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Thermodynamic evaluation of solar integration into a natural gas combined cycle power plant

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ABSTRACT

The term integrated solar combined-cycle (ISCC) has been used to define the combination of solar thermal energy into a natural gas combined-cycle (NGCC) power plant. Based on a detailed thermodynamic cycle model for a reference ISCC plant, the impact of solar addition is thoroughly evaluated for a wide range of input parameters such as solar thermal input and ambient temperature. It is shown that solar hybridization into an NGCC plant may give rise to a substantial benefit from a thermodynamic point of view. The work here also indicates that a significant solar contribution may be achieved in an ISCC plant, thus implying substantial fuel savings and environmental benefits.

1. Introduction

Concentrating solar power (CSP) utilizes mirrors to concentrate sunlight to heat a working fluid and generate electricity by combining the heated working fluid with a thermodynamic power cycle [1]. There exist four main CSP technologies: parabolic trough, linear Fresnel, power tower and dish/engine. CSP is particularly friendly to large-scale economic thermal storage which can provide valuable dispatchability to the electric grid. At the same time, a standalone solar thermal power plant with thermal energy storage typically requires intensive capital investment. In an effort to reduce cost, many low-cost CSP collector designs are under development, but lack of operating experience places them at higher investment risk [2]. Consequently, CSP has not yet been adopted as a reliable baseload power deployment, although its installation capacity has been steadily increasing at a rapid pace [3,4].

One way to deploy CSP with a lower investment risk while retaining power dispatchability, is solar hybridization into fossil-fuel power plants. This approach eliminates a large portion of the capital cost on a partially-operational power block. Additionally, a solar hybridized power plant may greatly reduce the fossil-fuel consumption, thus leading to the reduction of greenhouse-gas emissions and the associated costs. The thermal storage system may also be eliminated or significantly reduced for a solar hybrid plant because the fossil-fuel cycle provides an easy means to smooth power fluctuation under dramatic changes in solar irradiation. Due to these advantages, solar integration into different types of fossil-fuel power plants has been attracting more attention from industries [5]. Depending on the solar heat quality produced by a solar field, solar power may be integrated into a gas turbine, coal-fired Rankine cycle or natural gas combined-cycle (NGCC). A number of solar hybridization projects have been implemented or are under construction across the world [3,6].

An Integrated Solar Combined-Cycle (ISCC) system adds solar steam produced from a solar field into heat recovery steam generators (HRSG) in an NGCC plant. ISCC can provide significant solar integration allowance into the system [7,8] and has the potential to achieve substantial economic and environmental benefits, compared with solar integration into other types of power cycles. Previous work has shown that solar-to-electric conversion efficiency may reach around 31% with a solar contribution of 10% compared to the overall plant power generation [8]. McMahan and Zervos reported that retrofitting an NGCC through replacing duct burner capacity with solar input can provide economic values when compared to a standalone solar plant [9]. According to Ojo et al. [10], higher solar fractions may be achieved through new ISCC plant design than through retrofitting an existing NGCC plant with solar integration. Montes et al. [11] suggested that solar hybridization may be more beneficial in a hot, dry climate as it provides a natural offset to decreased gas turbine performance on hot days. When retrofitting an existing plant with solar, a thorough feasibility study is needed not only to evaluate the thermodynamic impact of solar

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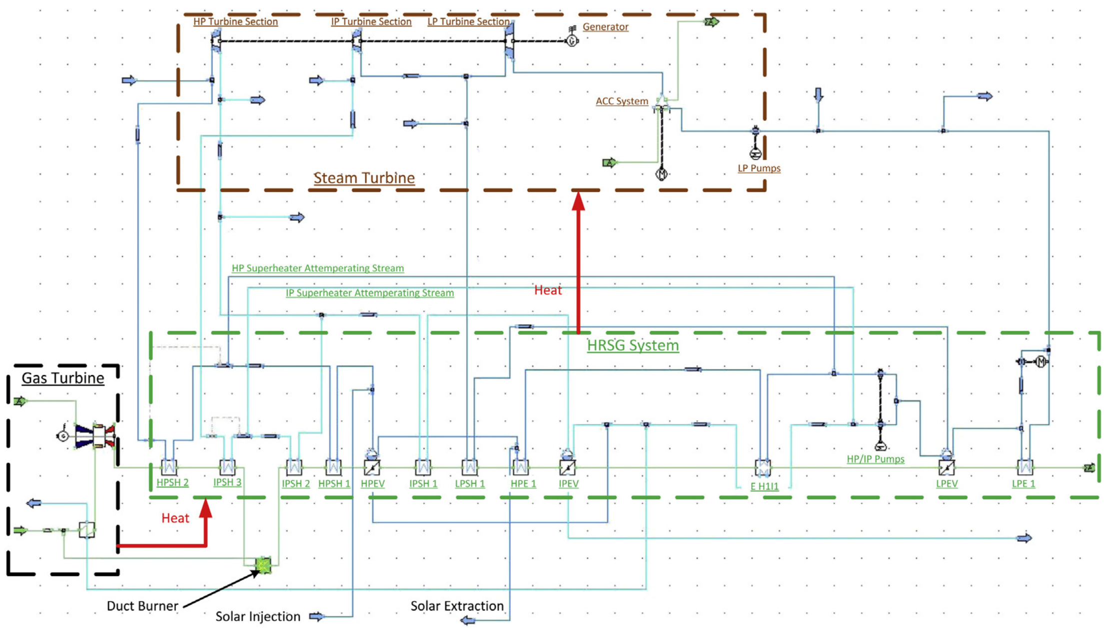

