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Economic impact of latent heat thermal energy storage systems within direct steam generating solar thermal power plants with parabolic troughs

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ABSTRACT

One possible way to further reduce levelized costs of electricity of concentrated solar thermal energy is to directly use water/steam as the primary heat transfer fluid within a concentrated collector field. This so-called direct steam generation offers the opportunity of higher operating temperatures and better exergy efficiency. A technical challenge of the direct steam generation technology compared to oil-driven power cycles is a competitive storage technology for heat transfer fluids with a phase change. Latent heat thermal energy storages are suitable for storing heat at a constant temperature and can be used for direct steam generation power plants. The calculation of the economic impact of an economically optimized thermal energy storage system, based on a latent heat thermal energy storage system with phase change material, is the main focus of the presented work. To reach that goal, a thermal energy storage system for a direct steam generation power plant with parabolic troughs in the solar field was thermally designed to determine the boundary conditions. This paper discusses the economic impact of the designed thermal energy storage system based on the levelized costs of electricity results, provided via a wide parametric study. A state-of-the-art power cycle with a primary and a secondary heat transfer fluid and a two-tank thermal energy storage is used as a benchmark technology for electricity generation with solar thermal energy. The benchmark and direct steam generation systems are compared to each other, based respectively on their annual electricity yields and their levelized costs of electricity at two different sites. A brief comparison of a passive and an active latent heat storage system is included. Finally, specific target costs for the new direct steam generation thermal energy storage system are determined based on the results of the parametric study.

1. Introduction

Several research projects on new concentrating solar power (CSP) technologies have been carried out. One of the main goals is the reduction of the levelized costs of electricity (LCOE), in order to increase the competitiveness of CSP in comparison with other renewable energy electricity generating technologies, for example photovoltaic (PV) power plants. A promising solution for decreasing the LCOE is the production of more electrical power via a better conversion efficiency of the power plant process. Commercial CSP plants, discussed by Dinter and Gonzalez [1], with parabolic trough collectors (PTC) are operated with synthetic oil as the primary heat transfer fluid (HTF). The most common oil has a limited temperature range. Higher conversion efficiencies can be attained with higher live steam parameters, which require the use of a primary HTF with higher temperature limits.

One approach to raising the temperature limits is the use of molten salts (e.g. nitrate mixtures) as the primary HTF. Wagner and Wittmann [2] describes a parabolic trough power plant with a direct molten salt storage, which was investigated using a transient simulation model. Kearney et al. [3] discusses the engineering aspects of such a system and proposes a prototype test as the next

Abbreviations: CAPEX, capital expenditures; CSP, concentrating solar power; DNI, direct normal irradiance; DSG, direct steam generation; EPC, engineering-procurement-construction; HTF, heat transfer fluid; HTX, heat exchanger; IAM, incidence angle modifier; LCOE, levelized costs of electricity; LHTES, latent heat thermal energy storage; OPEX, operational expenditures; PB, power block; PCM, phase change material; PTC, parabolic trough collector; PV, photovoltaic; SF, solar field; SHTES, sensible heat thermal energy storage; SOC, state-of-charge; TES, thermal energy storage; TMY, typical meteorological year.

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Nomenclature

A_{net}	net collector area	i	interest rate
A_{total}	total solar field area	n	payout time
C_{CAPEX}	capital expenditures	P_{el}	electrical power of power plant
C_{Fuel}	fuel costs of auxiliary heater	P_{int}	electrical internal consumption
C_{LCOE}	levelized costs of electricity	p_{TES}	pressure at water/steam side of TES
C_{OPEX}	operational expenditures	$\dot{Q}_{SF}$	thermal power of SF
E_{el}	electrical energy of power plant	$\dot{Q}_{PB}$	thermal power of PB
E_{TES}	thermal energy content of TES	$\dot{Q}_{TES}$	thermal power of TES
f_{AN}	annuity factor	η_{SF}	efficiency of SF
f_{SM}	solar multiple	η_{PB}	efficiency of PB
f_{SOC}	state-of-charge		
G_{DNI}	solar direct normal irradiance		

developmental step. The limitation with current molten salts as the HTF in the PTC is the high freezing point of almost 234 °C, given by Bradshaw and Siegel [4]. This leads to anti-freeze costs. A second approach is the use of water/steam within the solar field (SF), allowing for higher steam temperatures without the need of an energy intensive anti-freeze. A barrier for a broad market introduction of the direct steam generation (DSG) approach is the lack of suitable thermal energy storage (TES) concepts for solar thermal power plants with DSG, discussed by Laing et al. [5]. Feldhoff et al. [6] compared a DSG power plant to a state-of-the-art PTC technology with synthetic oil. It was concluded that a DSG-SF operated in a recirculation mode results in higher LCOE than the reference power plant. A DSG-SF with a once-through mode, on the other hand, was shown to lower the estimated LCOE.

