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Optimization of the solar field size for the solar–coal hybrid system

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HIGHLIGHTS

- The annual solar power with SM varies for typical solar hybrid plants was evaluated.
- An economic optimization of SM for each solar hybrid plant was presented.
- The influences of local solar radiation and turbine operation load were estimated.
- The results provide a theoretical reference in designing a solar–coal hybrid project.

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ABSTRACT

The hybridization of middle-temperature solar heat with traditional coal-fired power plants has profound and realistic implications for China. Most solar hybrid power plants, which differ from solar-only power plants, are not designed to include a thermal storage system to maintain system performance at nominal conditions during off-design solar radiation periods. Thus, a proper solar field size is an important design parameter. An excessively large field is partially useless under high solar irradiance, whereas a small field mainly reduces the work output and leads to the poor utilization of invested capital. This paper presents an economic optimization of the solar multiple (SM) for typical solar–coal parabolic trough plants with different unit scales (200–600 MW). The thermal performance for each solar hybrid power plant demonstrates that the methods to calculate the annual solar electricity produced with SM varies. Once the annual electric energy generation is identified, the levelized cost of energy (LCOE) and payback period (PP) for each case can be calculated. Thus, the optimized SM values yielding a minimum LCOE value or PP can be obtained. Furthermore, the influences of local solar radiation resources and turbine operation load conditions on the economic optimization of a system are estimated. Results indicate that the optimization of the solar field size is promising for the economic improvement of a solar–coal hybrid system. The results may also provide a theoretical reference for investors and government officials in designing a solar–coal hybrid project.

1. Introduction

The parabolic trough technology has been proven to be the most developed solar thermal technology available today. As a result, most projects for constructing commercial solar thermal power plants are based on this type of collector [1]; several parabolic trough power plants will be constructed in the USA, Spain, Northern Africa, Middle East, and so on. However, the cost of a solar-only parabolic trough power plant is not as competitive as that of a conventional fossil-fired power plant, unless the construction cost is subsidized. The problem may be attributed to the exceedingly low annual solar-to-electricity efficiencies of current parabolic trough plants (11–16%) [2]. Thus, a large solar field is required to generate electricity, which leads to high investment. High cost and low efficiency hinder the development of solar thermal power technology.

The commercialization of solar-only thermal power plants is stalled by high investment cost. Nonetheless, concentrated solar thermal energy is increasingly hybridized with fossil-fuel technologies. Kolb [3] pioneered the identification of economically beneficial configurations of hybridized solar thermal and combustion processes in Rankine cycle boilers. The cost of the solar energy component can be reduced by approximately 50% relative to a stand-alone plant by sharing the infrastructure with a fossil-fueled plant, specifically the condenser and turbine. Horn et al. [4] studied the technical and economic feasibility of an integrated solar combined cycle system (ISCCS) in Iran. This project was supported by a global environment facility. The electricity cost of the ISCCS is approximately 2.0 ¢/kW h, and the specific investment

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Nomenclature

Abbreviation

LCOE	levelized cost of solar electricity
PP	payback period
SM	solar multiple
DNI	direct normal irradiance
NCF	net cash flow
FiT	feed-in-tariff
OM	operating & maintain

Subscript

j	steam extraction point
inv	investment
col	solar field collector
c	heat-to-work conversion
sol-to-elec	solar-to-electricity conversion

Symbols

H	equivalent enthalpy drop
S	solar field area
h	steam extraction enthalpy
σ	heat change in the reheater
T	temperature
η	efficiency
q	heat releases of steam extraction
β	average annual investment coefficient
ω	annual solar field utilization ratio
P	pressure
m	mass flow
C	cost
n	plant life
i	discount rate
τ	enthalpy increase in feed water
W	net incremental solar power
γ	enthalpy drop in drain water

cost was $600/kW. Montes et al. [5] showed that the ISCCS scheme is a cheaper approach to exploit solar energy and produce electricity and can roughly cost 1.5 ¢/kW h in Las Vegas. Although the cost of the ISCCS method is still higher than those of the gas turbine power plant and of the combined cycle power plant, it is already superior to that of the solar-only parabolic trough power plant.

