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Co-located gas turbine/solar thermal hybrid designs for power production

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ABSTRACT

This paper describes gas turbine/solar trough hybrid designs that achieve a solar contribution greater than 50% and increase the solar-to-electric efficiency while reducing gas heat rate. Two conceptual designs are explored: (1) integrating gas turbines with conventional oil heat-transfer-fluid (HTF) troughs running at 390 °C, and (2) integrating gas turbines with salt-HTF troughs running at 450 °C and including thermal energy storage (TES). The latter system is also representative of molten-salt power towers, although the power towers run at temperatures near 565 °C and would require selection of an appropriate gas turbine to provide waste heat at those temperatures. Using gas turbine waste heat to supplement the TES system provides operating flexibility while enhancing the efficiency of gas utilization. The analysis indicates that the hybrid plant designs produce solar-derived electricity and gas-derived electricity at lower costs than either system operating alone.

1. Introduction

Over the last two decades the cost of solar power has dropped significantly [1]. Although solar prices have fallen, it remains more expensive than traditional generation sources and government incentives in the form of tax credits and renewable portfolio standards are required to promote its benefits of near-zero emissions, low life-cycle cost, and minimal impacts to global climate. More recently, production in shale gas has led to historically low prices for natural gas in the US. Low gas prices have been described as a "game-changing" development in power generation. Whether low gas prices hinder investment in renewables or enable renewable deployment is yet to be seen; however, one renewable technology is uniquely positioned to integrate with natural gas. Concentrating Solar Power (CSP) is a solar thermal technology that can utilize thermal energy storage (TES) or integrate alternative heat sources, such as burning natural gas or biomass. All CSP plants commonly use some natural gas to aid system startup and provide backup power. The key advantage of CSP is the use of TES and/or fossil backup to convert the intermittent solar energy into a reliable, dispatchable resource. This paper examines the prospects of integrating simple-cycle, gas turbines with CSP technology to achieve high thermal efficiency, high solar penetration, and good dispatchability.

Using TES allows CSP systems to produce power in the absence of sunlight; however, integrating this capability requires additional capital cost. TES is accomplished by storing hot heat-transfer-fluids (HTF) or by using the HTF to heat a storage media. The most obvious cost is that for the thermal storage media, but additional collector area is also required to provide the energy used to charge storage. In short, adding TES will substantially increase the installed capital cost of the solar plant. While the capital cost will increase, the levelized cost of electricity (LCOE) may increase or decrease, depending on the relative costs of the collector/TES systems and the power system, because TES allows for greater utilization of the fixed power system investment. At present, storage systems increase the LCOE for oil-HTF trough power plants and decrease the LCOE of molten salt power towers [2]. Although TES makes a CSP plant more valuable, the additional capital costs associated with TES make such plants harder to finance.

Almost all CSP plants incorporate some fossil energy to assist with start-up or provide a back-up energy source. In general the annual contribution of fossil energy to electricity production is low, typically less than 15%. The limitation is based on policy and economics – natural gas burned in a CSP plant has a heat rate governed by the steam cycle efficiency. A modern combined-cycle plant can

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achieve thermal cycle efficiencies greater than 55%, whereas a parabolic trough plant has a thermal cycle efficiency of less than 40%. The use of small amounts of natural gas is justified by the investment in the solar plant infrastructure, but the economics of burning natural gas in auxiliary boilers falls rapidly as gas consumption increases. A successful CSP/fossil integration must provide benefits to both the solar and gas components. In general, CSP/gas hybrid designs should:

- improve solar-to-electric efficiency versus solar-only plant,
- improve gas-to-electric efficiency (heat rate) versus gas-only plant,
- lower capital and operating cost versus two separate plants,
- achieve a high annual solar fraction (e.g., greater than 50%), and
- offer low technical risk through the use of existing, proven technologies.

This paper examines gas turbine/CSP hybrid designs that meet the objectives listed above and overcome the limitations of prior hybrid designs. Specifically this work examines the integration of gas turbines with CSP plants in a fashion that maintains high solar fraction and good gas heat rates. The approach is to co-locate CSP facilities with simple-cycle gas turbines and integrate the two systems to capture exhaust heat from the gas turbine within the HTF of the solar plant.