Such a TES for solar thermal power generation can be realized by the use of latent heat thermal energy storage (LHTES), using phase change materials (PCM) as discussed in the work of Steinmann and Tamme [7] for the evaporation or condensation of water or steam for solar thermal power plants with DSG. The different concepts for PCM-storages can be divided into passive concepts, such as the sandwich configuration, developed, among others, by Bayón et al. [8], using expanded graphite fins for the improvement of the low thermal conductivity of the storage material. The radial fin designs by, among others, by Laing et al. [9] uses milled aluminum fins for this purpose. Active concepts, such as a screw heat exchanger developed by Zipf et al. [10], aim to provide a constant power level during the charging and discharging of the storage, by removing used storage material from the heat exchanger fin geometry. The PCMflux concept, described by Pointner and Steinmann [11], uses several movable containers, which are filled with storage material, to fulfill this same constant-power criterion of active PCM systems. The main differences between passive and active concepts are their transient trends during the charging and discharging processes. If a passive concept, which can be built without complex mechanics, is used, the frozen PCM enhances the thermal resistance during the discharging process. In the case of an active concept, the frozen PCM is moved away from the heat transfer surface, but a PCM transport device is needed.

In this paper, the main focus is the economic impact of a passive LHTES system; a brief comparison with an active system is introduced at the end. For mitigation of the effects of low thermal conductivity of the PCM, additional heat transfer structures can be integrated in passive LHTES. Several approaches for the optimization of the heat transfer between the water/steam and the PCM are reviewed by Khan et al. [12]. It was concluded that an enhanced storage performance of PCM storages can be achieved by using optimized fins. Laing et al. [13] developed an axial aluminum fin profile with mounting clips made of spring steel. Johnson et al. [14] evaluated the thermal behavior of this fin structure by simulation and by an experimental setup. These axial fins can be produced as partial shells and mounted on the outside of the water/steam pipes via springs. This fin structure was identified by Laing et al. [13] to be cost-saving and can be adjusted in the fin geometry more easily compared to radial fins. A LHTES with axial aluminum fins with a thermal capacity of 1.5 MW h and a thermal power of 6 MW is being developed by Johnson et al. [15]. Based on this work, TES systems consisting of a sensible and a latent heat thermal energy storage, were designed by Seitz et al. [16]. The goal of this combination is the production of superheated steam during discharging for the power generation unit. A technical and an economical optimization process to identify the best fin concept was carried out by Hübner et al. [17]. With the developed LHTES concept, the partial load behavior of the new DSG-TES system was investigated by Seitz et al. [18].

This paper presents the results of a novel detailed economic evaluation of the developed DSG-TES system, based on the fin geometry "DSG-Store", compared to the reference HTF-Oil TES system with an indirect molten salt two-tank TES. In addition to the comparison between the DSG and HTF-Oil systems, the DSG system was calculated with both the optimized DSG-Store fin and a second not optimized passive fin profile "Brökelmann", based on the work of Laing et al. [13]. Active LHTES systems, based on the work of Pointner et al. [21], were evaluated in terms of target cost considerations as well. These comparisons are detailed in order to give a wider perspective on the system integration of LHTES.

The calculation of the annual electricity yields and the estimated investment and operational expenditures of the systems are evaluated. Based on these results, the LCOE of each system configuration is calculated. Such techno-economic studies, as conducted by Chacartegui et al. [19], are essential for the evaluation of the economic potential of a new technology, such as organic Rankine cycles. Trabelsi et al. [20] compared wet and dry cooled CSP plants in Tunisia and concluded that dry cooling systems are competitive with wet cooling systems in arid regions.

A parametric study was calculated with a variation of TES systems and SF sizes for two geographical sites and two cost estimation scenarios. These calculation results allow for the identification of the optimal SF size for each TES size by minimizing the LCOE. With these comparisons, it is possible to evaluate the differences between the state-of-the-art technology and the developed DSG-TES system.

2. Methods and system description

The complete CSP plant consists of the following sub-systems, which are evaluated during the calculation of the annual electricity yield of the power plant: