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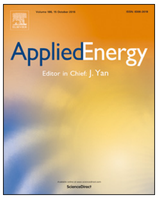

Optimal design and operation of integrated solar combined cycles under emissions intensity constraints

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HIGHLIGHTS

- A framework for combined design and operations optimization of an ISCC is developed.
- Physical and practical operational constraints are incorporated in the model.
- Most ISCC designs are infeasible, but optimization reveals six viable configurations.
- One configuration dominates all others with respect to NPV and CO_2 emissions.
- Tradeoffs between emissions and NPV are optimized for different economic settings.

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ABSTRACT

Direct integration of solar thermal and natural gas systems can be achieved through integrated solar combined cycle (ISCC) power generation. In this work, optimal ISCC system design and hourly operations are determined simultaneously using computational optimization procedures. The full optimization problem is intractable, so a series of problem reductions are employed to explore the ISCC design space while ensuring that individual designs can operate feasibly for a wide range of operating conditions and under realistic constraints. We construct bi-objective Pareto fronts for two conflicting objectives: net present value (NPV) and average CO_2 emissions intensity of power produced. A variety of ISCC designs are explored to find a superior configuration with physically feasible annual solar contribution (ASC) of up to 20%, a significant improvement over published designs. We then explore the sensitivity of the results to economic factors such as discount rate, power price, and capital cost. By examining the Pareto frontiers of each case, we quantify the economic cost of reduced CO_2 emissions. The resulting ISCC-derived mitigation costs are found to be competitive with other CO_2 mitigation technologies.

1. Introduction

The cost of renewable energy is decreasing quickly, and investment is growing [1]. Solar photovoltaic (PV) costs continue to drop globally and are now lower than conventional generation technologies in a number of locales [2]. Wind generation costs also continue to decline, and the potential resource is vast [3]. The key remaining challenge to very high renewable futures is therefore not the overall cost of renewable generation but the physically feasible and economically viable integration of time-varying renewables into the electric grid. While solar thermal or concentrating solar power (CSP) technologies have been eclipsed in the last decade by the rapidly falling costs of solar photovoltaics [4], CSP systems retain some inherent integration advantages. CSPs can readily incorporate energy storage for power generation in non-sunlight hours. CSP systems can also be directly hybridized with natural gas to create an integrated solar combined cycle (ISCC) power station with higher efficiency potential [5], which can maintain generation in dark or cloudy conditions.

ISCCs produce electricity from both a natural gas combustion turbine (NGCT) and from steam generated by a combination of hot NGCT exhaust and solar thermal heat transfer fluid (HTF) [6]. In this work, we focus on solar fields composed of concentrating parabolic trough arrays. A high-level ISCC schematic is shown in Fig. 1. The NGCT and solar thermal heat streams are integrated with complex heat exchanger designs called heat recovery steam generators (HRSGs), which aim to minimize thermodynamic losses of heat exchange. Ideally, ISCCs exhibit both the CO_2 emissions reductions of solar thermal energy with the flexibility and dispatchability of a natural gas combined cycle

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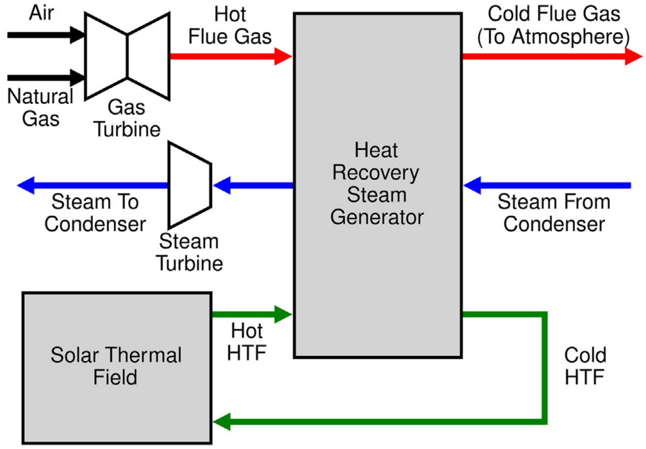

Fig. 1. High level overview of an ISCC. Electricity is produced from both the gas and steam turbines. Hot exhaust from the gas turbine and a solar thermal heat transfer fluid are both used to produce steam inside of a heat recovery steam generator.

(NGCC) [5,7,8]. While several studies have examined the benefits of individual ISCC systems [9–14], or even compared several system designs [15–19], optimization work remains scarce. Some initial optimization work [20,21] has demonstrated tradeoffs between capital investment and long-term economics, but did not consider dynamic system operations or detailed system design. Some recent work has highlighted a potential methodology for examining integration strategies [22], but it does not consider operations optimization within this framework. To our knowledge, no studies have implemented a combined design and operations optimization. Such a comprehensive search is necessary to optimize the tradeoff between ISCC system economics and CO_2 emissions.

