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Performance comparison of two-tank direct and thermocline thermal energy storage systems for 1 MWe class concentrating solar power plants

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ABSTRACT

This paper compares the performance of medium size CSP (Concentrating Solar Power) plants based on an ORC (Organic Rankine Cycle) power generation unit and using linear Fresnel collectors, thermal oil as heat transfer fluid and two-tank direct and thermocline energy storage systems. The comparative performance analysis was carried out by means of specifically developed simulation models and considering different values of solar multiple and thermal energy storage capacity. The results of the performance assessment demonstrate that if the CSP plant has to be optimized for the highest specific energy production, that is, for the highest solar energy conversion efficiency, two-tank energy storage systems show slightly higher performance than thermocline storage systems. However, the study also demonstrates that thermocline storage systems can be an interesting option to reduce the energy production cost of CSP plants.

1. Introduction

Concentrating Solar Power (CSP) plants are today one of the most interesting options in the field of solar energy technologies. CSP plants use solar collectors to increase the temperature of a Heat Transfer Fluid (HTF) and the high temperature thermal energy produced is converted into mechanical work by a suitable power generation section. Moreover, to offset the intermittence of solar energy and increase power plant dispatchability, CSP plants are usually coupled with a Thermal Energy Storage (TES) section. Today, the current CSP world generating capacity is around 3000 MW and is rapidly increasing. More than 1300 MW of additional CSP capacity is currently under construction and about 10 GW is expected before 2015. Spain is the country with the highest CSP production, thanks to the operation of more than 50 power plants with an installed capacity of more than 2300 MW [1,2].

The preferred choice for current CSP plants is based on large-size power generation units (often in the range of 20–50 MW) mainly due to their higher conversion efficiency and lower specific capital costs. However, the construction of large-size CSP units requires the availability of large areas and noteworthy capital investments (a typical 50 MWe CSP plant requires a total capital investment of about 250–300 M€ and the availability of about 150–250 ha of land). For this reason, the construction of medium-size CSP plants (around 1-5 MWe) may be a more suitable option for countries where large areas can be hard to find (as in Italy, for example).

During the design of CSP plants, different options are available for solar field (parabolic trough, linear Fresnel, solar tower and solar dish systems), heat transfer fluid (thermal oil, molten salts, steam, etc.), power generation section (steam Rankine and organic Rankine cycles, Stirling engines, combined cycles, etc.) and thermal energy storage (active, passive, two-tank, thermocline, etc.) [3–5].

For large-size CSP plants, the preferred configurations rely on solar fields based on Parabolic Trough Collectors (PTC) or solar tower systems, thermal oil as HTF and two-tank indirect systems using molten salts as storage medium for the TES section. The power generation section is almost always represented by steam Rankine cycles with superheated steam produced at about 370–380 °C and 80–100 bar, high-pressure and low-pressure steam turbines with reheating and 4-6 steam extractions for feed-water heating [6,7].

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Nomenclature

A	area (m^2)
C	annual operating cost (€/yr)
Cp	specific heat (J/kg K)
d	particle diameter (m)
DNI	direct Normal Irradiation (W/m^2)
E	energy (J)
F	focal length (m)
G	mass velocity (kg/m^2 s)
h	volumetric heat transfer coefficient (W/m^3 K)
H_B	bed height (m)
H_{ST}	hours of energy storage capacity (hr)
i	annual interest ratio (–)
I	investment cost (€)
k	thermal conductivity (W/m K)
L	collector length (m)
m	mass flow (kg/s)
N	operating lifetime (yr)
Nu	Nusselt number (–)
p	pressure (Pa)
Pr	Prandtl number (–)
q	specific thermal losses (W/m^2)
Q	thermal power (W)
R	lines distance (m)
Ra	Rayleigh number (–)
Re	Reynolds number (–)
SM	solar multiple (–)
t	time (s)
T	temperature (K)
U	global heat transfer coefficient (W/m^2 K)
V	volume (m^3)
W	collector width (m)
α	convective heat transfer coefficient (W/m^2 K)
ε	bed void fraction (–)
η	efficiency (–)
θ	incidence angle (°)
ρ	density (kg/m^3)

