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Simulation analysis of thermal storage for concentrating solar power

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ABSTRACT

The aim of this study was to evaluate the capacity and analyze the performance of thermal storage required for solar thermal electric power plants in order to increase their capability to supply base load power with less need for back up from fossil fuels. For this purpose, a mathematical-statistical model of hybrid solar-fossil power cycles was developed, which is based on energy balance equations and historical hourly data of direct normal irradiance and load profiles available in the literature. As follows from the computations performed for base load operations, an extremely large storage capacity equivalent to near a thousand full load operating hours should be available to a power plant to achieve continuous electricity production entirely on solar energy (solar fraction equal 1.0) during an annual operating cycle. For state of the art thermal storage technologies having a potential capacity of 10–14 full load operating hours for large-scale parabolic through solar power plants, the assessed solar fraction was 0.4–0.5 respectively, with relation to the specific conditions of calculations. The performance characteristics of thermal storage presented in the paper cover the whole extent of solar fractions from 0.2 (no storage applied) to 1.0 (pure solar operation of a power plant).

1. Introduction

In the last two decades, the concept of Concentrating Solar Power (CSP) has successfully demonstrated its capability of producing high-temperature steam to power the conventional Rankine cycle for electricity generation. Today, the CSP technology is under a wide deployment of large-scale solar power plants for 50 MW and more electrical power capacity in various sun rich regions around the globe [1–4].

The greatest technical challenge of producing electricity from the sun is the high intermittency of solar power supply that makes it incompatible with common types of electrical load profiles, such as domestic, commercial or industrial [5,6]. In order to stabilize power delivery and prolong daily operating hours, solar thermal power plants have the options of using either or both solar thermal storage and fossil fuel combustion. Depending on the installed backup power capacity, the solar plant can be run continuously at full load during the day and several hours in the nighttime [7–9].

The share of solar energy in the annual electricity production capacity of hybrid solar-fossil power plants is called the solar fraction or annual solar capacity factor. In fact, it is a primary indicator of the sustainability of solar thermal electricity generation technology. The capability of hybrid solar-fossil power systems without solar energy storage to match the typical grid load demands is limited to a solar fraction $\alpha = 0.13–0.25$ [4,6,8]. Consequently, a major part of the thermal power consumption, 75% or more, must come from conventional fossil energy sources, such as coal, natural gas, etc.

In terms of thermal storage capacity, it is customary in addition to units of energy to use units of time, e.g. hours, as an operating duration of a power plant when the full load demand is provided solely from the energy storage. Simulations performed for a parabolic trough power plant including a thermal storage capacity for the typically considered 6 full load operating hours yielded $\alpha = 0.4$ versus 0.25 without storage [10].

To reduce significantly the fossil fuel dependency of hybrid power plants by making the most of solar energy, CSP systems should have the ability to accumulate a large amount of solar energy during sunlight hours in order to retrieve the storage on a seasonal basis. For the purpose of storage, the CSP system must be increased so that part of the available solar power can be used to charge the thermal storage simultaneously with operating the power block, whenever the solar flux is sufficiently high. In principle, adequately sized seasonal thermal storage should permit uninterrupted electric power generation during on- and off-sun hours, 24 h a day, all year round, to a so-called pure solar power plant, for which the parameter $\alpha = 1.0$.

Although the subject of thermal storage has received considerable attention in the literature during the past few decades, basic

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Nomenclature[1]

CSP	concentrating solar power
E	storage energy [kWh/m^2; also, h, as full load operating hours or day = 24 h]
GS	Granada, Spain
LV	Las Vegas, USA
MR	Mitzpe Ramon, Israel
Q	thermal power [W/m^2]
t	time [h]
yr	annual operating cycle [8760 h]

Greek letters

α	solar fraction
β	solar collector factor
φ	nominal storage capacity [kWh/m^2; also, h, as full load operating hours or day = 24 h]
θ	annual average daily discharge duration of thermal storage [h]
χ	coefficient of variation

