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Optimal design and integration of solar thermal collection, storage, and dispatch with process cogeneration systems

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HIGHLIGHTS

- A hierarchical approach addresses design of cogeneration systems.
- Separates steady-state optimization from diurnal variability.
- A multiperiod approach optimizes energy mix.
- Integrates expected operation into design.
- A case study involves actual solar data in Saudi Arabia.

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ABSTRACT

This paper introduces an optimization approach to the design of process combined heat and power systems that integrate the thermal profile of the process, an external fossil fuel, and solar energy. A hierarchical design approach is proposed to stage the implementation of steady-state and dynamic calculations. Initially, energy integration is used to identify minimum heating and cooling utility targets. Next, a genetic algorithm approach is employed to optimize the external heating load and generated power of the cogeneration system that includes a steam Rankine cycle. An outer loop is used to optimize the flowrate, temperature, and pressure of the steam entering and exiting the turbine. A multiperiod optimization approach is developed to account for the diurnal variability of solar energy. Direct usage of collected solar energy is considered along with the option of thermal storage and dispatch. The solution of this mixed integer nonlinear program determines the optimal mix of energy throughout the year. A case study for a petrochemical plant in Jeddah, Saudi Arabia was solved to illustrate the applicability of the devised approach.

1. Introduction

Industrial processes are among the largest energy-demanding sectors. Appropriate management of energy within an industrial facility is a challenging task. There are different sources and demands for energy that should be properly matched. There are also different forms of energy (especially heat and power) that are transformed, exchanged, and used in the process. Energy integration techniques have been developed for the optimal design and management of energy throughout a whole industrial process and among different industrial processes. Specifically, energy integration techniques have been developed for the systematic design and optimization of heat exchange networks, process cogeneration that combines heat and power, and process trigeneration which integrates heating, refrigeration, and power. For general reviews of energy integration, the reader is referred to recent the literature on this subject (e.g., El-Halwagi and Foo, 2014; Klemeš, 2013; El-Halwagi, 2012; Kemp, 2009; Smith, 2005). Navid et al. (2014) developed a design approach of cogeneration systems based on economic, exergy, and environmental objectives. Hipólito-Valencia et al. (2014) developed a multiobjective optimization approach to the design of trigeneration systems. Bamufleh et al. (2013) accounted for economic, environmental, and social issues in the design of cogeneration systems. Stijepovic and Linke (2011) proposed a systematic approach to the effective utilization of process heat in industrial zones. An algorithmic approach to the optimal design of cogeneration systems was developed by Al-Azri et al. (2009). The

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concept of extractable energy was introduced by El-Halwagi et al. (2009) to determine cogeneration targets when excess process heat is used. Mohan and El-Halwagi (2007) developed an algebraic approach for the targeting of cogeneration systems when fossil fuels and biomass are used as energy sources. Mavromatis and Kokossis (1998) optimized steam levels and utility systems used in combined heat and power. Klemeš et al. (1997) developed a targeting approach for the reduction of fuel, power, and CO_2 emissions in industrial facilities.

Invariably, most industrial energy systems employ fossil fuels. Recently, several research efforts have endeavored to incorporate the use of solar energy into industrial processes to enhance the sustainability of energy usage and to reduce the greenhouse gas (GHG) emissions associated with the extensive use of fossil fuels. Most power plants that use natural gas are reported to emit between 360 and 575 g CO_2-eq/kW h_e (Weisser, 2007). On the other hand, Lenzen (1999) estimated that thermal solar power-generation systems emit about 90 g CO_2-eq/kW h_e. Tora and El-Halwagi (2009, 2010, 2011) developed multi-period optimization approaches for the design of power generation, absorptive refrigeration, and trigeneration systems that employ a combination of solar and fossil energies. Parvareh et al. (2014) reviewed the research efforts in the area of integrating solar energy in coal-fired power plants and the use of post-combustion carbon capture.

