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Performance model for parabolic trough solar thermal power plants with thermal storage: Comparison to operating plant data

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Abstract

This paper describes a simulation model that reproduces the performance of parabolic trough solar thermal power plants with a thermal storage system. The aim of this model is to facilitate the prediction of the electricity output of these plants during the various stages of their planning, design, construction and operation. Model results for a 50 MW_e power plant are presented and compared to real data from an equivalent power plant currently operated by the ACS Industrial Group in Spain.

Keywords: Renewable energy; Solar thermal; Parabolic trough; Thermal storage; Performance model

1. Introduction

Solar power technology has seen great advances over the past decade. Both photovoltaic (PV) and concentrating solar power (CSP) technologies now constitute feasible commercial options for large scale power plants as well as for smaller electricity and heat generating devices. PV energy is based on the direct generation of an electric current from a material (typically a semiconductor) that exhibits the photovoltaic effect when exposed to sunlight (direct or diffuse). The principle of CSP (also referred to as solar thermal power), on the other hand, is the use of the heat generated by direct solar radiation concentrated onto a small area with the purpose of producing electricity.

There are currently four basic commercially available CSP technologies. Two of them, parabolic trough and Fresnel linear collectors, concentrate direct sunlight onto a line, whereas the other two, parabolic dish and solar tower technologies, concentrate light onto a point.

The use of CSP with practical purposes dates back to the second half of the 19th century, when inventors such as the British William Adams, the French Augustin Mouchot, the Italian Alessandro Battaglia and the Swede John Ericsson demonstrated a number of solar energy devices such as solar cookers, water distillers, ice makers and boilers for steam engines, setting the basis for current CSP designs and even taking some first steps towards the development of energy storage (Bradford, 2006). In the beginning of the 20th century, home solar water heaters were commercialised in South West USA and the North-American Frank Shuman successfully completed a parabolic trough plant for powering an irrigation system in Meadi, Egypt, in 1913. The Italian Giovanni Francia designed and built the first linear Fresnel collector in Genoa, Italy, in 1964 and the first solar tower plant in Sant'Ilario, Italy, in 1965. The *Solar One* tower was built in 1981 in California as a demonstration project with a capacity of 10 MW_e. The nine parabolic trough Solar Energy Generating Systems (SEGS), built between 1984

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and 1990 in California, USA, remain the largest solar energy generating facility in the world today, with 354 MW_e of installed capacity. The world's first commercial solar tower, *PS10*, was finished in Seville, Spain, in 2007 and has a capacity of 11 MW_e.

From the available CSP technologies, parabolic trough is the most widespread today, with around 29 plants in operation and around 1220 MW_e of installed power in the world, corresponding to 96.3% of the total operational concentrating solar power as of the beginning of 2011 (see Fig. 1). Most of these plants are located in Spain and the USA, as shown in the same figure. With regard to projects under construction or announced, the proportion of tower, parabolic dish and Fresnel projects increases to approximately 28%, and a number of countries such as Australia, France, Egypt, Algeria, Morocco, South Africa, Sudan, United Arab Emirates, Israel, India and China are embracing the development of solar thermal power plants in their territories.

This paper presents a detailed performance model for a parabolic trough plant with thermal energy storage (TES) together with a comparison of the model results to measured data from an operating plant of this type. This is the first published detailed comparison of simulation results to actual data from an operating plant with storage. The good agreement obtained validates the model and confirms it as an effective tool for predicting the electricity output of these plants.

