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Techno-economic assessment of technological improvements in thermal energy storage of concentrated solar power

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ABSTRACT

The technological and economic impact of design changes in thermal energy storage of concentrated solar power (CSP) systems is assessed. It is shown that the system costs change with the types of storage tanks and also that the operation temperature is limited by the thermal properties of the thermal storage medium. In addition, the cost of energy can be substantially reduced by replacing the conventional power cycle with more advanced power cycles, such as a supercritical carbon dioxide power cycle. Using two types of thermal storage tanks and two thermal storage media, cases are generated incorporating combinations of the design options. A sensitivity analysis is used to investigate the impacts of each technological improvement. The results of this work will contribute to predicting the impact of research and improving the economics of the CSP system.

1. Introduction

Climate change and depleted fossil fuel reserves are drawing increased attention to renewable energy sources. The sun is a major source of energy for Earth, with an average of approximately 342 watts of solar energy for every square meter per year. In total, the sun delivers 4.4×10^{16} watts of solar energy to the Earth (NASA, 2005). Concentrated solar power (CSP) is one of the highly promising technical options for supplying baseload power with solar energy. In CSP, sunlight is collected and intensified so that the temperature can be high enough to make it applicable to the conventional steam cycle and to the more efficient power cycles, such as supercritical steam or carbon dioxide cycles.

However, the operation efficiency of the CSP process is considerably lower than that of fossil fuel-based power generation systems due to the intermittent supply of solar energy. This can be resolved by reserving the excess heat in a thermal energy storage (TES) unit for later use during nighttime or cloudy periods. In this way, a CSP plant with a TES unit may provide electricity with greater flexibility for planning a balanced system (Fthenakis et al., 2009; Izquierdo et al., 2010; Viehbahn et al., 2011; Lilliestam et al., 2012; Trieb et al., 2012; Usaola, 2012; Pfenninger et al., 2014; Casati et al., 2015; Petrollese et al., 2017). Nevertheless, introducing a TES unit also requires additional capital and operational costs. Since the levelized cost of electricity (LCOE) of a CSP plant is still higher than that of a fossil fuel-based power plant (Black and Veatch, 2012), care must be taken when designing a CSP plant integrated with a TES.

The evaluation of the LCOE may facilitate the assessment of potential cost reduction through technology improvements. Hernández-Moro and Martínez-Duart (2013) presented analytical expressions showing the future evolution of the LCOE of CSP based on the learning curve approach. Researchers at Sandia National Laboratories identified sectoral technology improvement opportunities and discussed their potential impacts on cost reduction (Kolb et al., 2011). Hübner et al. (2016) discussed the techno-economic optimization of heat transfer structures in large scale latent heat energy storage systems. Nithyanandam and Pitchumani (2014) discussed the cost of CSP plant with integrated EPCM-TES (encapsulated phase change materials based thermal energy storage) system, tank based HP-TES (latent thermal storage embedded with heat pipes) and 2-tank sensible storage system. However, the effect of molten salts properties on TES, power cycle units, and LCOE has not been reported yet.

This work evaluates the technological and economic potential of employing technological improvements in thermal storage and power

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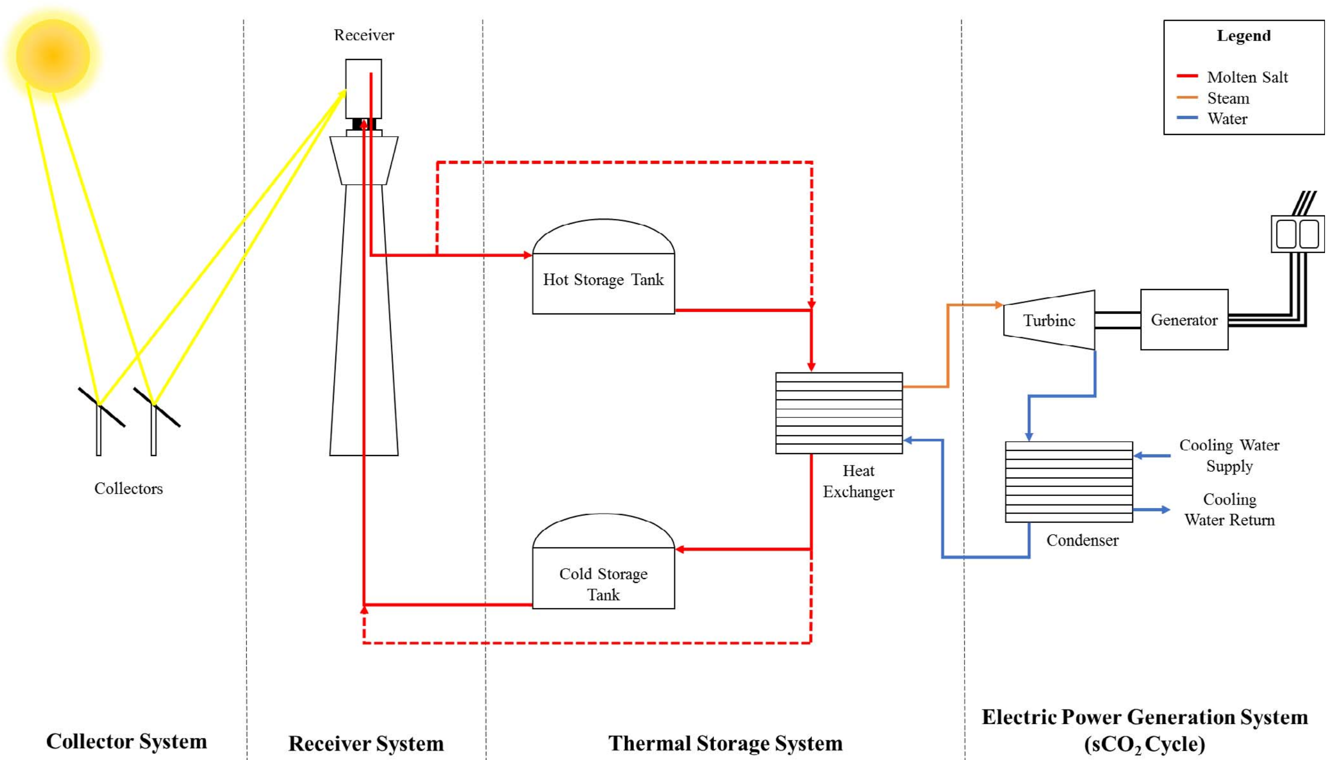