Fig. 1. Screenshot of the ISCC plant configuration in IPSEpro. HP stands for high pressure; IP stands for intermediate pressure; LP stands for low pressure; SH stands for superheater; EV stands for evaporator; E stands for economizer. The Economizer E_H1I1 is the dual heat exchanger for both high-pressure water and intermediate-pressure water.

integration to the plant, but also to examine realistic physical/operational limitations in the existing plant configuration. A series of reports led by the Electric Power Research Institute (EPRI) [12,13] showed that, even though a conceptual analysis may suggest a clear benefit from solar hybridization, physical limitations on the solar field size and location and existing power plant equipment limits may add practical constraints to an otherwise feasible solar integration.

In this work, a detailed physical ISCC plant model is used to investigate the thermodynamic impact of solar hybridization into an NGCC plant under design point and off-design operations for a wide range of important input parameters, such as ambient temperature and solar thermal input. In particular, the paper is organized as follows: first, the ISCC modeling is described; then, the solar injection strategy used to select the solar injection point is elaborated; a thorough parametric study over a wide range of system parameters is presented next to examine the thermodynamic responses of the ISCC system under varying off-design conditions; finally, conclusions and future directions are given.

2. Modeling of integrated solar combined-cycle plant

An NGCC plant includes gas turbines, steam turbines and HRSGs with an optional duct burner; the design of each may differ with respect to a wide range of design parameters. Furthermore, the performance of each of these components depends on that of the others. Accurate modeling of such a complicated system requires sophisticated modeling tools. Among these, IPSEpro, Thermoflex, GateCycle and Aspen are commercial software often used for power cycle simulations. There also exists some in-house codes that are often limited to a narrow range of NGCC plant operating conditions [14]. IPSEpro is able to provide flexible modeling options for components in an NGCC and is thus adopted as the modeling software here. By using IPSEpro, each component in an NGCC plant can be carefully evaluated at design point and off-design conditions, which allows detailed thermodynamic modeling of an NGCC plant with solar integration.

Table 1
Design parameters of NGCC power plant.

Parameters	Values	Units
Overall plant		
Nominal ambient pressure	0.96	bar
Nominal ambient temperature	20	°C
Gas turbine	2	–
HRSG	2	–
Steam turbine	1	–
Duct burner	Yes	–
Cooling	Dry	–
Total capacity – With duct burner	549	MWe
Total capacity – Without duct burner	480	MWe
Overall efficiency – With duct burner	0.52	–
Gas turbine		
Nominal power output	155	MWe
Nominal efficiency	0.358	–
Outlet temperature	608.3	°C
Pressure ratio	17	–
Steam turbine		
Nominal power output	239	MWe
Nominal cycle efficiency	0.358	–
HP steam turbine isentropic efficiency	0.84	–
IP steam turbine isentropic efficiency	0.92	–
LP steam turbine isentropic efficiency	0.87	–
HP steam mass flow rate	159.3	kg/s
HP inlet temperature	558.1	°C
HP inlet pressure	98.6	bar
IP steam mass flow rate	167.6	kg/s
IP inlet temperature	544.7	°C
IP inlet pressure	29.12	bar
LP steam mass flow rate	182.6	kg/s
LP inlet temperature	310.23	°C
LP inlet pressure	4.964	bar
LP outlet temperature	42.1	°C
LP outlet pressure	0.082	bar
Feedwater pump isentropic efficiency	0.7	–
HP feedwater pressure	110.1	bar
HRSG		
Flue gas inlet temperature	608.3	°C
Flue gas outlet temperature	72.9	°C
No. of HP exchangers	5	–
No. of IP exchangers	5	–
No. of LP exchangers	3	–