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Thermodynamic analysis of a novel integrated solar combined cycle

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HIGHLIGHTS

- A novel ISCC scheme with two-stage DSG fields has been proposed and analyzed.
- HRSG and steam turbine working parameters have been optimized to match the solar integration.
- New scheme exhibits higher solar shares in the power output and solar-to-electricity efficiency.
- Thermodynamic performances between new and reference systems have been investigated and compared.

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ABSTRACT

Integrated solar combined cycle (ISCC) systems have become more and more popular due to their high fuel and solar energy utilization efficiencies. Conventional ISCC systems with direct steam generation (DSG) have only one-stage solar input. A novel ISCC with DSG system has been proposed and analyzed in this paper. The new system consists two-stage solar input, which would significantly increase solar share in the total power output. Moreover, how and where solar energy is input into ISCC system would have impact on the solar and system overall efficiencies, which have been analyzed in the paper. It has been found that using solar heat to supply latent heat for vaporization of feedwater would be superior to that to be used for sensible heating purposes (e.g. Superheating steam). The study shows that: (1) producing both the high- and low-pressure saturated steam in the DSG trough collector could be an efficient way to improve process and system performance; (2) for a given live steam pressure, the optimum secondary and reheat steam conditions could be matched to reach the highest system thermal efficiency and net solar-to-electricity efficiency; (3) the net solar-to-electricity efficiency could reach up to 30% in the novel two-stage ISCC system, higher than that in the one-stage ISCC power plant; (4) compared with the conventional combined cycle gas turbine (CCGT) power system, lower stack temperature could be achieved, owing to the elimination of the approach-temperature-difference constraint, resulting in better thermal match in the heat recovery steam generator (HRSG) and thus more feedwater could be circulated.

1. Introduction

Solar thermal power generation is a promising technology to play an important role in fossil fuel saving and CO_2 emission mitigation. If solar collectors are used to generate steam to drive Rankine cycle in a power plant, the plant is referred as solar-only power plant. Generally, higher working fluid temperature is preferable in any thermal power systems for achieving higher heat-to-power efficiency. Efficiency of a solar-only thermal power generation plant is low due to the limit in the maximum temperature of the collectors used, especially at low collecting temperatures. For instance, the efficiency of Rankine cycle systems using organic working fluids is generally lower than 10% [1,2]. Increasing solar heat collecting temperature, however, associates with a significant increase in solar plant costs and reduced collectors' efficiency. In order to reduce the cost and improve the solar-to-electricity conversion efficiency, integration of solar energy and conventional fossil fuel fired power generation systems, such as gas turbines, combined cycles and fuel cells, becomes a new direction of development [3–11]. Integrated solar combined cycle system (ISCCS), initially proposed by Luz Solar International [12], which integrates parabolic trough solar field with combined cycle power plant, has been widely investigated.

Compared with the solar-only power plants, the ISCC plants exhibit several advantages [13]: (1) solar-to-electricity conversion efficiency is higher; (2) if the solar field is integrated with an

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Nomenclature

DNI	direct normal irradiation (W/m^2)
E	exergy (MW)
LHV	lower heating value (kJ/kg)
m_f	methane mass flow rate (kg/s)
m_s	steam mass flow rate (kg/s)
P	pressure (bar)
Q	heat (MW)
SR_f	fossil fuel saving ratio
T	temperature (K)
t	temperature (°C)
W_{net}	net power output (MW)
X_{sol}	solar thermal share

Greek symbols

η_{col}	solar collector efficiency
η_e	system exergy efficiency
η_f	fuel based net electricity efficiency
η_{sol}	net solar-to-electricity efficiency
η_{steam}	steam cycle thermal efficiency
η_{th}	system thermal efficiency

Subscripts and superscripts

a	air
ex	gas turbine exhaust
f	fossil fuel
incident	normal to the collector aperture area
ref	reference system
rad	radiation
SH	high-pressure level steam (live steam)
SL	low-pressure level steam (secondary steam)
SR	reheat steam
sol	absorbed solar heat
sol, unit	absorbed solar heat per unit collector area
0	ambient state

existing combined cycle power plant, incremental costs for a larger steam turbine are lower than the overall unit cost in a solar-only plant; (3) the thermal inefficiencies associated with the daily start-up and shutdown of the steam turbine can be avoided in an integrated plant; (4) the storage system is not required in the integrated configuration, which can also reduce the investment cost; (5) the ISCC provides a better annual off-design performance.

