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Impacts of solar multiples on the performance of integrated solar combined cycle systems with two direct steam generation fields ☆

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HIGHLIGHTS

- An ISCC scheme with two DSG solar fields has been proposed and analyzed.
- Thermodynamic analysis of solar multiple was performed to achieve optimum property.
- Economic analysis of solar multiple was carried out to give the best cost.
- Optimal scheme exhibits higher thermal efficiency and lower electricity cost.

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ABSTRACT

Integrated solar combined cycle (ISCC) systems coupled with direct steam generation (DSG) are more promising in terms of system efficiency and electricity cost than current solar-only power generation systems, as ISCC–DSG offers the advantages of higher net thermal efficiency and lower cost. However, the ISCC systems usually have to be operated at part-load conditions with low system efficiency when no or lower insolation than that at design point is available as most of state-of-the-art such systems have no thermal storage equipped. In order to improve system performance and prolong the system full-load operation hours, a proper solar field size represented as the solar multiple is a prime parameter to be determined during the design stage of the ISCC system. A too large solar multiple might cause the collected solar thermal energy to become partially useless without thermal storage and high investment cost, while a smaller one might worsen the part-load performance of the system.

This paper presents the thermodynamic and economic analysis for an ISCC system with two pressure level DSG solar fields (ISCC–2DSG), aiming to study the impacts of solar multiples on system performance with or without consideration of thermal storage. In the ISCC–2DSG system, the solar thermal energy produced from two solar fields is only used to supply latent heat for low- and high-pressure water vaporization, respectively. Feedwater preheating and steam superheating are achieved in a HRSG. The annual thermodynamic performance of several such ISCC–2DSG systems, with different solar multiple values but with identical design parameters in the power subsystem, is characterized. Based on these features, the *LEC* for each system is calculated and compared. An optimum solar field size (solar multiple), which gives the minimum *LEC*, for the ISCC–2DSG system can be finally obtained.

1. Introduction

With the rapid depletion of fossil fuels and their adverse effects on the environment, the use of renewable energy sources needs to be accelerated. Solar energy is gaining more and more attention as a clean, free, and non-depleting source of energy [1]. Between 1984 and 1990, a total of nine Solar Electric Generating Systems (SEGS) were built in the Southern California desert. All these plants used an indirect steam generation technique, namely parabolic trough solar collectors, to heat up a heat transfer fluid (HTF) like oil. The HTF then transfers the heat to water or steam through heat exchangers. The working fluid (steam) produced eventually drives conventional Rankine cycles [2,3]. The introduction of intermediate heat exchangers to the systems results in a relatively high investment cost and the thermal losses associated with that layout.

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Nomenclature

C	cost ($)
CCGT	combined cycle gas turbine
CF	capacity factor
DNI	direct normal irradiation (W/m^2)
DSG	direct steam generation
$E_{net,a}$	annual net electricity production (MWh)
fcr	capital recovery factor
HTF	heat transfer fluid
i	loan interest rate
ISCC	integrated solar combined cycle
LEC	levelized electricity cost ($/kW h)
LHV	lower heating value (kJ/kg)
m	mass flow (kg/s)
n	plant lifetime (y)
Q_f	fuel low heating value input (MW)
$Q_{abs,a}$	annual absorbed solar heat (MW h)
$Q_{rad.a}$	annual solar energy irradiated to solar field (MW h)
SEGS	solar electric generating system
$SM_{design\text{-}point}$	solar multiple at design-point
$SR_{f,a}$	annual fossil fuel saving ratio
W_{net}	nominal power output (MW)
$X_{sol,a}$	annual solar thermal share
$\eta_{col,a}$	annual solar collector efficiency
$\eta_{th,a}$	annual thermal efficiency
$\eta_{sol,a}$	annual solar-to-electricity efficiency

Subscripts

a	annual
col	solar collector
f/fuel	fossil fuel
net	net value
O&M	operation and maintenance
rad	radiation
ref	reference system
abs	absorbed solar heat
th	thermal
TPC	total plant cost

