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Thermal energy storage systems for concentrated solar power plants

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ABSTRACT

Solar thermal energy, especially concentrated solar power (CSP), represents an increasingly attractive renewable energy source. However, one of the key factors that determine the development of this technology is the integration of efficient and cost effective thermal energy storage (TES) systems, so as to overcome CSP's intermittent character and to be more economically competitive. This paper presents a review on thermal energy storage systems installed in CSP plants. Various aspects are discussed including the state-of-the-art on CSP plants all over the world and the trend of development, different technologies of TES systems for high temperature applications (200–1000°C) with a focus on thermochemical heat storage, and storage concepts for their integration in CSP plants.

TES systems are necessary options for more than 70% of new CSP plants. Sensible heat storage technology is the most used in CSP plants in operation, for their reliability, low cost, easy to implement and large experimental feedback available. Latent and thermochemical storage technologies have much higher energy density thus may have a bright foreground. New concepts for TES integration are also proposed, especially coupled technology for higher operating temperature and cascade TES of modularized storage units for intelligent temperature control.

The key contributions of this review paper consist of a comprehensive survey of CSP plants, their TES systems, the ways to enhance the heat and/or mass transfers and different new concepts for the integration of TES systems.

1. Introduction

The use of renewable energy is essential today to decrease both the consumption of fossil resources and the production of carbon dioxide partly responsible for the greenhouse gas effect [1,2]. Among every renewable resources (e.g., wind, ocean, geothermal and solar), solar energy is showing encouraging promises due to the great quantities of solar irradiation flux arriving on earth.

Among various solar energy technologies, concentrated solar power (CSP) is particularly attractive due to its advantages in terms of high efficiency, low operating cost and good scale-up potential [3,4]. Solar energy is converted into electricity by means of a CSP plant composed of four main elements: a concentrator, a high temperature solar receiver, a fluid transport system and a power generation bloc (e.g., Rankine cycle, Stirling cycle). It is estimated by IEA that the CSP will contribute up to 11% of the global electricity production in year 2050 [5].

1.1. CSP technologies

A wide range of concentrating technologies exist; the most developed are parabolic trough collectors (PTC), linear Fresnel reflectors (LFR), solar power towers (SPT) and parabolic dish collectors (PDC), as summarized in Table 1. PTC plants use parabolic reflectors to focus sunlights on an absorber tube located on the focal line of the parabola. Reflectors and the absorber tube can move together to follow the sun from sunrise to sunset [6,7]. LFRs consist of curved reflectors on each side of an absorber tube. A recent design called compact linear Fresnel reflector (CLFR) uses two parallel reflectors for each mirror's row, needing less area than a PTC to reach a given power output [8]. SPTs

Abbreviations: CLFR, Compact Linear Fresnel collector; CRS, Central Receiver System; CSP, Concentrated solar power; CST, Concentrated solar thermoelectric; DNI, Direct Normal Irradiance; DSG, Direct steam generation; HCE, Heat Collector Element; HFC, Heliostat field collector; HTF, Heat transfer fluid; IEA, International Energy Agency; LFR, Linear Fresnel reflector; PDC, Parabolic dish collector; PTC, Parabolic trough collector; M & O, Maintenance and Operation; n.a., not applicable; R & D, Research and development; SPT, Solar power tower; STC, Solar Tower Collector; TES, Thermal energy storage

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Table 1
Comparison between different CSP technologies [3,9,10].

CSP technology	Operating temperature (°C)	Solar concentration ratio	Storage integration possibility	Advantages	Disadvantages
PTC	20–400	15–45	Possible	– Relatively low installation cost [11]. – Large experimental feedback.	– Relatively large area occupied. – Low thermodynamic efficiency due to low operating temperature.
LFR	50–300	10–40	Possible	– Relatively low installation cost.	– Low thermodynamic efficiency due to low operating temperature.
SPT	300–1000	150–1500	Highly possible with low storage cost [12,13]	– High thermodynamic efficiency due to high operating temperature.	– Large space area occupied. – Relatively high installation cost. – High heat losses.
PDC	120–1500	100–1000	Difficult	– Relatively small area occupied. – High thermodynamic efficiency due to high operating temperature.	– Relatively high installation cost. – Little experimental feedback.

use heliostat field collectors (HFCs) to reflect and focus sunlights onto a central solar receiver located on the top of the tower. It is a relatively flexible technology because a variety of heliostat fields, solar receiver designs and heat transfer fluids (HTFs) could be used. PDCs concentrate sunlights on a focus point above a parabolic reflector. The reflector and receptor track the sun. Besides these conventional types, CSP technology can also be combined with thermoelectric systems (i.e., concentrated solar thermoelectric) for direct electricity production without using a power cycle [8].

