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Concentrated solar power plants: Review and design methodology

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ABSTRACT

Concentrated solar power plants (CSPs) are gaining increasing interest, mostly as parabolic trough collectors (PTC) or solar tower collectors (STC). Notwithstanding CSP benefits, the daily and monthly variation of the solar irradiation flux is a main drawback. Despite the approximate match between hours of the day where solar radiation and energy demand peak, CSPs experience short term variations on cloudy days and cannot provide energy during night hours unless incorporating thermal energy storage (TES) and/or backup systems (BS) to operate continuously. To determine the optimum design and operation of the CSP throughout the year, whilst defining the required TES and/or BS, an accurate estimation of the daily solar irradiation is needed. Local solar irradiation data are mostly only available as monthly averages, and a predictive conversion into hourly data and direct irradiation is needed to provide a more accurate input into the CSP design. The paper (i) briefly reviews CSP technologies and STC advantages; (ii) presents a methodology to predict hourly beam (direct) irradiation from available monthly averages, based upon combined previous literature findings and available meteorological data; (iii) illustrates predictions for different selected STC locations; and finally (iv) describes the use of the predictions in simulating the required plant configuration of an optimum STC.

The methodology and results demonstrate the potential of CSPs in general, whilst also defining the design background of STC plants.

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1. Introduction

1.1. Solar irradiance as worldwide energy source

More energy from the sunlight strikes the earth in 1 h than all of the energy consumed by humans in an entire year. In fact, solar energy dwarfs all other renewable and fossil-based energy resources combined.

We need energy – electrical or thermal – but in most cases where and when it is not available. Low cost, fossil-based electricity has always served as a significant cost competitor for electrical power generation. To provide a durable and widespread primary energy source, solar energy must be captured, stored and used in a cost-effective fashion.

Solar energy is of unsteady nature, both within the day (day–night, clouds) and within the year (winter–summer). The capture and storage of solar energy is critical if a significant portion of the total energy demand needs to be provided by solar energy.

Fig. 1 illustrates the world solar energy map. Most of the countries, except those above latitude 45°N or below latitude 45°S, are subject to an annual average irradiation flux in excess of 1.6 MW h/m^2, with peaks of solar energy recorded in some "hot" spots of the Globe, e.g., the Mojave Desert (USA), the Sahara and Kalahari Deserts (Africa), the Middle East, the Chilean Atacama Desert and North-western Australia.

1.2. Concentrated solar power plants

Concentrated solar power plants are gaining increasing interest, mostly by using the parabolic trough collector system (PTC), although solar power towers (SPT) progressively occupy a significant market position due to their advantages in terms of higher efficiency, lower operating costs and good scale-up potential. The large-scale STC technology was successfully demonstrated by Torresol in the Spanish Gemasolar project on a 19.9 MW$_{el}$-scale [2].

Notwithstanding CSP benefits, the varying solar radiation flux throughout the day and throughout the year remains a main problem for all CSP technologies: despite the close match between hours of the day in which energy demand peaks and solar irradiation is available, conventional CSP technologies experience short term variations on cloudy days and cannot provide energy during night hours. In order to improve the overall yield in comparison with conventional systems, the CSP process can be enhanced by the incorporation of two technologies, i.e., thermal energy storage (TES) and backup systems (BS). Both systems facilitate a successful continuous and year round operation, thus providing a stable energy supply in response to electricity grid demands. To determine the optimum design and operation of the CSP throughout the year, whilst additionally defining the capacity of TES and required BS, an accurate estimation of the daily solar irradiation is needed. Solar irradiation data for worldwide locations are mostly only available as monthly averages, and a predictive conversion into hourly data and direct irradiation is needed to provide a more accurate input into the CSP design. Considering that a CSP plant will only accept direct normal irradiance (DNI) in order to operate, a clear day model is required for calculating the suitable irradiation data.

The procedure, outlined in the present paper, combines previous theoretical and experimental findings into a general method of calculating the hourly beam irradiation flux. The basis was previously outlined by Duffie and Beckmann [3], and uses the Liu and Jordan [4] generalized distributions of cloudy and clear days, later modified by Bendt et al. [5], then by Stuart and Hollands [6] and finally by Knight et al. [7].

The present paper has therefore the following specific objectives:

- review the CSP technologies and discuss solar power tower advantages compared to the other technologies;
- estimate the hourly beam irradiation flux from available monthly mean global irradiation data for selected locations, and compare the results obtained of monthly data with calculations from the temperatures recorded at the locations;
- select an appropriate plant configuration, and present design preliminary recommendations using predicted hourly beam irradiation data.

In general, the study will demonstrate the global potential of implementing the SPT technology, and will help to determine the most suitable locations for the installation of SPT plants.

2. CSP technologies

2.1. Generalities

Concentrated solar power (CSP) is an electricity generation technology that uses heat provided by solar irradiation concentrated on a small area. Using mirrors, sunlight is reflected to a receiver where heat is collected by a thermal energy carrier (primary circuit), and subsequently used directly (in the case of water/steam) or via a secondary circuit to power a turbine and generate electricity. CSP is particularly promising in regions with high DNI. According to the available technology roadmap [8], CSP can be a competitive source of bulk power in peak and intermediate loads in the sunniest regions by 2020, and of base load power by 2025 to 2030.

At present, there are four available CSP technologies (Fig. 2): parabolic trough collector (PTC), solar power tower (SPT), linear Fresnel reflector (LFR) and parabolic dish systems (PDS). Additionally, a recent technology called concentrated solar thermo-