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Research Paper

Uncertainty based operating strategy selection in combined heat and power systems

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HIGHLIGHTS

- The uncertainties in cost savings of combined heat & power (CHP) systems are evaluated.
- We use modular uncertainty analysis to compare the different operation strategies.
- Selecting the CHP operating strategies cannot always be clearly determined due to overlapping uncertainty bands.
- CHP operating strategies may be decided based on ease of implementation and operation.

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ABSTRACT

Combined heat and power (CHP) research has focused on optimizing the operation of CHP systems based on various criteria, such as cost savings, energy usage, or emissions. In literature, different operating strategies, such as base loading (BL), following electric load (FEL), and following thermal load (FTL), of a CHP system are typically compared and the best operation strategy selected based on the desired optimized parameter. To date, a literature survey indicates that the uncertainties associated with these calculations have not been considered in the operating strategy selection process. Therefore, this study considers the uncertainties in the cost savings associated with operating the CHP system under BL, FEL, and FTL operating strategies. Modular uncertainty analysis techniques are used to compare the uncertainties associated with the cost savings of the different operating modes. Results indicate that, due to overlapping uncertainty bands, the choice between different CHP operating strategies cannot always be clearly determined for power generation units with nominal sizes less than approximately 60% of the building's maximum electric load. In such cases, the choice between CHP operating strategies may be decided based on ease of implementation and operation.

1. Introduction

A building's heating and electrical needs are often met by purchasing fuel and purchasing electricity from the grid. A combined heat and power (CHP) system helps meet a building's heating and electrical needs by way of a power generation unit (PGU). PGU in a CHP system produces electricity that partially or completely offsets the amount of electricity that must be purchased from the grid to satisfy the building electric load. The heat generated by the PGU is used to partially or completely offset the amount of heat that must be supplied by the conventional heating system of the building. There are several operating strategies that can be used to control the operation of a CHP system. The most common operating strategies are base loading (BL), following the electrical load (FEL), and following the thermal load (FTL). The BL operating mode, as discussed by Smith et al. [1], consists of operating the PGU at a constant base load such that the PGU always produces a constant amount of heat and electricity that is used to offset the building's heating and electrical requirement. Any excess electricity that might be produced from a CHP operating under BL can be sold back to the grid to reduce the operating cost of the CHP system. However, selling excess electricity that is produced by the CHP system is not always an option available in every geographical location. The FEL operating mode consists in running the PGU such that it meets the building's electrical requirement. The heat that is produced by the PGU while operating under FEL is used to offset the building's heating requirement. On the other hand, the FTL operating mode consists of operating the PGU such that the heat generated by the PGU follows the instantaneous building's heating requirement. The electricity that is produced while operating under FTL is used to offset the building's electrical requirement. Just as in the case of the BL mode, any excess electricity that is produced when using a FTL mode may be sold back to the grid, if possible.

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The performance of CHP systems have been a popular topic of research, as can be seen in the works of Jannelli et al. [2], Kong et al. [3], Li et al. [4], Skorek-Osikowska et al. [5], Sun et al. [6], Toja-Silva and Rovira [7], Thorin et al. [8], and Sonar et al. [9]. Sonar et al. [9] conducted a review of micro-trigeneration CHP systems [9] and discusses the added benefits of CHP systems such as energy security, reducing environmental threats, and sustainability. Jannelli et al. [2] evaluated a small-sized combined cooling, heat, and power (CCHP) system using simulation techniques. They showed that the proposed CCHP system was rated on three system performance criteria: energy utilization factor (EUF), exergy utilization factor (ExUF), and trigeneration primary energy saving (TPES). The best performance was found when the cooling power demand was low. Kong et al. [3] experimentally investigated a micro-CCHP system driven by a gas engine. They found that the proposed system had combined thermal and electrical efficiencies over 70%. Li et al. [4] studied the utilization of energy sources for CCHP systems, and the fuel energy saving ratio (FESR) was compared for many configurations and sizes of CHP systems. Skorek-Osikowska et al. [5] investigated the effectiveness of using biomass gasification in CHP systems. They found that the economic viability depends on many factors. The price of green certificates and the price of fuel are factors that showed the most influence. They found that green certificate prices must be greater than 26.75 €/MWh and fuel prices lower than 9.62 €/GJ in order for CHP systems utilizing biomass gasification become economically feasible. Sun et al. [6] analyzed a CHP system consisting of an ejector heat exchangers and absorption heat pumps. They found that implementing such components decreased the amount of steam extracted from a steam turbine by 41.4% and increased the heat transmission capacity of the existing primary heating network by 66.7%. Toja-Silva and Rovira [7] studied the use of hydrogen-fueled microgas turbine for use in a CHP system. Their analysis showed that use of such a turbine resulted in an energy efficiency of 89.4% and an exergy efficiency of 45.7%. Thorin et al. [8] developed a method for long-term optimization of a CHP system using linear-programming and Lagrangian relaxation to maximize profit.

