Applied Energy 88 (2011) 4055–4066

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Energy management in solar thermal power plants with double thermal storage system and subdivided solar field

Antonio Rovira [a,*], María José Montes [a], Manuel Valdes [b], José María Martínez-Val [b]

[a] E.T.S. Ingenieros Industriales – UNED, C/Juan del Rosal, 12, 28040 Madrid, Spain
[b] E.T.S. Ingenieros Industriales – UPM, C/José Gutiérrez Abascal, 2, 28006 Madrid, Spain

ARTICLE INFO

Article history:
Received 28 October 2010
Received in revised form 11 April 2011
Accepted 12 April 2011
Available online 6 May 2011

Keywords:
Solar thermal power plant
Thermal storage
Energy management
Solar field layout

ABSTRACT

In the paper, two systems for solar thermal power plants (STPPs) are devised for improving the overall performance of the plant. Each one attempts to reduce losses coming from two respective sources. The systems are simulated and compared to a reference STPP.

They consists on: (a) a double thermal energy storage (DTS) with different functionalities for each storage and (b) the subdivision of the solar collector field (SSF) into specialised sectors, so that each sector is designed to meet a thermal requirement, usually through an intermediate heat exchanger. This subdivision reduces the losses in the solar field by means of a decrease of the temperature of the heat transfer fluid (HTF). Double thermal energy storage is intended for keeping the plant working at nominal level for many hours a day, including post-sunset hours. One of the storages gathers a fluid which is heated up to temperatures above the nominal one. In order to make it work, the solar field must be able to overheat the fluid at peak hours. The second storage is the classical one. The combination of both allows the manager of the plant to keep the nominal of the plant for longer periods than in the case of classical thermal energy storage.

To the authors' knowledge, it is the first time that both configurations are presented and simulated for the case of parabolic through STPP with HTF technology. The results show that, if compared to the reference STPP, both configurations may raise the annual electricity generation (up to 1.7% for the DTS case and 3.9% for the SSF case).

1. Introduction

Solar thermal power plants (STPPs) are one of the most promising systems for generating electricity in any scenario of sustainable development. At present, installation of these kinds of power plants is spreading widely. Since much of this technology is recent, there is still room for improving designs, and emerging concepts are often proposed and analysed.

Among the available options, STPP based on parabolic trough collectors is the most extended option, although other technologies as central tower receiver and reflection Fresnel with a linear receiver seem to have more potential of improvement in the collectors, which is a fundamental part of the plants. Other parts of the plants deserve attention as well.

With the aim of improving the performance of solar thermal power plants, in this paper two configurations of STPP are analysed. Each configuration enhances the annual performance of the power plant through the reduction of the losses coming from two respective sources.

On the one hand, future STPPs will likely include a thermal storage system [1–3]. Thermal storage provides the advantages of damping the transients and, together to an appropriate solar multiple selection, enlarging the annual operation time of the power plant. This issue may be the key to increase the yearly revenues of operators [4] and, thereby, to accelerate the installation of this type of plants. Thus, improvements in thermal storage system should be explored. In [5] some desirable features for storage systems are described, like reducing heat losses and avoiding temperature degradation. A great amount of works focused on the search for these requirements and also considering the costs may be found in the technical literature. For example, in [6] it is proposed a solid media storage system, in [7] authors investigate additives for molten salts [8], studies a thermocline system and in [9] is proposed a methodology to assess different technologies.

All these systems have a common feature, what is exemplified as follows in the case of an indirect storage system. In such system, when the STPP works at nominal conditions, part of the thermal energy produced in the solar field is transferred to this system from a heat transfer fluid (HTF). Charge of the thermal storage system

* Corresponding author. Tel.: +34 913988224; fax: +34 913987615.
E-mail addresses: rovira@ind.uned.es (A. Rovira), mjmontes@ind.uned.es (M.J. Montes), manuel.valdes@upm.es (M. Valdes), mval@etsii.upm.es (J.M. Martínez-Val).