The structure of the energy consumed in China mostly originates from coal. Hence, the hybridization of solar energy with traditional coal-fired power plants has profound and realistic implications for this country. Solar heat collected at approximately 300 °C matches well with the feed water back to the boiler. Solar heat can be utilized to replace steam extractions and heat the feed water, which can increase the work output of a steam turbine. The advantages of this kind of solar–coal hybrid power plants are as follows: (i) The middle-temperature solar heat (below 300 °C) can ease the degradation of glass-to-metal sealing and selective coating and allow the utilization of cheaper heat transfer oil. (ii) The solar area size for per kWe solar electricity can be reduced using larger-scale turbines with higher efficiency. (iii) The high costs for a storage device can be avoided through hybridization with coal-fired power plants. Previous studies have demonstrated the thermo-economic performances of this kind of solar–coal hybrid power [5–14]. The results indicate that high-capacity power plants facilitate solar integration [7]. Moreover, solar heat is used to replace different steam extractions of a typical coal-fired power plant, and the solar–coal hybrid is the most efficient system at the feed water heater with maximum pressure [8]. Another study has also presented the thermodynamic benefits of power boosting and fuel-saving models [9].

The further improvement of the thermo-economic performances of the solar–coal hybrid system requires the optimum design of the solar field size because the solar field represents the major investment in a solar thermal power plant. The solar field size for solar thermal power plants is always greater than the calculated value under the design solar radiation to achieve nominal conditions in the power block during a longer time interval. Nevertheless, a large solar field size for parabolic trough plants that exceeds the thermal storage capacity leads to thermal energy overproduction, which cannot be used to generate electricity and increases the cost of solar electricity because of non-profitable solar field inversion [15]. The methods for calculating the optimum field size of solar-only power plants have been described in some works [15–17]. For example, the optimum solar multiple (SM) value for a solar field costing 206 €/m^2 in Plataforma Solar de Almería (PSA) is 1.16 [15] without thermal storage for a 50 MW solar-only parabolic trough power plant. Meanwhile, the optimized size of the solar field is 1.4 and 2.3 times under zero and six hours of thermal storage, respectively, for another 50 MW parabolic trough power plant in India [16]. However, the solar field design for the solar–coal hybrid power plant is quite different from that of a conventional solar-only power plant, such that its operation can be more stable with coal hybridization rather than part-load operation at off-design solar radiation without storage. Thus, the required solar field size can be decreased accordingly with the same assumptions.

This study proposes a concise optimum design of solar field size to evaluate the economic benefits of a solar–coal hybrid system, assess its potential capability to lower solar electricity cost with different unit scales of coal-fired power plants, and evaluate the appropriate solar field size under different local solar radiation conditions and turbine operation loads.

2. System description

In solar–coal hybrid power plants, typical coal-fired power plants are hybridized with solar heat at approximately 300 °C. This solar heat, which is collected by the parabolic troughs, is utilized to replace the highest-pressure steam extraction for preheating feed water before it enters the boiler. Fig. 1 depicts the flow sheet of the coal-fired power plant that is hybridized with solar heat. The thermodynamic parameters of solar heat hybridization with 200, 330, and 600 MW typical coal-fired power plants at 100% turbine load are listed in Figs. 2a and 2b. For example, the main steam of a 200 MW coal-fired power plant is produced by the boiler (A) at a mass-flow rate of 610 ton/h at 13.0 MPa and 535 °C. Under the same temperature, the reheated steam has a mass-flow rate of 597.5 ton/h at 2.2 MPa. After the steam expansion in the turbines, the condensate water can be pumped into the low-pressure feed water heaters and the deaerator. The temperature can be increased to 163 °C by the steam extractions from the mid- and low-pressure turbines. The feed water is pumped continuously into two high-pressure feed water heaters (F) and is preheated up to 218 °C by the extractions from the high- and mid-pressure turbines.

The feed water is heated further to 247 °C in a water–oil heat exchanger (G) by the solar heat at approximately 300 °C when the steam extraction of the coal-fired power plant at maximum pressure is replaced by solar heat. Thus, the relevant steam extraction process can be eliminated. Additionally, the work output of

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