Generally, there are two kinds of ISCC schemes. In one of the schemes, thermal oil is used as heat transfer fluid in the parabolic trough solar field. The feedwater of the bottoming steam cycle is heated by the exhaust gas from the topping gas turbine in a heat recovery steam generator (HRSG) until saturation status. The saturated feedwater then enters and evaporates in the oil-to-water/steam heat exchanger (also called solar steam generator), in which solar heat is transferred into the water/steam through the oil. Out of the solar steam generator, saturated steam returns to the HRSG to be superheated, as shown in Fig. 1. Some ISCC plants with this scheme are being built in India, Egypt, Morocco and Mexico [14–16]. Kelly and co-workers [17] conducted optimization studies on this type of plant and found that the efficient way to make use of solar thermal energy was to produce high-pressure saturated steam. By doing that the solar share in the total power generated could also be maximized. They indicated that annual solar share up to 12% in an integrated plant should offer economic advantages over a conventional solar-only parabolic trough power plant. Dersch et al. [18] thermodynamically and economically investigated the integrated solar combined cycle systems and showed the advantages and disadvantages of ISCCS compared with the solar-only power plants and the conventional combined cycle power plants. Fuel based net electric efficiency of 68.4% for the ISCC cycle was obtained, higher than that in the reference systems. Baghernejad and Yaghoubi [19] utilized genetic algorithm to exergoeconomically analyze and optimize an integrated solar combined cycle system, showing that the cost of electricity (*COE*) generated by gas turbine and steam turbine in optimum well-designed ISCC plants could be lower than that in the conventional combined cycle power plants by about 1.17% and 7.1%, respectively.

In the other scheme of integrated solar combined cycle systems, direct steam generation (DSG) parabolic trough solar collector is coupled with the bottoming steam cycle, through which the feedwater passes directly and vaporises. In this scheme (similar to Fig. 1, only substitution of DSG for HTF) the oil-to-water/steam heat exchanger between the solar field and the power plant is no longer needed, leading to lower thermal and exergy inefficiencies and investments. Montes [13] proposed and analyzed an ISCC with DSG, in which solar heat was incorporated to preheat and evaporate part of the high-pressure steam for two pressure levels Rankine cycle, pointing out that a good hybridization effect could be achieved and it was an economical mode to solar heat application. 52.2% annual global efficiency and 21.5% annual net incremental solar efficiency were obtained with 1.23% annual net electrical solar fraction. Further, they analyzed and compared different ISCC layouts, revealing that the only-evaporative DSG configuration, i.e. the high-pressure steam was only evaporated in the DSG parabolic trough solar field, became the best choice, since it could benefit of both low irreversibility at the heat recovery steam generator and high system thermal efficiency (50.4%) [20]. In other cases, similar configurations were also proposed by some scholars [21,22], in which the high-pressure feedwater were preheated, evaporated and superheated in the DSG parabolic trough solar collector.

There are other schemes for solar energy integrating into combined cycles being proposed. One of them is preheating or heating air using solar heat before it fed into the combustor or directly drove the gas turbine [23,24]. In other configurations, the collected solar heat was used to provide heat for endothermic reaction of some fossil fuel (fuel decomposition or reformation). The produced upgraded solar fuel was then used to generate power in gas turbines [7,8].

For the ISCC configurations with DSG technologies, working parameters of HRSG and steam turbine have some impacts on overall system performance. However, few previous studies have focused on these. In addition, most of previous systems studied have only one-stage solar thermal energy integration. In this paper, a novel two-stage integrated solar combined cycle system using DSG parabolic trough solar technology (two-stage ISCC-DSG), in which a dual pressure level HRSG and the only-evaporative DSG layouts are introduced, has been proposed and analyzed.

2. Configuration of the novel integrated solar combined cycle system

The novel two-stage ISCC-DSG plant is configured based on a reference combined cycle gas turbine (CCGT). The reference CCGT