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Dynamic optimization of a hybrid solar thermal and fossil fuel system

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Abstract

This work illustrates the synergy that exists between solar thermal and fossil fuel energy systems. By adding degrees of freedom and optimizing the system, more solar energy can be harvested by operating in a "hybrid" mode, where a portion of the demand is met by solar energy, with the remainder provided by a supplemental fuel, such as natural gas. This requires allowing temperatures in the solar field and storage tanks to vary, permitting the system to meet the demand by a combination of solar and fossil energy, rather than one or the other, and by allowing the heat transfer fluid to bypass storage. The addition of thermal energy storage provides the opportunity for dynamic optimization, where the degrees of freedom can be exploited over the entire time horizon to yield optimal results: maximizing the total amount of solar energy harvested. The problem is solved using a simultaneous solution method that concurrently minimizes the objective function and solves the system's constraints. This methodology is demonstrated on a parabolic trough solar thermal plant with a two-tank-direct thermal energy storage system. Results show that 9% more solar energy can be harvested on a sunny day by using this methodology. On a day with intermittent sunlight, 49% more solar energy can be harvested with the same system. Dynamic optimization enables more cost effective solar integration in areas with lower or intermittent sources of solar incidence.

Keywords: Dynamic optimization; Hybrid solar thermal systems; Thermal energy storage

1. Introduction

Solar energy has tremendous potential to produce emission-free electricity (Zhang et al., 2013). With similarities to conventional power generation methods, solar thermal, or concentrated solar power (CSP), can be a low-cost alternative to fossil-fuel-based systems (Barlev et al., 2011). In order to provide reliable base load power, however, CSP systems must be equipped with large-scale thermal energy storage (TES) and/or a backup energy source, such as natural gas or diesel fuel (Kuravi et al., 2013; Zhang et al., 2013).

Because of the intermittency of solar energy, it generally must rely on other energy technologies to ensure that consumer demand for power is always met. Hybrid systems, which combine solar thermal and other energy technologies, have been proposed as an alternative to solar-only power generation (Peterseim et al., 2013). For instance, solar thermal power can be combined with conventional power generation technology so that solar energy is aided by proven power generation technology, such as gas and steam turbines (Jamel et al., 2013). When gas and steam turbines are used in tandem, solar energy can be used to

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Nomenclature

Symbol	Description
A_A	absorber pipe cross-sectional area (m^2)
$A_{A,i}$	inner pipe cross-sectional area for absorber pipe (m^2)
A_E	glass envelope cross-sectional area (m^2)
$A_{P,i}$	inner pipe cross-sectional area for boiler pipe (m^2)
A_t	tank area subject to heat transfer (m^2)
C_A	absorber pipe specific heat capacity (J/(kg K))
C_E	glass envelope specific heat capacity (J/(kg K))
C_F	heat transfer fluid specific heat capacity (J/(kg K))
h_{air}	ambient convective heat transfer coefficient ($W/(m^2 K)$)
h_p	convective heat transfer coefficient for inner pipe ($W/(m^2 K)$)
I_C	solar radiation incident on collector surface (W/m^2)
I_N	solar irradiance in direction of rays (W/m^2)
$\dot{m}$	mass flow rate (kg/s)
$P_{A,i}$	inner absorber pipe perimeter (m)
$P_{A,o}$	outer absorber pipe perimeter (m)
$P_{E,o}$	outer glass envelope perimeter (m)
$P_{B,i}$	outer boiler pipe perimeter (m)
$\dot{p}_{pump}$	pumping power (MW)
$\dot{q}_d$	power demanded (MW)
$\dot{q}_{solar}$	solar thermal power (MW)
$\dot{q}_{supp}$	supplemental thermal power (MW)
$r_{E,i}$	inner glass envelope radius (m)
$r_{A,o}$	outer absorber pipe radius (m)
t	time (s)
T_A	temperature of absorber pipe (K)
T_{AIR}	ambient air temperature (K)
T_{SKY}	effective sky temperature for radiative heat transfer (K)
T_B	boiler water temperature (K)
T_E	temperature of glass envelope (K)
T_F	temperature of heat transfer fluid (K)
U	storage tank overall heat transfer coefficient ($W/(m^2 K)$)
V	volume of fluid in storage tank (m^3)
w	width of mirror aperture (m)
x	distance along solar collector length (m)
z	distance along boiler pipe length (m)
β	conversion factor for pumping power to thermal power (MW_{th}/MW_e)
χ	control move penalty coefficient (None)
ε_A	absorber pipe emissivity (None)
ε_E	glass envelope emissivity (None)
$\eta_{optical}$	total optical efficiency (None)
ρ_A	absorber pipe density (kg/m^3)
ρ_E	glass envelope density (kg/m^3)
ρ_F	heat transfer fluid density (kg/m^3)
σ	Stefan–Boltzmann constant ($W/(m^2 K^4)$)

supplement the steam cycle in an integrated solar and combined cycle (ISCC) power plant (Cau et al., 2012). With concentrating solar collectors, solar heat can be delivered at higher temperatures to improve the Carnot efficiency of a solar gas turbine, where the air is heated by solar radiation before entering the gas turbine (Barigozzi et al., 2012; Schwarzbözl et al., 2006).

Hybrid solar systems have also been proposed to include chemical processes, such as methane steam reforming as an intermediate step before combustion and delivery to a gas turbine (Sheu and Mitsos, 2013) or chemical looping combustion (Jafarian et al., 2013). Studies have also been done to determine how CSP can be coupled with other renewable technologies, such as wind, to better match consumer electricity demand (Vick and Moss, 2013).

Hybridization of CSP with other power production technologies represents a paradigm shift: rather than competing with other technologies as a sole power source, CSP can be used to complement these technologies. For instance, combining solar thermal systems with a fossil fuel, such as natural gas, gives the system operator more flexibility to determine how to run the system. While these fossil fuels are generally thought of as backup fuel sources to use during periods of cloud cover, dynamic optimization reveals that there are times when it is beneficial to use natural gas as a supplement while so that solar collectors can be run at lower temperatures. Optimizing the system so that the maximum amount of solar energy is harvested allows the solar and fossil components of the system to perform synergistically, resulting in more efficient performance. TES, when combined with CSP, provides additional flexibility, so that power can be produced on demand (Manenti and Ravaghi-Ardebili, 2013; Powell and Edgar, 2012; Slocum et al., 2011). These degrees of freedom can also be exploited using optimization, so that an objective can be maximized or minimized over a time horizon (Lizarraga-Garcia et al., 2013; Wittmann et al., 2011). The goal of this work is to illustrate that the addition of fossil fuel to a CSP system can actually increase the total amount of solar energy that can be harnessed. This requires dynamic optimization, so that the degrees of freedom from both the backup fuel and the TES can be fully exploited to achieve an objective: maximizing the total solar energy collected over a 24 h period.