The CHP operating strategy selection has also been the point of focus by many researchers including Alipour et al. [10], Cardona and Piacentino [11], Fumo et al. [12,13], Jalalzadeh-Azar [14], Kang et al. [15], Knizley et al. [16], Mago et al. [17–19], Smith and Mago [20], Smith et al. [1], Sun et al. [21], Wang et al. [22], and Wu and Wang [23]. Cardona and Piacentino [11] conducted analyses of a pilot plant implementing a CHP system in different operating strategies. They found that implementing any type of operating mode for the CHP system would produce annual savings for their plant. Fumo et al. [13] studied the effects that CHP systems have on the primary energy consumption (PEC). They found that the CHP system studied increased the site energy consumption (SEC). Kang et al. [15] compared a CHP system to a combined cycle system using a 5 MW-class gas turbine fueled with biogas. The CHP system of their study showed higher economic benefits when compared to the combined cycle they studied. Wang et al. [22] conducted a study of a CHP system operating under FEL and FTL strategies in a simulated building in Beijing, China. They found that the FEL operating mode produces more benefits in the Winter than in the Summer when energy consumption and emissions were of concern. Mago et al. [17] conducted analyses of a CHP system implementing different operating strategies where operating cost and PGU emissions were studied. The study found that the only operating mode that reduced the operating cost and emissions was the FTL mode for all the locations studied; Boston, MA, San Francisco, CA, Columbus, MS, and Miami, FL. It was also found that the FEL mode reduced the operating cost for the city of San Francisco, CA. Mago et al. [19] conducted a study of a CHP system that takes advantage of using two PGUs implementing FEL and FTL. They compared a dual CHP (DCHP) system against a typical CHP system with one PGU implementing BL, FEL, and FTL strategies. Their study found that, for Atlanta, GA and San Francisco, CA, all operating strategies studied reduced operating cost and emissions. For the city of Duluth, MN, the study finds that a DCHP system implementing a FTL operating mode is the only operating mode that reduces both operating cost and emissions. For the city of Phoenix, AZ, the study finds that a CHP system operating a single PGU in a FTL operating mode is the only configuration that presents a operating cost reduction. They found the FEL mode applied to either a CHP or DCHP system was the only operating mode to reduce emissions. Jalalzadeh-Azar [14] investigated the overall system efficiency of a CHP system implementing both FEL and FTL on a monthly basis. He found that for the months of March through October, the overall system efficiency of the CHP system rises for both operating strategies. The highest overall system efficiency was found in the month of July and the lowest overall system efficiency in the month of November for both operating strategies. Smith and Mago [20] studied a CHP system implementing FEL and FTL along with a hybrid method. The hybrid method used either a FEL or FTL operating mode depending on the electrical and heating requirements of the building to minimize any excess electricity or heat that would have been generated by a CHP system implementing solely a FEL or FTL operating mode. They found that the hybrid method is more efficient than operating solely by FEL or FTL.

To date, a literature survey indicates that the uncertainties associated with a cost reduction analysis have not been considered in the operating strategy selection process. Therefore, the objective of this paper is to investigate the uncertainties associated with the cost savings that could be obtained for the different operating strategies including BL, FEL, and FTL. To achieve this, modular uncertainty analysis techniques are used to compare the uncertainties associated with the cost savings of the different operating strategies evaluated in this paper.

2. Analytical methods

2.1. CHP model

The CHP model presented in this section is adapted from Mago et al. [18]. The building and associated components consist of a typical Chicago, Illinois restaurant, a boiler, a power generation unit (PGU), a heat recovery system, and a heating coil. A schematic of the building and associated components can be found in Fig. 1. The building description can be found in Table 1. The electric and heat requirement of the building are generated by using EnergyPlus software [24]. EnergyPlus is a software package produced by the United States Department of Energy that simulates a building's energy usage based upon user input building parameters and historical weather data. The restaurant building used in this paper is part of the U.S. Department of Energy (DOE) commercial reference building data set [24] that may be found on the U.S. DOE website. The building's fuel usage, $\dot{F}_b$, can be found by

$$\dot{F}_b = \frac{\dot{Q}_b}{\eta_{boiler}\eta_{hc}} \quad (1)$$

The building's heating requirement, $\dot{Q}_b$, is supplied by the building's heating coil. The heating coil heat requirement, $\dot{Q}_{hc}$, is

$$\dot{Q}_{hc} = \frac{\dot{Q}_b}{\eta_{hc}} \quad (2)$$

The nominal PGU size, $\dot{E}_{nom}$, is expressed as a fraction of the building's maximum electrical load as follows.

$$\dot{E}_{nom} = \alpha max\left(\dot{E}_b\right) \quad (3)$$