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Performance analysis of an Integrated Solar Combined Cycle using Direct Steam Generation in parabolic trough collectors

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A B S T R A C T

The contribution of solar thermal power to improve the performance of gas-fired combined cycles in very hot and dry environmental conditions is analyzed in this work, in order to assess the potential of this technique, and to feature Direct Steam Generation (DSG) as a well suited candidate for achieving very good results in this quest. The particular Integrated Solar Combined Cycle (ISCC) power plant proposed consists of a DSG parabolic trough field coupled to the bottoming steam cycle of a Combined Cycle Gas Turbine (CCGT) power plant. For this analysis, the solar thermal power plant performs in a solar dispatching mode: the gas turbine always operates at full load, only depending on ambient conditions, whereas the steam turbine is somewhat boosted to accommodate the thermal hybridization from the solar field.

Although the analysis is aimed to studying such complementary effects in the widest perspective, two relevant examples are given, corresponding to two well-known sites: Almería (Spain), with a mediterranean climate, and Las Vegas (USA), with a hot and dry climate. The annual simulations show that, although the conventional CCGT power plant works worse in Las Vegas, owing to the higher temperatures, the ISCC system operates better in Las Vegas than in Almería, because of solar hybridization is especially well coupled to the CCGT power plant in the frequent days with great solar radiation and high temperatures in Las Vegas. The complementary effect will be clearly seen in these cases, because the thermal power provided by the solar field compensates the gas turbine part load performance due to the high temperatures. The economical analysis points out that this hybrid scheme is a cheaper way to exploit concentrated solar energy, although it is limited to a small fraction of the combined cycle power. The analysis also shows that the marginal cost of solar electricity is strongly influenced by the goodness of coupling, so this cost is lower in Las Vegas than in Almería.

1. Introduction

Integrated Solar Combined Cycle (ISCC) power plants have been widely studied as an alternative to the conventional arrangement of parabolic through collectors coupled to a Rankine power cycle (that will be referred as solar-only plant in this work). In this paper, a specific configuration of ISCC plant is proposed, and the coupling between the solar field and the combined cycle is studied. For that, the annual performance of the proposed configuration and its corresponding reference Combined Cycle Gas Turbine (CCGT), defined in next sections, have been carried out in two locations, comparing both the electricity production and the costs, for each of the selected locations.

There are several advantages of the ISCC plants over the solar-only plants [1,2]. For instance, overall solar-to-electric conversion efficiency is higher in the ISCC systems. Also, integration arrangements overcome thermal losses associated to the daily start-up and shutdown processes of the steam turbine. Finally, if solar integration is accomplished on an existing CCGT power plant, incremental costs of replacing the steam turbine by a greater one are lower than the overall unit cost in a solar-only plant. Besides the advantages mentioned above, it may be added that this configuration does not require any storage system (but it may be included in the scheme) to ensure a manageable range of electricity output, which is one of the crucial issues in electricity production by renewable energy. Dersch showed that, whether the strategy adopted is a solar dispatching or a scheduled load operation mode, there is always a power level of the plant that is guaranteed [1]. The difference between the two performance strategies is based on the use of an auxiliary back-up fossil boiler to supply energy when solar energy is not available.

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Nomenclature

CCGT	Combined Cycle Gas Turbine
DNI	direct normal irradiation
DSG	Direct Steam Generation
HRSG	Heat Recovery Steam Generator
ISCC	Integrated Solar Combined Cycle
LCE	Levelized Cost of Energy
TMY	typical meteorological year

Several thermal power plants with this scheme are being constructed, like the ISCC projects in Egypt, Morocco and Algeria [3]. The configuration proposed in those projects basically consists of a parabolic trough solar field coupled to the bottoming steam cycle of a CCGT power plant. Parabolic troughs are cooled by synthetic oil, so an intermediate oil-to-water/steam heat exchanger is needed between the solar field and the power block. This particular configuration is called Heat Transfer Fluid (HTF) technology, and it is the most used in parabolic trough thermal plants, where the power block is usually a Rankine cycle. A conventional ISCC scheme with a HTF solar field is shown in Fig. 1.