Fig. 1. Process flowsheet of CSP with TES.

cycle units. Technological improvements in thermal storage media and storage tank type are investigated for developing high efficiency CSP processes. Their contributions to LCOE reduction are assessed based on the simulation of an integrated CSP process.

2. Methodologies

2.1. Process simulation

An integrated CSP process simulated in this study consists of a collector, a receiver, a thermal storage unit, and a power cycle unit as shown in Fig. 1. A list of assumptions is given for the design of the integrated CSP process. The solar field data are assumed to be those of the 279 MW CSP plant in Daggett, California (NREL, 2010; Turchi and Heath, 2013), where the direct normal isolation (DNI) is 950 W/m^2, tower height 203 m, and full load thermal storage is 10 h. To estimate the pressure and heat loss, the pipeline is specified to be of schedule 40 S stainless steel (SS), 12 in in diameter with a roughness of 0.0675 mm. The heat transfer coefficient is assumed to be 0.05 W/m^{2}K.

The process was simulated in Aspen Plus V9. The Peng-Robinson equation of state with the Boston-Mathias alpha function (PR-BM) was used as the fluid package for the molten salt system. The IAPWS-95 and REFPROP models are used to simulate the steam and supercritical carbon dioxide (sCO_2) cycle properties, respectively, in the wide temperature and pressure range of interest (Aspentech, 2013). The turbine efficiency is assumed to be 80% in the steam cycle and 93% in the sCO_2 cycle (Neises and Turchi, 2014; Elliott Turbo, 2015).

2.2. Case study

A commercially viable CSP plant with a thermal energy storage unit is taken as the base case. In this system, the TES unit is operated with Solar Salt and consists of hot and cold storage tanks. A steam cycle, in which a steam-driven turbine is used to generate electricity, is used for power generation as it is in most demonstration and commercial plants (IEA, 2010; Kolb et al., 2011; IRENA, 2013).

In the following case studies, the process design is improved with technological changes to lower the cost of energy from that of the base case. First, a change of the storage media is considered to increase the operation temperature of TES unit, and, therefore, increase the power cycle efficiency. The operation of the TES unit is limited to 550 °C with Solar Salt due to salt decomposition above this temperature. Recently, a few salt mixtures have been proposed to resolve this issue, and one of them is shown in Table 1. The operation of the TES unit operation at higher temperatures is expected to elevate the power generation efficiency of the CSP plant by introducing a high efficiency power cycle, such as supercritical carbon dioxide power cycle (Kelly, 2010; Kolb et al., 2011). Even while maintaining the steam power cycle, the

Table 1
Properties of molten salts for case study.

Name	Composition (wt%)	Melting temperature (°C)	Decomposition temperature (°C)	Density (kg/m^3)	Specific heat capacity (kJ/kg K)	Price (US $/ton)
Solar Salt[a]	$NaNO_3$–KNO_3 (60–40)	220[a]	600[a]	1910–1720[b]	1.49–1.55[b]	600[c]
Salt A[c]	KCl–Na_2CO_3–K_2CO_3 (20–40–40)	427[c]	877[c]	2054[d]	1.6 (at 450 °C)[c]	640[c]

[a] Heller (2013), Li et al. (2014).
[b] Heller (2013).
[c] Kim et al. (2016).
[d] Estimated value.