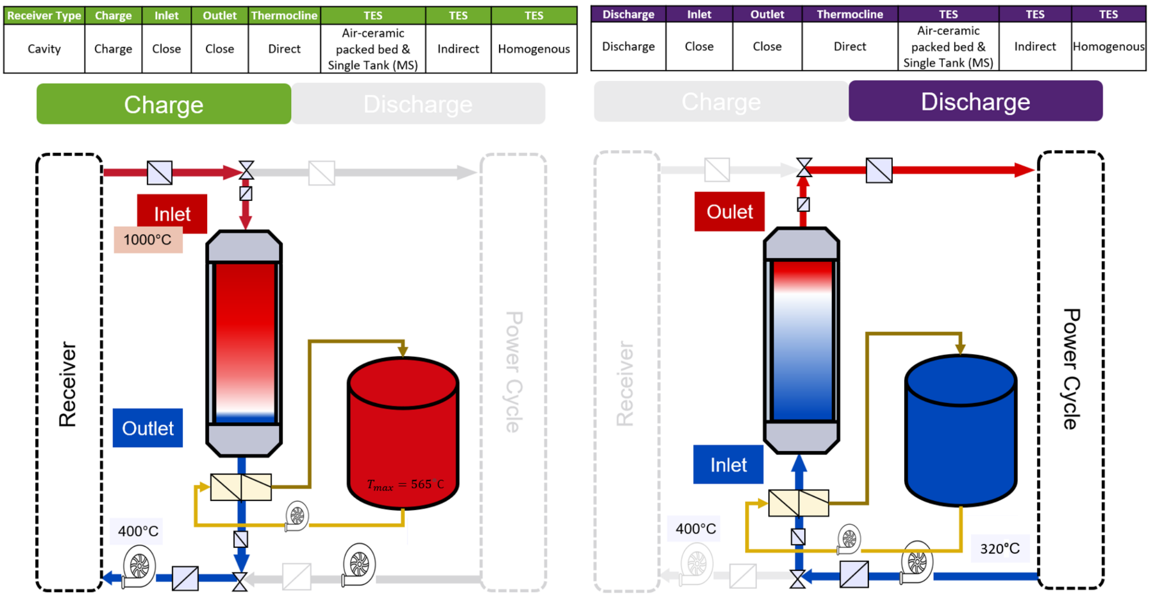

Figure 3. *Configuration (B) Cascade of two TES configuration of high temperature operation of an air/ceramic packed bed and a single molten salt tank (as heat sink) connected to the central receiver of solar tower power plant during the charge phase and to the power block of combined cycle (Bryton-Rankine) during the discharge using the single molten salt tank as preheater.*

For the *configuration C*, two major differences are presented as part of the design configuration. First, the solar receiver is proposed to be tubular in an open loop between the TES and the solar tower, setting the maximum temperature of the system to 590°C after the air/molten salt heat exchanger (*Figure 4*). Second, during the discharge phase, the thermocline system is proposed to indirectly transfer heat to the power cycle's working fluid via an heat exchanger, as some literature suggested that small particles due to ceramic collisions inside the air/ceramic packed bed could severely damage the turbine on the power cycle. Thus, the discharge considers two heat exchangers, accordingly. Note that there is a fan on the discharge loop of the packed bed.

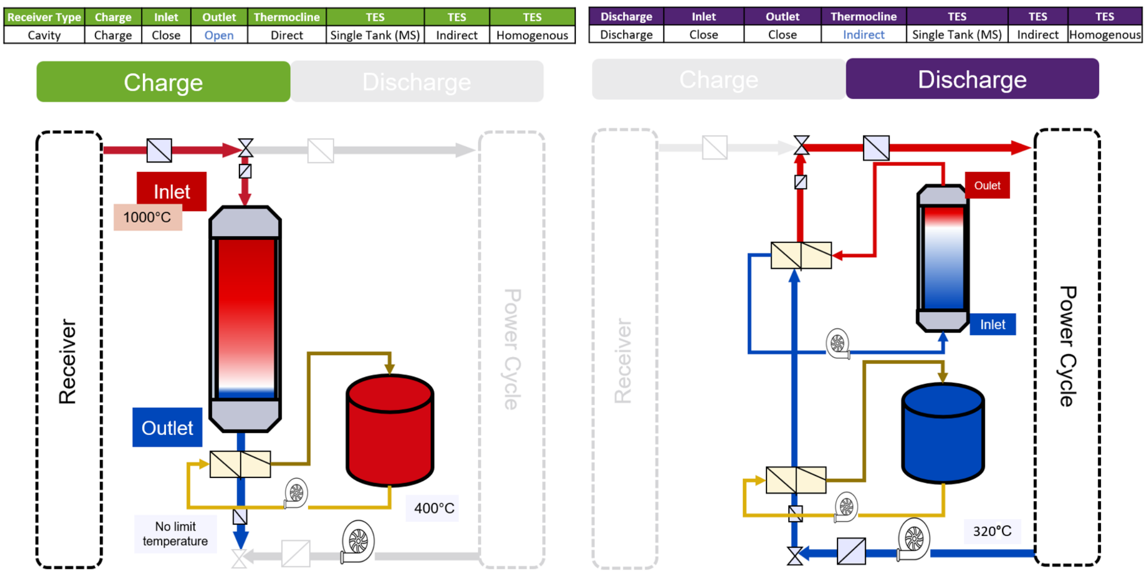

Figure 4. *Configuration (C) Cascade of two TES configurations of high-temperature operation of an air/ceramic packed bed and a single molten salt tank in an open loop during charge showing the discharge through two heat exchangers, one for the molten salt tank and one for the thermocline system.*