0306-2619/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apenergy.2011.04.036

Nomenclature

Symbols

BOP	block of power
c_p	specific heat coefficient (J kg^{-1} K^{-1})
D	characteristic diameter of the thermal storage tank (m)
DNI	direct normal irradiation (W m^{-2})
DTS	double thermal storage system
E	thermal energy (J)
F	correction factor
h	specific enthalpy (J kg^{-1})
h_{conv}	convective heat-transfer coefficient (W m^{-2} K^{-1})
HSS	high temperature storage system
HTF	heat transfer fluid
k	thermal conductivity (W m^{-1} K^{-1})
L	length of the collector modules (m)
LSS	low temperature storage system
$\dot{m}$	mass flow rate (kg s^{-1})
M	molten salt mass stored (kg)
P	power of the power plant (W)
$\dot{Q}_{loss}$	thermal losses (W)
$\dot{Q}_{th}$	thermal power (W)
SG	steam generator
SSF	subdivided solar field
STPP	solar thermal power plants
t	time (s)
T	temperature (K)
UA	UA factor, product of the overall heat-transfer coefficient and the heat exchange area (W K^{-1})
W	width of the collector modules (m)

Greek letters

Δ	increment
η	efficiency (–)
χ	level of stored molten salt (–)

Subscripts

col	collector
des	design
Ec	economiser
Ev	evaporator
exch	heat exchanger
LM	logarithmic mean
max	maximum
min	minimum
ref	reference
Rh	reheater
s	molten salts
Sh	superheater

takes place in parallel to the heat transfer from the HTF to the working fluid of the thermodynamic cycle, core of the block of power (BOP). The temperatures of both thermal storage system and working fluid have to be slightly lower than that of the HTF, as a consequence of the heat exchange process. When there is not enough solar irradiation to produce as much HTF mass flow as required, discharging of the thermal storage system begins. In this operation mode, the storage system supports or replaces the solar irradiation. Therefore, the system transfers the stored thermal energy to the HTF and then it heats the working fluid of the thermodynamic cycle. In this case, the final temperature of the working fluid further decreases due to the new heat exchange process between the thermal storage system and the HTF.

As it is well known, the lower is the temperature of the working fluid, the lower the thermodynamic cycle efficiency. Thus, at low or null irradiation conditions, there is a drop in the overall efficiency of the power plant, despite using the stored thermal energy, because it is impossible to keep in the storage fluid the original temperature of the HTF when the storage process started. Such behaviour has been reported in [10,11]. As conclusion, the decrease of the HTF temperature at low or null irradiation conditions represents a loss which is susceptible to be reduced.

According to [5], the temperature of the stored fluid should be as high as possible. As response to the higher temperature requirement, a configuration with double thermal storage (DTS) system is proposed. One system has the objective of supporting or replacing the solar irradiation in terms of energy (at a lower temperature), while the other one is aimed at keeping the nominal temperature of the working fluid in periods of time without enough solar irradiation. The latter is a new proposal, based on the possibility of reaching HTF temperatures slightly above the nominal ones, in the peak of sun irradiation. This high temperature storage fluid overheats the bulk storage along the discharge process, and the final outcome is that the fluid enters the block of power with a temperature very similar, or equal, to the nominal one.

On the other side, as it is shown in [12], linear collectors (like parabolic troughs and reflection Fresnel collectors) suffer from important losses. Some of them are due to the heat losses from the receiver to the environment. These losses are larger as the HTF temperature increases [13], which is an additional problem, because the HTF temperature has to be higher than that of the working fluid of the thermodynamic cycle. This hierarchy of temperatures has to be properly analysed in order to optimise the duty of the system, i.e., the actual capability of the thermal system to produce a useful work.

In this regard, a second tool for management is considered in this paper: the linear collector field is subdivided into sectors, and each sector has a definite function in the whole process of capturing solar irradiation for activating a thermodynamic cycle. In particular, each sector has an associated heat exchanger for heating a fraction of the working fluid and each one works at different temperature. The aim of this arrangement, which is called subdivided solar field (SSF), is to reduce the HTF temperature throughout the solar field.

This issue has been studied to some extent in the technical literature. For example, analogue arrangements of the solar field have been proposed for the case of a solar boiler [14] and for a solar tower [15]. Likewise, a similar arrangement for parabolic trough plants has been proposed in [16–18], although without reporting numerical results or simulations, like in the present work, and with the aim of studying solid media storage systems.

Both systems, DTS and SSF, are presented in Section 2 as part of a parabolic trough collectors STPP. The proposed systems are simulated and then compared to the usual one (STPP without these two systems). Section 3 shows the methodology for the simulations. In Section 4, the main results are presented and discussed; and last section is devoted to summarise the findings of the analysis and to identify future works.

2. Description of DTS and SSF systems

2.1. Reference STPP

This section describes the STPP configuration that is considered as the reference one. It consists on a parabolic trough collector STPP with thermal storage, similar to Andasol I [19]. Fig. 1 shows