2. Overview of prior solar/fossil hybrid designs

2.1. Gas backup

The most common form of solar/gas hybrid design is the simple integration of a gas backup system in a CSP power plant (see Fig. 1). The benefit of gas to the solar plant is clear: faster startup in the morning, freeze protection heat, and greater tolerance of and ability to generate power during poor weather. However, the benefit from the gas perspective is marginal: low capital cost because the CSP power block exists. Because gas electric generation costs are dominated by fuel costs, the low efficiency of the CSP power block does not justify use of much gas in such a design. Ideally, a hybrid design will offer clear benefits to both thermal contributors.

2.2. Integrated solar combined cycle

The best known example of a hybrid that meets this criterion is the integrated solar combined cycle (ISCC) design. In the 1990s, Luz, the builders of the several trough plants in California, proposed hybrid plant designs where solar steam would be used to supplement a combined-cycle power plant. Kelly et al. [3,4] later examined the potential of such designs through an analysis of power cycle performance. Kelly used GateCycle to model the behavior of the power system for systems where boiler feedwater was extracted and heated by the solar HTF to produce steam. The solar steam was injected into the power system at different integration points. Kelly concluded that the hybrid plant offered three advantages:

- Solar energy was converted to electric energy with an efficiency of about 39%, which is about two percentage points better than in a stand-alone solar plant;
- The incremental cost for increasing the steam turbine size in the integrated plant was less than the overall unit cost in a solar-only plant; and
- Thermal inefficiencies a solar-only plant normally suffers from daily startup and shutdown were minimized.

The primary disadvantages of the ISCC design are due to the intermittent nature of the solar resource. A fossil plant designed to accept a solar contribution operates its steam turbine at partial loads during cloudy weather and at night. Such operation increases the fossil fuel heat rate, which effectively subtracts from the annual thermal contribution of the solar field. Second, the annual solar contribution for plants is in the range of only 2–8% because higher contributions lead to lower overall annual efficiency due to the on/off availability of the solar input.

Work by the Electric Power Research Institute (EPRI) examined the optimum design for ISCC plants and the means for augmenting coal plants with solar thermal energy [5]. The EPRI study highlighted the advantages of integrating solar steam into combined cycle plants that contain gas-fired duct burners between the gas turbine and heat recovery steam generator (HRSG). Plants with duct firing are designed with slightly oversized steam systems.

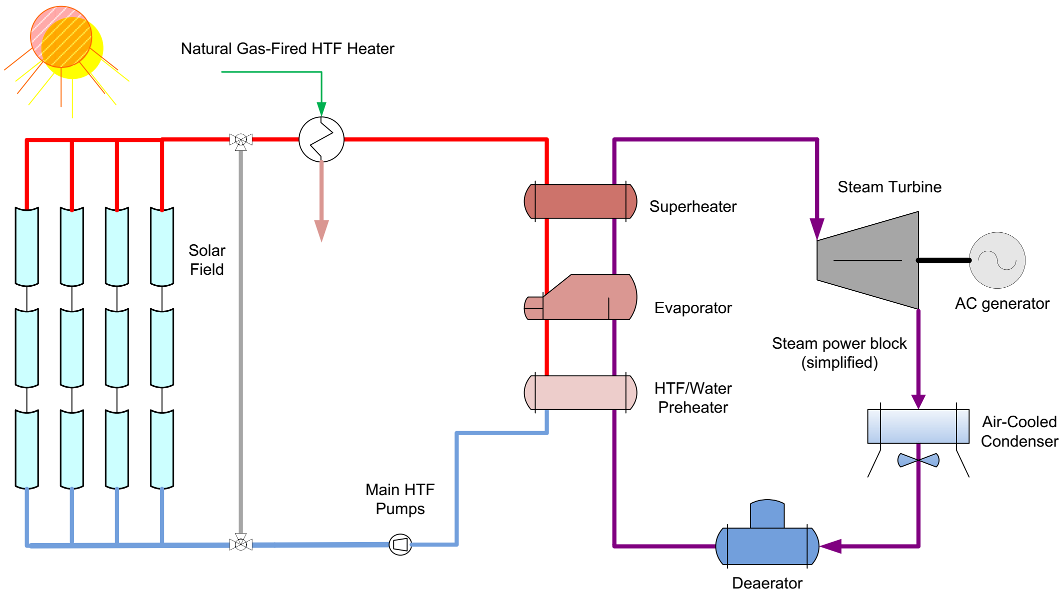

Fig. 1. Traditional CSP plant with gas-burner backup.