The limited amount of systematic computational optimization work on ISCCs is at least partly due to the enormous computational complexity involved in ISCC design optimization. To address this issue, we previously developed and verified a computationally efficient ISCC model, and demonstrated its ability to assess a single system design by optimizing the system operations [8]. Rather than simulate every operating condition (e.g., mass flow rates of HTF), this model uses instead a very fast statistical proxy model. This statistical model is constructed from more than 1000 runs of a solar thermal simulation platform, the System Advisory Model (SAM) from the U.S. National Renewable Energy Laboratory [23]. Our statistical proxy provides a factor of 10^6 speedup relative to full SAM simulations. This proxy model is integrated into the Hybrid Power Plant Optimization software (HyPPO), developed to explore combined design and operations optimization of clean power systems [24–29].

Recognizing the multi-faceted nature of long-term investment decisions, we use this model here to perform dual-objective optimization to explore the tradeoff between net present value (NPV) [USD] and the CO_2 emissions intensity of the technology [kg CO2eq./MWh]. The tradeoff between economics and CO_2 emissions is particularly apparent in hybrid ISCCs because of their flexible nature and fuel switching capability. Average CO_2 emissions intensity and NPV are long-term metrics that are influenced by both the design of an ISCC as well as its operations. Consequently, we simultaneously optimize both the system design and operations of ISCC configurations.

A series of simplifications is applied in this work to enable these optimizations. Specifically, we evaluate ISCC operations over a set of realistic representative days rather than over all days in the year [28,30]. Additional model reductions are also required to explore the ISCC design space while still ensuring that individual designs can successfully operate under a wide range of realistic operating conditions. The reduced optimization problem is, however, still a mixed integer nonlinear programming (MINLP) problem with a large number of nonlinear constraints. Each function evaluation (HyPPO model run) requires the solution of nonlinear systems of algebraic equations to resolve the ISCC physics. This level of representation is necessary to ensure that the constraints inherent in ISCC operations are respected.

We begin by describing the methods used to perform the optimization described above. This includes descriptions of the design decision variables and constraints, the operating decision variables and constraints, the framing of the optimization problems, and the simplifying assumptions employed to make these optimizations computationally tractable. We next explore a set of ISCC designs given a preselected single NGCT-side heat exchanger configuration. We then broaden our search by investigating the effect of various economic factors on the optimal design. By examining the Pareto frontiers of the design under various economic conditions, we quantify the cost of reduced CO_2 emissions for ISCCs that have different annual solar contributions (ASCs). We conclude with a comparison of these ISCC results to those for other CO_2 mitigation technologies, and a discussion of how the methods developed here can be applied in future work.

2. Methods

In this section we describe the methods used to perform combined design and operations optimization on an ISCC. Because of the operations optimization approach employed, a traditional control strategy is not incorporated. Rather, the objective function (either electricity or profit maximization) determines the combination of operating variables used to run the plant for a specific design. The optimization is performed through a series of layers (or tiers), whereby the operations optimization is an inner loop within the design optimization. In the operations optimization, a large number of HyPPO ISCC model runs are required, each of which draws on both electricity data as well as many individual executions of the System Advisory Model (SAM) [23] (for the latter we use a proxy model). Fig. 2 highlights the major aspects of the combined design and operations optimization.

The ISCC model applied during optimization was developed and validated in Brodrick et al. [8,31]. The model has four primary components: a natural gas combustion turbine, a steam turbine, a heat recovery steam generator, and a parabolic trough solar thermal field. These components are characterized by nonlinear thermodynamic equations, and the state of the system is resolved with a damped Newton solver. The electricity prices and weather conditions used here are (adjusted) from southern California in 2010. The proxy model used to characterize the solar field [8] is dependent on location-specific meteorological factors including irradiation, temperature, and wind speed.

The heat recovery steam generator is solved using the effectiveness-NTU method as in Brodrick et al. [8], with the heat exchanger sizes determined as decision variables (see Section 2.1). The gas and steam turbines are modeled as described in Brodrick et al. [8], with off-design efficiency penalties following Spencer et al. [32] as well as Kim and Ro [33]. While the efficiency penalties vary based on the design and operations decision variables, in the case of operating a system at 60% part load, with pressure levels of 3, 15, and 75 bar and a steam turbine exit quality of 0.95, the total off-design combined-cycle efficiency would be approximately 94%. This is consistent with other reported penalties [33].

Neither the heat recovery steam generator nor the gas turbine models consider off-design ambient temperature effects. Off-design ambient temperature effects can penalize electricity production of the gas turbine by up to 14% (or approximately 9% of the total gas-side electricity production) when ambient temperatures reach 40 °C, or increase electricity production by up to 9% (or approximately 6% of the total gas-side electricity production) when ambient temperatures fall to 0 °C, for a particular design [34]. These efficiency changes are mitigated to some extent by changes in the gas turbine exhaust temperature