Other performance models for parabolic trough CSP plants can be found in the literature. Full models for plants with no TES have been presented in Lippke (1995), Price et al. (1995), Patnode (2006), Jones et al. (2001) and have been validated against experimental data from a SEGS plant with no TES system. Price (2003) expands the work in Price et al. (1995) by including a TES system in the simulation. There are several documented complete models for trough plants with storage, namely: System Advisor Model (*SAM*) (Price, 2003; Blair et al., 2008b,a; Wagner et al., 2010; SAM, 2011) from the National Renewable Energy Laboratories in the USA (NREL), *Greenius* (Dersch et al., 2008; Hennecke et al., 2010; Greenius, 2011) from the German Aerospace Centre (DLR), *SOLERGY* (Stoddard et al., 1987) from Sandia National Laboratories

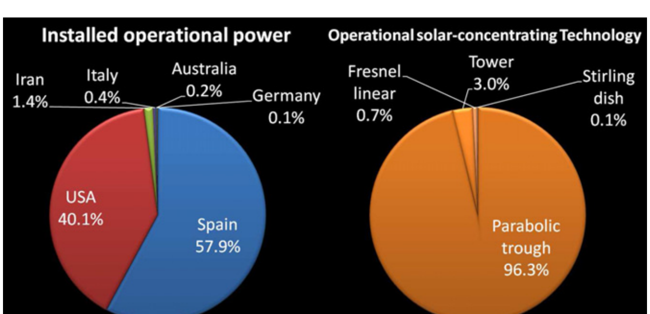

Fig. 1. Solar thermal power plant projects in operation in the world (March 2011). Left: installed power by country. Right: installed power by technology.

in the USA (originally a model for tower plants, it has been updated over the years to accurately model trough plants (Kolb, 2011)) and the model in Montes et al. (2009). However, reports of detailed comparison to actual trough plant data are not easily found. More recent performance models for trough plants with no TES can be found in Rolim et al. (2009), Larrain et al. (2010). A comprehensive list of software tools for CSP performance modelling is presented in Ho (2008), while the quantification of uncertainties and sensitivities through probabilistic modelling is specifically addressed in Ho et al. (2011).

An effort towards the standardisation and benchmarking of solar thermal performance models is currently being made by the international community within the *SolarPACES guiSmo* project, which brings together experts from the DLR, NREL, Sandia National Laboratories, the Centre for Energy, Environmental and Technological Research in Spain (CIEMAT), the National Centre for Renewable Energy in Spain (CENER), etc., as well as several industrial partners.

The model presented in this paper was benchmarked within work package 9.2 of the *guiSmo* project, which focused on the modelling of a SEGS-VI-like trough plant without energy storage or fossil back-up. Relevant result variables for three representative weeks of a year were compared to those from 10 other models. Our results for total daily gross electric energy generated differ on average from those from DLR, Sandia National Laboratories and NREL by no more than 11%, 5% and 2%, respectively (further details available on request).

2. Parabolic trough power plant with thermal storage

A simplified schematic for a parabolic trough solar thermal power plant with thermal storage is shown in Fig. 2. These plants typically consist of three main circuits: the Solar Field, through which the heat transfer fluid (HTF) circulates, the Power Block, which circulates water and steam, and the TES system. The HTF and water-steam

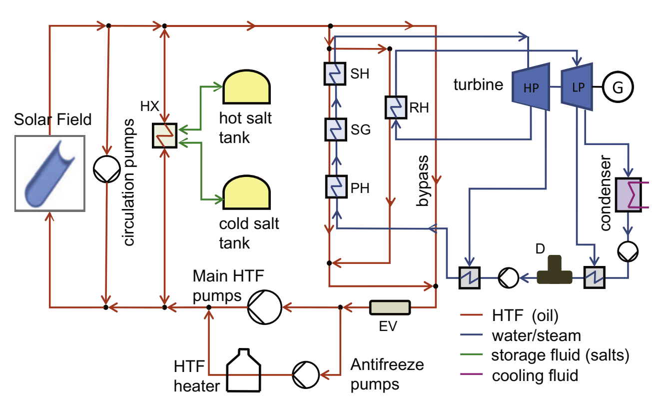

Fig. 2. Schematic diagram of a parabolic trough solar thermal power plant with thermal storage. In the figure, HX stands for heat exchanger, PH, SG, SH and RH for preheater, steam generator, superheater and reheater, respectively, D stands for deaerator and EV for expansion vessel.