1.2. Thermal energy storage

A major drawback of solar energy is its temporal intermittency. To overcome this problem, one solution is to use a backup system (energy hybridization) that burns fossil fuel or biomass. A second solution is to use a thermal energy storage (TES) system to store heat during sunshine periods and release it during the periods of weak or no solar irradiation (Fig. 1).

The development of an efficient and cost-effective TES system is crucial for the future of CSP technologies [14]. Economically, TES allows an increase in the duration of electricity production. Moreover, integrating a TES system in specific CSP configurations permits optimization of electricity resale and the CSP electricity production [15]. Indeed, as shown in Fig. 2 [16], electricity prices vary during a day depending on demand. The solar intensity's largest periods do not correspond to the electricity's most expensive periods. Adding a TES allows heat storage during high solar intensity periods and provides productions during high electricity cost periods.

There are currently three kinds of TES systems available: sensible heat storage, latent heat storage and thermo-chemical heat storage [17,18]. Sensible heat storage systems are the most mature. They are widely used in industrial plants, most notably in Spain within the "PS10" and "PS20" projects (2007 and 2009), the "Andasol 1" and "Andasol 2" plants (2008) and also in the USA (e.g., within "Solar One",

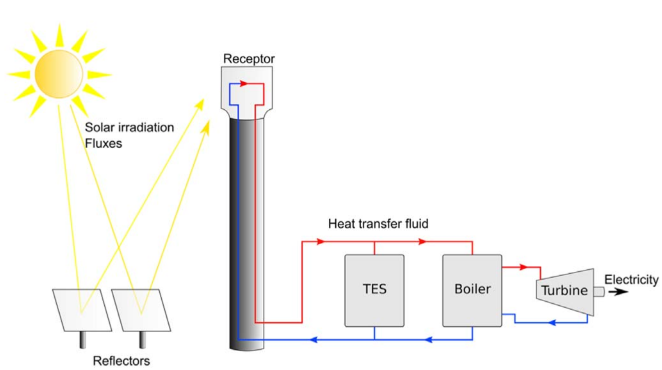

Fig. 1. CSP plant with a TES system.

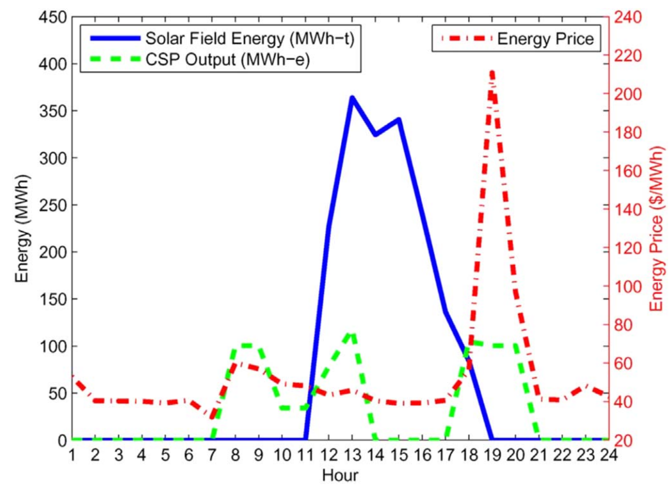

Fig. 2. Example of peak energy production and cost of energy for a CSP plant [16].

1982) [18]. Latent heat storage allows large amounts of energy to be stored in relatively small volumes (high energy density) and is cost competitive. Among these techniques, thermochemical heat storage receives increasing attention. Two recent reviews were published, focusing on low to medium temperature (0–300 °C) thermochemical reactions pertaining to long-term sorption solar energy storage [19] and to chemical heat pump technologies [20]. Cot-Gores et al. [21] and Prieto et al. [22] also presented reviews on sorption and chemical reaction processes for TES application. Reaction candidates for medium or high temperature applications (250 – 800 °C) were listed by Felderhoff et al. [23].

1.3. Objectives of this paper

Based on the existing literature, we observe that CSP plants worldwide and their characteristics (e.g., power, presence of a TES system, storage capacity) are partially (e.g., in [24]) presented, but a full description would be beneficial. In parallel, TES materials for CSP application need to be updated, especially those for thermochemical heat storage. Moreover, the issue of appropriate and new concepts for TES integration in CSP plants which is very important, is discussed here in more detail.

The present paper has therefore the following objectives:

- The most complete survey on CSP plants in operation, under construction and in project all over the world and on the trends of development in order to highlight the economic necessity of the integration of TES systems in CSP plants to compete with current energy production technologies.