Instead of that approach, another scheme is proposed in this paper. This scheme consists of a Direct Steam Generation (DSG) parabolic trough plant coupled to the bottoming steam cycle of a CCGT power plant. This layout presents several advantages compared to conventional ISCC layouts. For example, there is no need of an intermediate heat exchanger between the solar field and the steam cycle, resulting in lower investment. Thermal and exergy losses associated to that system are also avoided, improving overall efficiency. Furthermore, coupling with DSG presents another important advantage for the deployment of this technology: the ability of guaranteeing the electricity production during non-radiation periods without using a thermal storage, a system that is still under development for the DSG technology [4,5].

A similar arrangement to the one studied in this paper is proposed in [6]. There, two different DSG solar fields are used to produce high pressure (100 bar) and low pressure (5 bar) steam. However, in the configuration proposed in this work, only the high-pressure level (at 90 bar) is considered for the solar coupling, with the aim of using the solar thermal energy at the highest exergy level, as it will be explained later. Furthermore, not only the boiling process is accomplished in the parabolic troughs but also the preheating, which reduces the average temperature of the water in the troughs and, therefore, the thermal losses from the tubes to the environment decreases. Thus, the water is conducted to the solar field before the inlet to the Heat Recovery Steam Generator (HRSG).

Another similar arrangement is the one proposed in [7]. In this case, preheating, boiling and superheating are accomplished in the parabolic trough collectors, to supply steam to the high pressure steam turbine. The proposed design aims to avoid the steam superheating in the parabolic troughs, which introduces several technical difficulties [8].

2. Integrated Solar Combined Cycle proposed

The ISCC scheme proposed has been already presented by the authors of this paper in [9]. That work was focused on the analysis of different solar hybridization sizes for the same location (Canary Islands, Spain). In this paper, only one hybridization size (50 MW_{th} approximately, at the design-point conditions, although the steam turbine has only been oversized in 25 MW_{th}, as it will be explained later) has been simulated, but in two different locations with different warm climates.

The scheme proposed is based on a conventional CCGT power plant around the 220 MW_e power rating. The CCGT consists of a 2×1 configuration: two gas turbines of 72.5 MW_e each, two HRSGs that produce steam at high pressure (90 bar) and at low pressure (8 bar) and a steam turbine of 75 MW_e. As it can be seen in Fig. 2, there is only one extraction line from the steam turbine, and it is directed to a deareator. Liquid water from the deareator is pumped to the low and high pressure economisers of the HRSG, and to the solar field.

DSG parabolic trough plant is coupled to the high-pressure level in the HRSGs. Integration is carried out at the higher pressure level. This pressure is in the optimum working pressures range to oper-

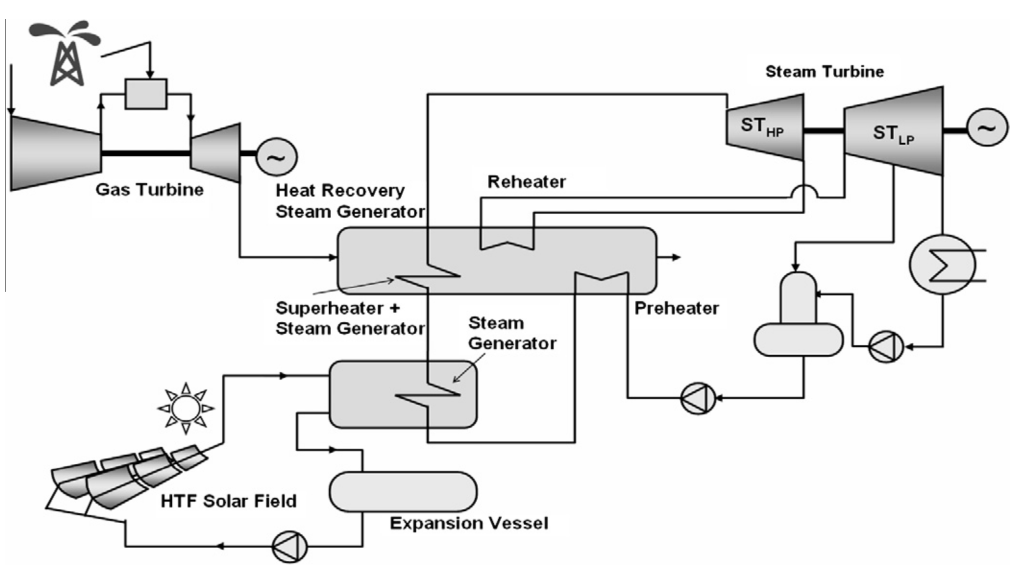

Fig. 1. Conventional ISCC with a HTF parabolic trough field.