To improve the efficiency of solar thermal power generation and to reduce cost, an Integrated Solar Combined Cycle System (ISCCS) was initially proposed by Luz Solar International in the early 1990s, as a means of integrating a parabolic trough solar field with a combined cycle power plant [4,5]. This integrated plant consists primarily of a conventional combined cycle plant, a solar collector field and a heat transfer fluid-to-water (or steam) heat exchanger. During the day, when solar heat is available, feed water is withdrawn from the combined cycle plant heat recovery steam generator (HRSG), heated by HTF and converted to saturated steam. The saturated steam is returned to the heat recovery steam generator to be superheated. With the solar heat input and same heating capacity in HRSG, the steam flow rate could be increased, thereby increasing the output of the Rankine cycle. During cloudy periods or at night when solar heat is not available, the integrated plant operates as a conventional combined cycle facility [3]. There are several thermal power plants using this scheme, such as the ISCC projects in Algeria, Egypt [2,6,7]. Behar et al. [2] presented the performance of the first such integrated solar combined cycle system in Algeria. The results showed that the power plant can produce about 134 MW with the fuel based net electricity efficiency equals 57.5% at night, and 157 MW and 67% at daytime. Horn [6] carried out an economic analysis of an ISCC power plant in Egypt and concluded that "ISCC system provided an environmentally beneficial and economically attractive option for renewable power generation in Egypt". The results showed that 25,000 tons of CO_2 emission could be reduced per year compared with the reference fossil fired combined cycle (CC) power plant and the levelised electricity cost (*LEC*) was estimated to be 0.031 $/kW h.

A direct steam generation (DSG) solar field was then developed for the ISCC system. The DISS (Direct Solar Steam) project was initiated by Zarza in 1996 [8], aiming to reduce the cost by eliminating the heat exchangers. It was estimated that an ISCC with DSG system could reduce the levelized electricity cost (*LEC*) by 10% when the DSG process is combined with improved components of the solar collectors [9].

DSG technology presents some advantages when compared with HTF technology. Parabolic troughs are cooled by HTF (oil), so an intermediate oil-to-water (or steam) heat exchanger is needed between the solar field and the power block. This particular configuration is called HTF technology [10]. There is no need for an intermediate heat exchanger between the solar field and the steam cycle in DSG configuration, resulting in lower investment costs. Thermal and exergy losses associated with the heat exchanger are also avoided, resulting in improvements in the overall efficiency. Nezammahalleh et al. [11] studied three cases: an integrated solar combined cycle system with DSG technology (ISCCS-DSG), a solar electric generating system (SEGS), and an integrated solar combined cycle system with HTF technology (ISCCS-HTF). This study showed that ISCCS-DSG had higher solar heat-to-electricity net efficiency in comparison with ISCCS-HTF because of higher temperature levels in the solar field. CO_2 emission for the ISCCS-DSG is about 2.5% lower than that for ISCCS-HTF. The levelized electricity cost (*LEC*) for the ISCCS-DSG is the lowest among three systems. Cau et al. [12] carried out a study on performance and cost assessment of Integrated Solar Combined Cycle Systems using CO_2 as the heat transfer fluid. The results show that the use of CO_2, instead of the more conventional thermal oil, as a heat transfer fluid allows for an increase in the temperature of the heat transfer fluid and thus in solar energy conversion efficiency. The solar energy conversion efficiency ranges from 23% to 25% for a CO_2 maximum temperature of 550 °C. This is similar to the predicted conversion efficiencies of the direct steam generation solar plants (22–27%).

The ISCC–DSG has a higher net solar-to-electricity efficiency and lower investment cost than a solar-only system [13]. ISCC–DSG does not usually require thermal storage when the direct normal irradiance (*DNI*) is low or nil because the basic power output level can be assured in the power subsystem. However, like all other solar systems, the performance of the ISCC system depends on solar radiation, which can vary significantly. There are times when the systems run under part-load conditions, resulting in a compromise of the system efficiency. In order to accomplish the nominal power output for a longer time period, the solar field is normally oversized. The degree of oversize is termed as a solar multiple, which is defined as the ratio of the solar thermal energy produced by the solar field to that required by the power block at the design point [14].

Solar multiple is a prime parameter which should be determined at the design stage. If the solar multiple chosen was too big for a system without thermal storage, it would cause collected solar energy to be wasted alongside unnecessarily high investment costs. A small solar multiple would make the system work under part-load conditions for a longer time period. This paper conducts

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