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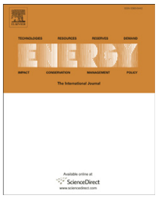

Cost and performance analysis of concentrating solar power systems with integrated latent thermal energy storage

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ABSTRACT

Integrating TES (thermal energy storage) in a CSP (concentrating solar power) plant allows for continuous operation even during times when solar irradiation is not available, thus providing a reliable output to the grid. In the present study, the cost and performance models of an EPCM-TES (encapsulated phase change material thermal energy storage) system and HP-TES (latent thermal storage system with embedded heat pipes) are integrated with a CSP power tower system model utilizing Rankine and s-CO_2 (supercritical carbon-dioxide) power conversion cycles, to investigate the dynamic TES-integrated plant performance. The influence of design parameters of the storage system on the performance of a 200 MW_e capacity power tower CSP plant is studied to establish design envelopes that satisfy the U.S. Department of Energy SunShot Initiative requirements, which include a round-trip annualized exergetic efficiency greater than 95%, storage cost less than \$15/kWh_t and LCE (levelized cost of electricity) less than 6 ¢/kWh. From the design windows, optimum designs of the storage system based on minimum LCE, maximum exergetic efficiency, and maximum capacity factor are reported and compared with the results of two-tank molten salt storage system. Overall, the study presents the first effort to construct and analyze LTES (latent thermal energy storage) integrated CSP plant performance that can help assess the impact, cost and performance of LTES systems on power generation from molten salt power tower CSP plant.

1. Introduction

CSP (Concentrating solar power) technologies integrated with TES (thermal energy storage) have the ability to dispatch power beyond the daytime hours. Thermal energy storage can significantly increase the capacity factor of CSP plants which, in turn, can reduce the LCE (levelized cost of electricity) produced. In 2011, the US Department of Energy launched the SunShot Initiative and has put forth an aggressive R&D (research and development) plan to make CSP technologies cost-competitive with other energy generation sources on the grid by the end of the decade [1]. The goal of the SunShot Initiative is to reduce the LCE from solar power plants to 6 ¢/kWh without subsidies, by 2020, which would pave way for rapid and large-scale adoption of solar electricity. The SunShot 2020 goal calls for reduction in the upfront investment costs through reduced installation and manufacturing costs, and performance improvements in the various sub-systems of the CSP plant, some of which include, reducing the optical losses of heliostats, developing storage systems with high volumetric energy density and high exergetic efficiency.

One potential contributor to the reduction in CSP plant capital cost arises from operation at high temperatures (>650 °C) using advanced cycles such as s-CO_2 (supercritical CO_2) Brayton cycle, which offers the potential of high cycle efficiency and reduction in power block cost compared to the currently existing Rankine cycle operation. The supercritical CO_2 cycle can achieve thermal efficiency as high as 55% for turbine inlet temperature and pressure of 850 °C and 20 MPa, respectively [2–4]. The main improvement of cycle efficiency comes from compressor work reduction due to a rapid increase of CO_2 density, when it is compressed near the critical point (30.98 °C, 7.38 MPa) [2–4]. Other benefits of s–CO_2–Brayton cycle include the ability to achieve high efficiency at low temperatures and the high operating pressure allows small sized components (reduction in power block cost). In addition to the reduction in power block cost, operation at high temperatures requires only less volume of HTF material in the solar field, thus offering a reduction in the HTF material cost [1].

Thermal energy storage systems for potential integration with the operation of a CSP plant fall into one of the following three types (a) sensible heat storage, (b) latent heat storage and (c)

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thermo-chemical storage [5]. Most of the thermal energy storage systems in operation are based on sensible heat storage. Stekli et al. [5] provided a comprehensive list of studies in the literature that are focused on each of the three storage systems and enumerated the technical challenges concerned with each of the three storage systems. Of primary interest among researchers is the deployment of latent heat based thermal storage system in a CSP plant operation. Storing thermal energy in the form of latent heat of fusion of PCM (phase change material) in addition to sensible heat significantly increases the energy density of the storage system, resulting in a reduced storage capital cost per unit thermal energy. However, a major technology barrier that is limiting the use of latent thermal energy of PCM is the higher thermal resistance provided by its intrinsically low thermal conductivity. Several efforts [6–10] are underway to reduce the thermal resistance of PCM's, which includes packing PCM within a high thermal conductivity matrix, mixing high thermal conductivity particles into the PCM, use of extended surfaces and encapsulating PCM, to name a few. Another approach is to embed heat pipes in a tank based LTES (latent thermal energy storage system) to enhance the heat transfer rate between the HTF (heat transfer fluid) and PCM [11–14]. Nithyanandam and Pitchumani [11] considered a large-scale shell-and-tube LTES with embedded heat pipes and identified a unit cell based on the regular repeating design. The influence of the various geometric and operational parameters on the performance of the unit cell was analyzed using simplified thermal resistance network model [11]. A detailed computational modeling of the heat pipe integrated LTES unit cell is reported in Ref. [12] to elucidate the complex interplay between the governing heat transfer and fluid dynamics phenomena for various configurations. The analysis presented in Ref. [12] corresponds to individual charge and discharge process starting from fully discharged and charged state, respectively. Subsequently, the authors analyzed the dynamic performance of heat pipe integrated LTES unit cell subjected to several cyclic charge and discharge processes in Ref. [13]. Shabgard et al. [14] analyzed the performance of large scale LTES with gravity-assisted heat pipes for a single charge and discharge cycle using thermal resistance network model. The studies reported on the performance enhancement techniques for LTES are based either on analysis of a single module [11–13] or on analysis of large scale LTES without accounting for weather transients [10,14], which is an important consideration in CSP plant operation.