Configuration D introduces the idea of a thermocline operation of the secondary storage. In Configurations B and C, the single molten salt tank has been assumed to be at a homogeneous temperature, which is physically sorted with a mixing process (*Figure 5*). This proposal uses a heat exchanger for the single tank during the charge, and on the discharge both, with a thermocline operation. The primary and secondary storage systems are modeled with heat exchangers for the discharge. Note that there is a fan on the discharge loop of the packed bed. The Temperature of the hot side of the molten salt (thermocline) will be set at 565°C and the cold temperature at 290°C

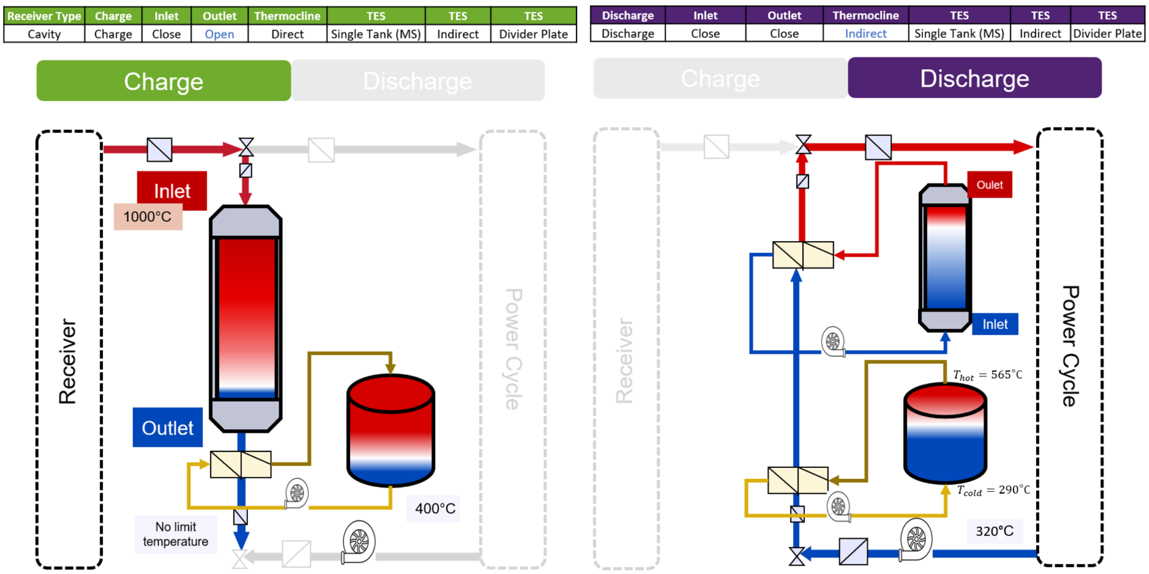

Figure 5. *Configuration (D) TES configuration of high-temperature operation of an air/ceramic packed bed in an open loop to the central receiver during the charge phase and to the power block of a combined cycle (Bryton-Rankine) during the discharge.*

6. Discussion and Conclusion

With the current tendency to increase energy efficiency, thus, temperature in solar towers CSP plants, it is essential to analyze which technologies can scale and adapt to achieve global energy demands. This research presents different configurations by introducing two mature TES that have not been considered for CSP as a single solution. It proposes a literature review analysis of the different combinations to integrate them. The literature review additionally aims to identify optimal combinations for developing an appropriate mathematical model in subsequent research. The first is an air/ceramic packed bed thermocline system, and the second is a single-tank molten salt. The major advantage is the operational temperature of 1000 °C compared to standard commercial power plants, whose limited temperature is around 600 °C. Thus, the theoretical efficiency of the proposed configuration is higher.

The configurations proposed based on the literature review of different components are presented in Figures 2 to 5. Although many more are possible, the scope of the research is limited to four configurations, based on an extensive literature review, that are the most convenient for the system's dependency on the TES with the solar tower and the power block. Configuration A has drawbacks to the gradient during charge and discharge due to the limiting temperature at the end of the loop. A double cascade TES is proposed to increase the charge and discharge of the system to its maximum possible of the thermocline with configurations B, C, and D. Although configuration C simplifies the heat exchange of the thermocline system, the risk analysis on the deposition of small particles in the turbine from the ceramic-packed bed was considered based on references in the literature. Overheating of the fans at the thermocline may occur during the discharge phase in configurations C and D, particularly given that the lower temperatures of the thermocline may be elevated due to deep charging of the thermal storage system. Implementing an open-loop configuration could potentially address this issue, although it may also result in significant energy losses. Thus. further work will consider the mathematical model of the configurations' overall energy production and capabilities. Also, an economic analysis should be developed.

Author contributions

- Brenda Hernandez Corona: Writing – original draft, Investigation
- Dr. Thomas Fasquelle: Software, Visualization
- Muhammad Abdullah: Writing – review & editing
- Dr. Nicolas Lopez Ferber: Methodology, Validation, Writing – review & editing
- Dr. Jean-Francois Hoffmann: Software
- Dr. Mathieu Martins: Resources, Writing – review & editing
- Dr. Ahmad Mayyas: Resources. Supervision. Writing – review & editing
- Dr. Nicolas Calvet: Conceptualization, Funding acquisition, Writing – review & editing.

Competing interests

The authors declare that they have no competing interests.

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