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Modelling and simulation of parabolic trough plants based on real operating data

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ABSTRACT

In recent years, parabolic trough power plants have been built in a large number and on a very large scale. Operating data from these plants are rarely published, however. In the present work detailed operating data from a commercial parabolic trough power plant (Andasol 3, Guadix, Spain) are analysed and compared with simulation results. Ten consecutive days of three different months (July, September and November) representing different seasons were selected. The simulation results have been obtained using the Fraunhofer in-house tool ColSimCSP. In the analysis, special attention is given to the operating strategy e.g. storage discharge strategy and start time of focusing for the various seasons. Understanding the real operating boundaries for more realistic yield estimation by implementing them in the performance model is a novelty of this work.

The existing simulation model in ColSimCSP is expanded and further developed according to the results of the evaluation of measured data. A detailed comparison on component level is performed between simulation and measured data for plant performance parameters such as solar field thermal power and net electrical energy yield. The lowest mean deviation is seen in solar field thermal power (0.59%), which shows the accuracy and reliability of the solar field modelling approach. The mean deviation of the net electrical energy yield is 2.29%, which still shows a relatively good match between simulation result and operating data.

Since the validation is performed against a wide range of real operating data of 30 days from a variety of months and days with different weather conditions, the results are highly relevant for developing large-scale concentrating solar power (CSP) plant models and validating related modelling and simulation software.

1. Introduction

Parabolic trough technology with thermal oil as heat transfer fluid (HTF) is the most widely implemented concentrating solar power (CSP) technology. Many of the plants include an indirect two-tank molten salt thermal energy storage system. In Spain alone, 20 plants of this type with 50 MW nominal power and at least 7.5 h of storage are in operation (National Renewable Energy Laboratory, 2016). Several studies on modelling and simulation of parabolic trough plants have been carried out to date. The main purpose of these works was performance model validation and analysis of different operating strategies. In most cases operating data from Spanish plants have been used. In one of the studies, García et al. (2011) demonstrate an algorithm to reproduce the behaviour of a parabolic trough plant with thermal energy storage system in order to predict the electricity output of the plant and compare their simulation result with measured data of 42 summer days of an equivalent plant in Spain. A similar work by García-Barberena et al. (2012) subsequently analysed the influence of four different operating strategies on the performance of the plant. They compare the simulation result of 12 days to the measured data and use the mean deviation as figure of merit to validate their model. Additionally, a study has been carried out recently by Dinter and Gonzalez (2013) on operability and reliability properties of CSP plants based on the experience acquired during the first operation year of Andasol 3. They demonstrated that storage-integrated CSP plants are able to deliver power on demand by means of example operating days from the first year of the plant operation. The present paper summarizes the result of our detailed analysis on the plant optical and thermal performance considering the main components including the solar field, storage system, and the power block by employing operating data from different seasons. We then compared the processed data to simulation results on component level for three ten-day periods consisting of clear, partly cloudy and overcast days. In order to generate simulation results, a numerical model of the Andasol 3 plant has been implemented in the simulation software ColSimCSP developed at Fraunhofer ISE. All plant parameters and characteristics are set according to the design parameters and measured

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Nomenclature

$\dot{Q}_{abs}$	thermal power induced by absorption at the surface of the receiver
$\dot{Q}_{avail}$	available radiant solar power; product of the net aperture area and the direct normal irradiance
$\dot{Q}_{loss,rec}$	receiver heat loss power
$\dot{Q}_{PB}$	thermal power transferred to the power block
$\dot{Q}_{SF}$	solar field thermal power
$\bar{\eta}_{net,solar}$	average net plant overall sun to electricity efficiency over a given time period
$\bar{\eta}_{net}^{PB}$	average power block net efficiency over a given time period
A_{net}^{SF}	solar field effective aperture area
E_{net}	net electrical energy
G_{bn}	direct normal solar irradiance
P_{gross}	gross electrical power
P_{net}	net electrical power
Q_{PB}	thermal energy transferred to the power block
Q_{SF}	solar gain energy
$\dot{m}$	mass flow rate
γ_s	solar azimuth angle
η_{clean}	cleanliness factor
η_{end}	end loss factor
$\eta_{opt,0}$	optical efficiency at normal incidence
η_{opt}	optical efficiency
η_{shad}	factor accounting for shading losses incidence angle
θ_Z	zenith angle
CSP	concentrating solar power
HCE	heat collecting elements
HTF	heat transfer fluid
K	incidence angle modifier
OP−MODE	plant operating mode
PTC	parabolic trough collector
SCA	solar collector assembly
SCE	solar collecting element
SF	solar field
dp	pressure drop
ϑ_{abs}	absorber inner surface temperature

values. As a novel feature compared to previous studies, the operating strategy is adapted according to the operating data; weather forecasting is integrated into the model as well. As in other works, the mean deviation is used to compare the thermal energy output of the solar field, thermal energy transferred to the power block and the net electrical energy yield between operating data and simulation.