Subscripts

F	fossil fuel power in the hybrid mode
L	thermal power equivalent to electric load
R	direct normal irradiance
rj	rejected solar power
S	storage; bend point in Figs. 4 and 5
0, 1, 2, 3	thermal power variables shown in Fig. 1

researches and developments concerning CSP applications have been mainly focused on short-term storage systems capable to provide a few full load operating hours [1,7]. Until now, there are only a few credible studies concerning the impact of large-scale storage systems on the operating efficiency of solar power plants. As follows from simulations carried out in [11] for solar thermal electric power plants, solar fractions as large as $\alpha = 0.75$–0.9 are achievable with modest storage capacities ranging from $\varphi = 10$ to 50 full load operating hours respectively, for the site of Albuquerque, USA. According to the estimates of storage capacity presented in [12], a solar fraction value resulting from $\varphi = 12$ h is $\alpha = 0.53$, and due to [13], a larger storage capacity $\varphi = 15$ h leads to $\alpha = 0.65$–0.71.

As a whole, the capability of thermal storage to replace fossil fuels in backing solar operating cycles has not yet been thoroughly explored and deserves to be studied in depth. The objective of this work was to analyze the general case of hybrid solar thermal power systems combining thermal storage and fossil fuel backup facilities to produce electric power required by grid and to explore the ways of reducing the fossil fuel consumption by increasing the capacity and operating efficiency of energy storage. For this purpose, an energy balance model of yearlong solar operating cycles comprising historical hourly data of direct normal irradiance and load demand was developed and applied to base load power plants located at different geographic sites. The computations performed allowed quantifying the amount of stored energy as function of the solar fraction in the whole range of storage capacities, from a few to more than a thousand full load operating hours.

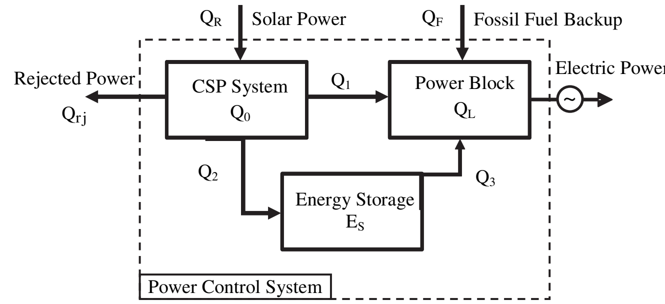

Fig. 1. The schematic model of a solar thermal electric power system.

2. Energy balance modeling

The studied model of solar thermal electric power plants is shown in Fig. 1. It consists of three major components: a CSP system (considering in particular a parabolic trough solar collector), a thermal energy storage facility (in general, a well-insulated tank containing the thermal storage material), and a power block (e.g. the Rankine cycle including fossil fuel backup). The core of the model is a power control system, as depicted in Table 1 and explained below. Primarily, the CSP system converts the incident solar power Q_R (direct normal irradiance) into the thermal power Q_0 of the high-temperature heat transfer fluid (HTF: e.g. 300–400 °C, thermal oil). Then, the available power is distributed by means of the HTF flow between the power block, Q_1, and the thermal storage, Q_2. Simultaneously, some amount of power, Q_3, can be extracted from the storage and directed to the power block. In addition, fossil-fueled power generation, Q_F, might be required in order to operate the power block at a specified load level, Q_L.

The control concept of the power flow through a solar power plant is based on the following energy balance being evaluated at every instant of operating time:

$$Q_1 + Q_2 = Q_0 \tag{1}$$

$$Q_1 + Q_3 + Q_F = Q_L \tag{2}$$

The basic simplification of the considered approach is that the storage heat losses and auxiliary energy consumptions were not taken into account for these factors are rather related to the system design and in any case should constitute a relatively small fraction of the energy balance.[2] Then, the contribution of solar energy in the continuous generation of power over an annual operating cycle is expressed with the aid of the solar fraction α in the following integral form:

$$\int_0^{yr} Q_0(t)dt = \alpha \int_0^{yr} Q_L(t)dt, \quad 0 < \alpha \le 1 \tag{3}$$

The amount of solar energy directly delivered to the power block is part of the total amount of energy provided by the CSP system:

$$\int_0^{yr} Q_0(t)dt = \beta \int_0^{yr} Q_1(t)dt \tag{4}$$

[1] Energy and power variables (e.g. E, Q and φ) pertain to one square meter of the solar collector aperture area.

[2] A few sophisticated software packages are available for a comprehensive techno economic evaluation of particular thermal storage designs integrated into CSP systems [14,15].