In order to achieve the SunShot Initiative goals, a system-driven approach that examines the cost and efficiency of CSP systems is necessary to understand the benefits of CSP with thermal energy storage, which forms the focus of the present study. The SAM (Solar Advisor Model) [15] developed by the NREL (National Renewable Energy Laboratory) and the Sandia National Laboratories provides the framework to investigate the impact of geographical, geometrical and operating parameters on the performance of various CSP technologies including parabolic trough, molten salt power tower and dish stirling power plants. Purohit and Purohit [16] and Jain et al. [17] investigated the potential application of parabolic trough solar power plant in India using SAM and presented a sensitivity analysis to evaluate the impact of solar irradiation on project economics and performance. Janjai et al. [18] also used SAM to find the suitable location for the installation of CSP plant in the tropical climate of Thailand. Similar system analysis studies evaluating the performance of parabolic trough solar power plant with two-tank thermal energy storage system are reported in the literature [19–23]. Kolb [24] and Burkhardt et al. [25] have compared the economics and performance of parabolic trough plant with 2-tank and thermocline energy storage system filled with quartzite rocks. Based on the annual power production of the CSP plant, Kolb [24] concluded that the annual performance of parabolic trough power plant with 2-tank and thermocline energy storage system was nearly identical. On the contrary, Burkhardt et al. [25] presented a detailed life cycle assessment of parabolic trough CSP plants and concluded that CSP plants equipped with dry-cooling and 12 h of thermocline TES (thermal energy storage) minimize both greenhouse gas emissions and water consumption. Robak et al. [26] performed an economic study of LTES system with embedded thermosyphons for integration with a parabolic trough solar power plant and reported a 15% reduction in LTES capital cost compared to a two-tank sensible storage system. A detailed review of the design and economic aspects of the various thermal storage systems published in the literature can be found in Ref. [27].

In developing TES technologies, round-trip energy efficiency is often cited as a key metric of performance; however, it is in fact most critical that the exergetic efficiency be very high to ensure that heat quality is maintained after storage [1]. As per the U.S. Department of Energy SunShot Initiative requirements, the optimal design of a TES for integration into CSP plants should yield a round-trip exergy efficiency greater than 95% and a storage capital cost less than $\$15/\mathrm{kWh_t}$ for a minimum discharge period of 6 h [1]. Although the round-trip exergetic efficiency of sensible TES can attain close to 100%, the storage capital cost of current 2-tank sensible TES is reported as $\$27/\mathrm{kWh_t}$ [28]. Nevertheless, an optimally designed latent TES has the potential to reach both storage capital cost less than $\$15/\mathrm{kWh_t}$ and exergetic efficiency greater than 95%.

The goal of this study is to expand on the limited literature and evaluate the cost and performance of power tower CSP plant (net annual energy production, storage capital cost, capacity factor and LCE) operating on either Rankine or s-CO_2 cycle with integrated EPCM-TES (encapsulated PCM based thermal energy storage) system, tank based HP-TES (latent thermal storage embedded with heat pipes) and 2-tank sensible storage system. The system analysis studies in the literature have concentrated on parabolic trough CSP plant operation based on Rankine cycle integrated with direct/indirect 2-tank sensible energy storage system. However, the SunShot Initiative's projected goal of 6 ¢/kWh by the end of 2020 is expected to be achieved with molten salt power tower CSP plant [1]. In the present study, the feasibility of the LTES (latent thermal energy storage) systems is studied by integrating the physics-based model of the storage systems with the performance model of the molten salt power tower CSP plant. The SunShot 2020 goal aims to achieve a LCE of 6 ¢/kWh without subsidies for a 200-$\mathrm{MW_e}$ molten salt power tower CSP plant with 14 h of TES and a capacity factor of 66.6%. To this end, a systematic analysis of the various design configurations of two different types of latent thermal storage systems on s-CO_2 based CSP plant operation is conducted and for the first time, a methodology for deriving design envelopes of the two different types of latent thermal storage system based on the aforementioned constraints is illustrated. Optimum design configuration of the latent thermal storage system based on minimum LCE from the design windows is reported and compared with the CSP-plant operation based on Rankine cycle integrated with 2-tank direct sensible energy storage system.

2. Model and analysis methodology

2.1. CSP Plant performance model

A schematic of the integration of LTES in a power tower CSP plant working on Rankine cycle is shown in Fig. 1a for a typical charging operation and Fig. 1b shows the discharge operation of a power tower CSP system based on s–CO_2–Brayton cycle. As shown in Fig. 1, a power tower CSP plant comprises of five sub-systems namely, the heliostat field, central tower/receiver, power block,

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