2. Analysis of operating data

Operating data from the Andasol 3 plant for the first ten days of July, September and November of the year 2013 are analysed here. The available data include weather data, e.g. ambient temperature, humidity and direct normal solar irradiance, G_{bn}, as well as technical parameters of the plant, e.g. storage tank levels, HTF mass flow rates, HTF temperatures, cooling water mass flow rate as well as gross and net electric output. Through a set of calculations (using mass and energy balance) the power and energy flows, efficiencies of each component and the heat losses were extracted. Results of this analysis are presented in this section.

Fig. 1 shows the values of projected irradiance in addition to the direct solar irradiance for the whole period considered for this study. The projected irradiance is the product of optical efficiency, $\eta_{opt,}$ (see Eq. (2)) and G_{bn}. Corresponding optical efficiencies were taken from simulation results. This figure gives an overview on the daily solar radiation in different periods and shows the amount of irradiance which cannot be absorbed theoretically due to optical losses. The optical loss includes different factor which are described in Section 3.1. However, a large portion of optical losses is due to the reduction of irradiance caused by the non-perpendicular incidence, sometimes referred to as "cosine loss".

In order to ensure that this study covers various daily radiation patterns the days are categorized in three groups based on the radiation condition and its effect on the plant operation. A clear day is defined as an operating day in which the G_{bn} curve has an approximate parabolic shape where all the G_{bn} values are higher than 80% of the G_{bn} resulting from a clear sky model. The G_{bn} of the clear sky model has been calculated using the Hottel clear-day model (Stine and Geyer, 2001). A partly cloudy day is identified with short transient periods due to clouds passing over the solar field and fluctuating reduced G_{bn}, which still allow the solar field to operate partially during most of the time of the day. The rest of the days are known as overcast days in which the G_{bn} drops to zero several times and/or for a long period of time. There were six clear days in July with the maximum projected irradiance of 720 W/m^2, while most of the days in November were partly cloudy or overcast with an average projected irradiance of around 100 W/m^2. Table 1 shows the distribution of days in different categories.

Fig. 2 illustrates the energy flow throughout the plant. Available solar irradiance, $\dot{Q}_{avail}$, solar field thermal power, $\dot{Q}_{SF}$, thermal power of the power block, $\dot{Q}_{PB}$, and the electrical power of the power block, P_{net}, sorted in descending order for each 10-day period are shown. Although the maximum $\dot{Q}_{avail}$ values are nearly the same for the three periods, the maximum absorbed thermal power $\dot{Q}_{SF}$ and the total absorbed energy in the solar field are significantly less in November due to the lower solar field optical efficiency and the reduced number of sunshine hours. It can also be seen that the power block operating hours are almost equal

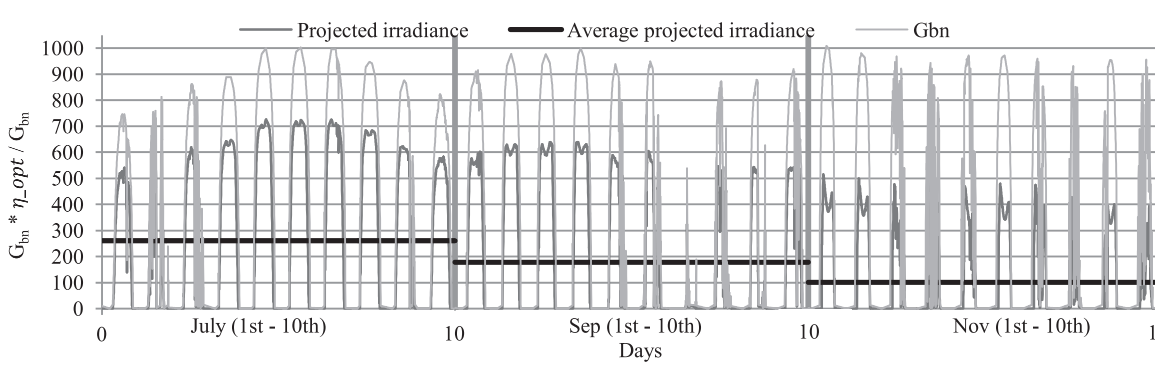

Fig. 1. Available solar resource and direct normal irradiance in the analysed periods.