Because of the intermittent nature of solar energy, it is beneficial to consider energy storage systems to store and dispatch energy depending on availability and demand. The key idea is to transfer heat to an intermediate medium which can later be used to transfer heat to the intended application through heat exchangers. Solar energy transformed to thermal energy may be stored in various forms such as pumped or compressed systems, electrochemical batteries, thermal-electric systems, flywheels, chemical systems, and thermal storage (e.g., Dincer, 1999). In addition to extended hours of operation, the use of thermal energy storage may offer economic benefits by trading off the cost of the solar-collector areas with the cost of thermal storage. Furthermore, environmental benefits may accrue as a result of using solar collectors and thermal storage in addition to fossil fuels. Thermal energy storage typically uses sensible or latent heat (e.g., Dincer, 2004). In the case of sensible-heat storage, elevation in temperature is used to store heat in media such as rocks, sand, oil, or water. Heat is collected by reducing the temperature of the storage medium to its initial temperature either directly through a heat exchanger or indirectly through a heat-transfer medium. Latent-heat storage involves phase change which can later be reversed to collect the stored heat. Pintaldi et al. (2015) and Kuravi et al. (2013) provided a review of thermal energy storage technologies for solar systems. Guédez et al. (2014) proposed an optimization approach for thermal storage systems for solar power plants. Lira-Barragán et al. (2014) developed an approach for thermal storage of solar energy for subsequent use in absorption refrigeration systems.

Notwithstanding the value of the aforementioned research contributions, they are limited by at least one of the following restrictions:

- Cogeneration systems are driven by fossil energy exclusively.
- Solar systems are not integrated with the processing facility (e.g., no integration with excess process heat).
- Solar energy is treated in a lump sum manner without accounting for its diurnal variability.
- Solar energy is used directly without thermal storage.

The purpose of this paper is to develop an optimization approach for the design of cogeneration system which integrates excess process heat, fossil fuels, and solar energy. A multi-period approach is used to discretize the operation and to account for the diurnal changes associated with solar energy. Thermal storage is used to aid in managing the dynamic variability. The approach is applied to a case study for an industrial process in the city of Jeddah in Saudi Arabia where actual solar data were collected, correlated, and employed in conjunction with excess process heat and fossil fuels.

2. Problem statement

Given an industrial process with known heating, cooling, and power demands, it is desired to develop a systematic approach for the optimum design and operation of heat integration, solar energy collection and co-usage with fossil fuels, thermal storage and dispatch, process cogeneration, and overall energy integration for the cost-effective conservation of energy and reduction of GHG emissions. Fig. 1 is a schematic representation of the problem addressed in the paper. The heating and cooling requirements for the process are to be integrated and the process is to be modified so as to minimize the external heating and cooling utility demands. The external utilities are to be provided by a combination of fossil fuels and solar energy. In spite of the diurnal variation of solar energy, it is necessary to provide a steady supply of energy to the process. This may be achieved by a time-based variation in fossil fuel usage such that the total sum of all energy supply is steady. Another alternative is to use time-based solar-energy storage and dispatch.

To solve the abovementioned problem, the following design questions should be addressed:

- What are minimum heating and cooling utility demands for the process and at what temperature levels are needed?
- How much and at what levels of temperature are the external heating utilities needed for the process?
- What is the optimal dynamic distribution of using fossil energy, excess process heat, and solar (direct and indirect) energy?
- How much steam should be fed to the turbine? At what temperature and pressures?
- What should be the outlet temperature and pressure of the steam leaving the turbine?

The next section describes an optimization approach that addresses the foregoing design challenges.

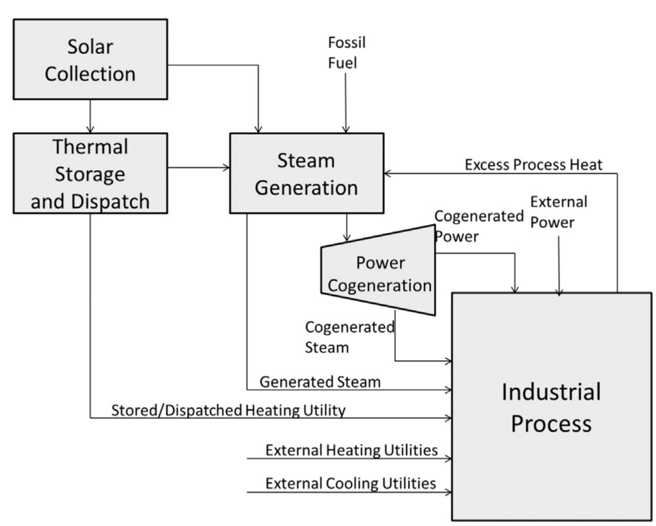

Fig. 1. Schematic representation of the problem statement.