Acronyms

CSP	concentrating solar power
DSG	direct steam generation
HTF	heat transfer fluid
IAM	incidence angle modifier
LCOE	levelized cost of energy
LFC	linear fresnel collector
ORC	organic Rankine cycle
PTC	parabolic trough collector
TCI	total capital investment
TES	thermal energy storage

For medium-size CSP plants the technology options differ from those of large-size plants. In fact, for power outputs in the range of 1 MWe Organic Rankine Cycles (ORC) can be a more viable alternative to steam Rankine cycles for the power generation section. ORC systems use organic fluids with high molar weight instead of steam and require thermal energy inputs with temperature levels starting from 80 to 100 °C (low temperature ORC cycles) up to 300–400 °C (high temperature ORC cycles). Low temperature ORC cycles often use refrigerants as working fluid while high temperature ORC cycles often use siloxanes, even if different working fluids can be used in both cases [8–10]. Moreover, with such temperature levels, the most suitable option for the heat transfer fluid is today represented by thermal oils (whose maximum bulk temperature is 390–400 °C), since molten salts (60% $NaNO_3$ and 40% KNO_3) and the direct production of steam in the solar field (Direct Steam Generation, DSG) are specifically developed to raise the maximum HTF temperature, especially for large-size units [11,12].

For the solar field of medium-size CSP plants, linear concentrating collectors appear to be the most tailored choice. Moreover, Linear Fresnel Collectors (LFC) may be a viable alternative to PTC, especially if the land requirement is a key feature. In comparison to PTC, LFCs have a simpler design, use less expensive mirrors and tracking systems, show lower land requirements and lower capital costs. On the other hand, the optical efficiency of LFC is lower than that of PTC [13–16].

With reference to the TES section, thermal energy can be stored as sensible heat, latent heat or chemical energy. Latent heat and chemical energy are considered the most promising technologies but sensible heat storage is the simplest method to store thermal energy and some technological and economic aspects make it superior, especially in the case of medium-size CSP systems [17–23]. In particular, the most mature solution for the TES section is today represented by two-tank direct systems, composed of a low-temperature and a high-temperature tank, where thermal oils are used as storage medium. To reduce the cost of the TES section, the two-tank configuration can be substituted by a thermocline system, based on a single-tank packed bed containing a low-cost filling material [24–28]. In thermocline systems the hot HTF is pumped into the top of the tank, flows downwards and gradually heats the filling material. During the charging phase the high temperature zone is separated from the low temperature zone by a thermal gradient that moves downwards in the tank. During the discharging phase the cold HTF is pumped into the bottom of the tank so that the thermal gradient moves upwards. The use of low-cost filling materials in a single-tank system reduces the cost of the TES section and the volume of thermal oil required [24]. However, owing to the presence of the temperature gradient inside the tank, thermocline systems are less efficient than two tank systems because the useful thermal energy recovered during the discharging phase is lower than that supplied during the charging phase [28].

Recent studies on thermocline TES systems mainly focus on large-size CSP plants and on the use of molten salts [29–32]. However, for medium-size CSP units, the use of thermal oil can be a more interesting choice due to the lower operating temperatures. A thermal oil thermocline TES system was used from 1982 to 1987 by the Solar One CSP plant [33]. More recently, a similar TES systems was proposed for the 1 MW Saguaro CSP plant [34]. Studies on thermocline systems using thermal oil were also presented in Refs. [35–38].

In the field of medium-size units, a comparative performance analysis of CSP plants based on parabolic trough and linear Fresnel collectors was carried out in a previous paper [39]. The performance of the CSP plants were evaluated on the basis of a 1 MW ORC unit and with the use of thermal oil as heat transfer fluid and as storage medium in a two-tank direct thermal storage system. The results of the performance assessment demonstrate that CSP plants based on linear Fresnel collectors lead to higher values of electrical energy production per unit area of occupied land while parabolic troughs gives better values of energy production per unit area of solar collector owing to their better optical efficiency.