Annual comparative performance and cost analysis of high temperature, sensible thermal energy storage systems integrated with a concentrated solar power plant

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The present study conducts a comprehensive techno-economic analysis of some near-term sensible thermal energy storage (TES) alternatives to the ‘standard’ two-tank molten salt system for concentrated solar power (CSP) plants. As such, we conducted detailed, relative annual transient simulations for single-medium thermocline (SMT), dual-media thermocline (DMT), and shell-and-tube (ST) systems. To be consistent with recent literature, the DMT and ST systems use concrete with a porosity of 0.2 (e.g. where concrete occupies 80% of the system) as their low cost filler material. The systems were integrated into a validated 19.9 MWe Gemasolar CSP model, which has a solar multiple of 2.5. For a relative analysis, the storage capacity of each TES alternative was fixed at 722 MWh (15 h storage) for all TES alternatives. Based on this capacity, a geometric optimization was performed on DMT and ST systems to maximize the discharged power and minimize the pressure drop. Using the optimum designs, it was found that a CSP plant with a two-tank molten salt system enables the highest amount of electricity generation in a year followed by the SMT and DMT systems, which resulted in 7% and 9% less electricity generation, respectively. As the worst performer, a CSP plant integrated with a ST system generates 20% less electricity over a year. This implies that despite having the same theoretical capacity, the real performance is not same for the alternatives. While these losses may seem egregious at first, large TES cost reductions are made possible in these alternatives due to the fact that a single tank or concrete can be used (noting that concrete is <1/20th the price per kg of molten salt). We propose herein that the true techno-economic advantage (or lack thereof) of choosing alternative TES systems should be judged by a ‘normalized cost of thermal energy storage (NCOTES)’ which normalizes the cost of storage systems with regards to their annual electricity generation capacity. According to our analysis, optimized DMT and ST systems without embedded pipes (e.g. bored or formed concrete) can achieve 55% and 46% reductions relative to the NCOTES of the two-tank system, respectively (with 650 K as cut-off discharge temperature), while the SMT system has an 13% lower NCOTES than the two-tank system. With embedded pipes, however, the ST design has a higher NCOTES (+1% to +100%, depending on the discharge cut-off temperature), indicating that embedded piping is the biggest cost driver and that the elimination of piping should be a priority in ST systems. Overall, this study provides a methodology for the relative comparison of various sensible TES alternatives, and it gives insight into the most promising alternatives for moving beyond two-tank molten salt systems.

1. Introduction

Concentrated solar power (CSP) plants are likely to play a big role in the future of large-scale electricity generation (Oró et al., 2012). Today’s CSP market is dominated by the parabolic trough technology, but the future ascendancy of tower systems seems evident (Dowling et al., 2017; Liu et al., 2016; Lovegrove et al., 2012; Reddy et al., 2013). The fundamental reason for this shift is related to the higher receiver temperature (~800 K as compared to ~600 K) in tower systems due to their higher concentration ratios (~1000 × as compared to ~100 × in parabolic trough plants) (Behar et al., 2013).
One of the big advantages of CSP plants (over photovoltaics) is their ability to couple with thermal energy storage (TES) systems. At present, considering an average storage cost of 22 US$/kWhth for the commercial thermal energy storage system in CSP plants, the cost of TES systems for utility scale applications is still ~30–150 times lower than that of electricity storage systems (Lai and McCulloch, 2017; Luo et al., 2015). TES systems are able to increase the dispatchability of solar power plant to 24 h (Law et al., 2016; Law et al., 2014).

TES systems can be classified into three broad categories (Gil et al., 2010; Kuravi et al., 2013): (1) sensible heat storage systems, which make use of solid and/or liquid media, (2) latent heat storage systems, which make use of phase change materials (PCM), and (3) thermochemical storage systems, which make use of reversible thermochemical reactions. This work focuses on the first, most near-term category of TES systems—sensible thermal energy storage systems. Even among this first group there are still a multitude of sensible thermal energy storage materials and configurations, so further down-selection is required.

The overall cost and performance of a TES system is highly dependent on the storage medium and its configuration. The (sole) commercial example of this technology is the two-tank-storage system using molten salts—a technology which has been deployed in many CSP plants, including the 19.9 MWth Gemasolar CSP-tower plant in Spain (Burgaleta et al., 2012; Kuravi et al., 2013). While this method of storage has been successful in current plants, if CSP is to be economically competitive in the future, the storage cost must be reduced considerably (Gil et al., 2010). Furthermore, it has been shown that the two-tank molten salt storage is also limited by environmental and health impacts, so reducing the amount of salt in TES alternatives is required (Jacob et al., 2016). To achieve favorable economics and a reduction in environmental impact requires alternative TES systems.

One frequently proposed option utilizes the natural thermal stratification phenomena, where a difference in density enables both the hot and cold fluid to be present in a single tank. This thermal-induced gradient is called a ‘thermocline’ and an immediate potential cost saving is realised by simplifying the TES system to a single tank. Single-medium thermocline (SMT) systems employ a single liquid storage material only, while dual-medium thermocline (DMT) systems utilize low cost solid fillers such as concrete or rocks alongside the liquid medium to decrease the amount of solar salt needed in the system (potentially reducing total material costs) (Dincer and Rosen, 2002; Mira-Hernández et al., 2015; Tehrani et al., 2013a). The third alternative to conventional two-tank molten salt systems is the shell-and-tube (ST) or embedded tube storage systems where the storage medium is usually located in shell, while the heat transfer fluid, typically solar salt, flows inside the tube (Bai and Xu, 2011; Strasser and Selvam, 2014). A schematic of the TES alternatives analyzed in this study are depicted in Fig. 1.

### 1.1. 2-tank molten salt system

In this system, the salt volume is equal to the volume of one storage tank only. Since the two-tanks molten salts system configuration relies on the separation of the hot and cold fluid in two different tanks, its efficiency is based on a constant outlet salt temperature when discharging, which leads to the requirement of no stratification effect in the storage tanks (Prieto et al., 2016a). Although this system is the sole commercial unit in the market, different aspects of this system is still under development. The recent researches on this system are concerned with the amount of heat loss present in the system (Prieto et al., 2016a; Prieto et al., 2016b), developing detail modelling tools (Zaversky et al., 2013), reducing the degree of corrosion between salt and tank (Guillot et al., 2012; Stekli et al., 2013), optimizing the charging and discharging performance of system (Abutayeh et al., 2015), and investigation of safe cooling process of the salt (Suárez et al., 2015).

### 1.2. Thermocline system studies

The number of studies on DMT systems for CSP applications easily outnumbers that of SMT systems (see Table 1). SMT tanks are applied in power conversion technologies in the literature (e.g. combined heat and power plants, district heating systems,
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