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Life cycle assessment of solar aided coal-fired power system with and without heat storage

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ABSTRACT

Pollutant emissions from coal-fired power system have been receiving increasing attention over the past few years. Integration of solar thermal energy can greatly reduce pollutant emissions from these power stations. The performances of coal-fired power system (S1), solar aided coal-fired power system with thermal storage (S2), and solar aided coal-fired power system without thermal storage (S3) with three capacities of each kind of system (i.e., nine subsystems) were analyzed over the entire life span. The pollutant emissions and primary energy consumptions (PECs) of S1, S2, and S3 were estimated using life cycle assessment (LCA). The evaluation value of global warming potential (GWP), acidification potential (AP), respiratory effects potential (REP) and PEC were obtained based on the LCA results. Furthermore, the system investments were estimated, and grey relation theory was used to evaluate the performance of the three types of systems comprehensively. Finally, in order to find the effect of some main factors on the solar aided coal-fired power system (SACFPS), uncertainty analysis has been carried out. The LCA results show that the pollutant emissions and PEC mainly take place in the fuel processing and operation stages for all three system types, and S2 performs the best among the three systems based on the grey relation analysis results. And the uncertainty analysis shows that with longer life span, the power system have better performance; with higher coal price, the power system will have worse performance; with lower solar collector field cost, the solar aided coal-fired power system will be more profitable than the base-case coal-fired power system.

1. Introduction

Using coal, the most polluting fuel, as the main energy source to generate power has caused serious problem to human society. The energy consumption of coal-fired power system accounts for over 37% of the total energy use, and the pollutant emissions from coal-fired power system also take a large part [1,2]. Hence, finding clean, renewable energy to replace the use of all or part of fossil fuels is an urgent need. In China, solar energy resources are abundant [1], which means that the development of solar aided coal-fired power system has good prospects. Solar aided coal-fired power system (SACFPS), which uses solar energy collected by the solar collector to heat feed-water and replace part of high quality extraction steam to achieve indirect power generation, is a solar and conventional fuel hybrid power system. The replaced steam can be more effectively converted into work with the aid of the relatively large capacity units of coal-fired power system with high turbine internal efficiency [3]. Therefore, SACFPS will not only reduce coal consumption and emissions of polluting gases, but also improve the thermal efficiency of thermal power units.

When compared with the solar thermal power system, which uses the solar energy as the main energy source, the SACFPS has plenty of advantages, such as lower investment, higher thermal efficiency and less pollution emissions. A considerable number of studies since 1990 have investigated the general effects of thermodynamic performance and its mechanism of SACFPS. Popov found that using solar energy to replace high-pressure steam to preheat feed-water could cause the temperature to exceed its original design value; the proportion of solar power generation can reach up to 23%, having an efficiency of more than 39% for the best solar hours of the year [4]. Hou et al. analyzed solar-aided feed-water heating of coal-fired power generation (SAFHCPG) system performance under different loads and found that lower solar energy in coal-fired power system leads to reduced efficiency of solar energy conversion to electricity. For the SAFHCPG system, performance is mainly dependent on solar radiation and load demand from the grid side [5]. Peng et al. studied the thermodynamic performance

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of a solar aided coal-fired power plant that uses solar heat with temperature lower than 300 °C to replace the extracted steam from a steam turbine to heat the feed water. The results indicate that a solar aided coal-fired power plant could achieve better off-design performance and economic performance than a solar-only thermal power plant [6]. On the mechanism aspects, Peterseim et al. found the best technologies for concentrated solar power (CSP) hybrid plants with an abundance of data for analysis. Their findings suggest that Fresnel systems are the best technology for feed-water preheating applications, while parabolic troughs using thermal oil rank second for all CSP integration scenarios with steam temperature <380 °C. Generally, when the steam temperature is above 450 °C, solar towers with direct steam generation are better than solar towers that use molten salt and Big Dish technology [7]. Peng et al. proposed a rotary tracking device and found that compared with single-axis tracking method, the energy losses of the solar-field area of a SACFPS would decrease by 4%. In addition, they studied a 300 MW unit located in Xinjiang province of China and proposed possible schemes for improving a SACFPS on off-design operation [8,9]. Zhao et al. simulated a 200 MW solar aided coal-fired power system and found that the net solar-to-electric efficiency of the system is expected to reach up to ~21% under the design daily normal insolation. These findings provide theoretical support for the development of SACFPS [10]. Analytical techniques enable researchers to examine complex relationships of SACFPS. Bakos et al. used Transient System Simulation Program to simulate SACFPS in both power boosting and fuel saving modes, and calculated power output, fuel consumption, CO_2 emissions, and economics of the units [11]. Suresh et al. compared the SACFPS and coal-fired power system from the aspects of thermal efficiency, exergy efficiency, environmental behavior, and economics. They found that the coal consumption of SACFPS, compared with traditional coal-fired power system that can be reduced by 14–19%, CO_2 emissions can be reduced by over 60,000 tonnes per annum, and thermal and exergy efficiencies of the unit will also increase [12]. Zhu et al. used five common evaluation methods of solar contribution to study the performances of SACFPS (1000 MW, 600 MW and 330 MW). The authors claimed that this study can be used as a theoretical reference for future research needs [13].

However, previous studies on SACFPS mainly focused on thermal efficiency, exergy efficiency, and operating performance. Few studies have focused on the energy consumption and pollutant emissions of the units over their entire lifetime. In order to estimate the energy consumption and pollutant emissions of a system accurately, it is not adequate to consider only on-site impacts, because off-site impacts are also need to be accounted for, if not internalized [14]. Life cycle assessment (LCA) methodology can be used to analyze both on-site and off-site environment related problems and energy consumption produced by any process [15]. In order to evaluate the system's environmental impact, a number of scholars have applied LCA to study coal-fired power system, solar thermal power system and solar thermal hybrid power system. A LCA was conducted to estimate whole-plant (coal fired) greenhouse gas emissions in UK by Odeh et al. The results indicated that the majority of the greenhouse gas emissions occur in fuel combustion stage, and when the efficiency of the plant rose from 35% to 38%, the emissions can be reduced by 7.6% [16]. Burkhardt et al. examined the manufacturing, construction, operation and maintenance, decommissioning, and disposal stages associated with a wet cooled 103 MW parabolic trough CSP plant, and compared the greenhouses gas emissions of this reference plant model with four other plant designs. The results of their analysis range from 24 to 39 kg CO_2eq/MW h [17]. Oró et al. compared the environmental impact of three different thermal energy storage systems for solar thermal power system [18]. Piemonte et al. analyzed the performance of the CSP plant from an environmental point of view by using LCA methodology [19]. On the solar thermal hybrid system aspects, Lechón et al. evaluated the environmental impacts derived from the electricity production of a 17 MW solar thermal plant with central tower technology and a 50 MW solar thermal plant with parabolic trough technology, both of them hybrid operation power plants [20]. Klein et al. compared the life cycle greenhouse gas emissions of CSP plants with wet and dry cooling and with three energy backup systems: (1) minimal backup, (2) molten salt thermal energy storage, and (3) a natural gas-fired heat transfer fluid heater. The finding showed that plants with a natural gas-fired with conventional heat transfer fluid to have 4–9 times more life cycle greenhouse gas emissions than plants with molten salt thermal energy storage, and plants with molten salt thermal energy storage generally have twice as many life cycle greenhouse gas emissions as the minimal backup plants [21].

The aim of this work is threefold: firstly, to compare the pollutant emissions and PEC of coal-fired power system, SACFPS with thermal storage system, and SACFPS without thermal storage by using the LCA while taking the investment of the three systems into consideration. The three kinds of systems with 300, 600 and 1000 MW capacities (a total of nine subsystems) are considered; secondly, to assess the performance of the systems by the grey relation analysis; and finally uncertainty analysis has been carried out to find the influences of some main factors on these systems. The finding shows that the pollutant emissions and PEC mainly take place in the fuel and operation stages for all three system types, and S2 performs the best among the three systems based on the grey relation analysis results. Moreover, the uncertainty analysis shows that with longer life span, the units have better performance; with higher coal price, the units will have worse performance; with lower solar collector field cost, the SACFPS will be more profitable than the base-case coal-fired power system.

2. Solar aided coal-fired power system

2.1. System description

Fig. 1 shows a schematic of the SACFPS with thermal storage, which mainly contains the "solar side" and the "coal-fired side." The "solar side" is composed of the solar collector, thermal storage, and heat exchange systems. The solar collector plant uses molten salt as the working medium. The thermal storage system is of the typical two-tank type, which also uses molten salt as the storage media. The system uses one storage tank to store hot media and the other to store cold media [18]. In this way, the hot and cold tanks are placed separately. When solar energy is available, heat is stored in the hot tank. When solar energy is insufficient, heat is released from the hot tank, which then heats the molten salt and then the water. The heat exchanger is a salt-water exchanger type. When the molten salt passes through the heat exchanger, its temperature will decrease, increasing the water temperature.

In the "coal-fired side," the unsaturated feed-water from the condenser enters the boiler after going through the condensate pump, four low-pressure reheaters (H5, H6, H7, and H8), a deaerator, feed-water pump, and three high-pressure reheaters (H1, H2, and H3). Then, the feed-water absorbs heat in the boiler and becomes superheated steam. The superheated steam from the boiler is transported to the high-pressure cylinder in the turbine to produce power. The steam from the high-pressure cylinder enters the boiler and is reheated to improve work capacity. Then, the reheated steam is transported to the intermediate and lower pressure cylinders to produce power. The final exhaust is condensed in the condenser.

The first-stage extraction from the high-pressure cylinder has the highest temperature, pressure, specific enthalpy in all the