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Analysis of a combined cooling, heating, and power system model under different operating strategies with input and model data uncertainty

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ABSTRACT

Combined cooling, heating, and power (CCHP) system models have been used by many researchers to compare their performance with conventional systems. However, decisions based on the results of computer simulations need to take into account the uncertainty of these results to get insight into the level of confidence in the predictions. This paper presents an analysis of a CCHP system model under different operating strategies with input and model data uncertainty. However, the uncertainties that underlie the variation in input parameters such as the thermal load, natural gas prices and electricity prices are not readily available. Additionally, engine performance uncertainty can be difficult to characterize because of the nonlinearity of engine efficiency curves. This paper presents practical and novel approaches to estimating the uncertainty in these and other input parameters. A case study using a small office building located in Atlanta, GA, is described to illustrate the importance of the use of uncertainty and sensitivity analysis in CCHP system performance predictions, and how the primary energy consumption, operational cost, and carbon dioxide emissions are affected by the uncertainty associated with the model input parameters.

1. Introduction

The term CCHP describes all electrical power generation systems that utilize recoverable waste heat for space heating, cooling, and domestic hot water purposes. In a typical CCHP system, electricity is generated on-site from the combustion of a fuel source in an electrical generation set (prime mover and generator). This combustion produces recoverable heat in the form of heated engine coolant and high temperature exhaust. The use of the recoverable thermal energy for space heating and cooling purposes is the driving factor behind the increased overall energy usage from conventional power generation systems. With this added benefit, approximately 80% of the energy put into a system can be used for either electrical power or heating and cooling purposes. A traditional power plant will generally only convert 30% of the system energy input to electrical energy. The other 70% may be released into the atmosphere as waste heat. In addition, CCHP systems have the advantage of increased energy reliability as compared to that of the traditional power plant.

Modeling of CCHP systems operating under different strategies has been evaluated by many researchers such as Moran et al. [1], Longo et al. [2], Bruno et al. [3], Sun and Guo [4], Malico et al. [5], Khan [6,7], Mago et al. [8], and Cho et al. [9]. In general, CCHP system models are used to determine the energy consumption, the cost of operation, the system efficiencies (electrical, thermal, and total), and in some cases the emissions generated. However, decisions based on the results of computer simulations need to take into account the uncertainty in the results. A quantitative uncertainty analysis uses currently available information to provide insight into the appropriate level of confidence in model simulation predictions. For problems where data are limited and where simplifying assumptions have been used, uncertainty analysis can be employed to help identify the strength of the conclusions that can be made about the model predictions [10]. Additionally, an uncertainty analysis can lead to the identification of the key sources of uncertainty, which merit further research, as well as the sources of uncertainty that are not important with respect to a given result. This identification of the key sources of uncertainty can help target data gathering efforts for improving the model.

The objective of the current study is to perform a detailed uncertainty analysis on simulation predictions of the performance parameters of the CCHP system model presented below. As in Mago et al. [8] and other studies, the CCHP system performance presented in this work is evaluated based on primary energy consumption, operational cost, and carbon dioxide emissions. Following the example of previous studies [8,9], two different operational strategies are employed and analyzed: following the electric load (FEL) and following the thermal load (FTL). A benchmark building

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Nomenclature

b	intercept for the engine fuel/power linear relationship
$Cost$	cost
COP_{ch}	coefficient of performance
E	electricity
E_m	electricity registered at the meter
F_m	natural gas registered at the meter
F	fuel energy input
m	slope for the engine fuel/power linear relationship
$E_{\mathrm{PGU\_nom}}$	nominal (rated) engine power output
$E_{\mathrm{PGU\_min}}$	minimum engine power output
Q	thermal load
Q_{REQ}	required thermal energy from engine or boiler
Q_{REC}	recovered thermal energy from the engine
Q_{REC_min}	recovered heat from engine at minimum power output
Q_{REC_nom}	recovered heat from the engine at nominal (rated) power output
s_{pgu}	engine performance factor efficiency
η_{hc}	heating coil efficiency
η_{rec}	recovery system efficiency
η_b	boiler efficiency
U_i	uncertainty in parameter i
C_{tl}	thermal load factor covariance matrix

Subscripts

b	boiler
c	cooling
ELE	electricity
$grid$	electricity imported from the grid
h	heating
NG	natural gas
pgu	power generation unit

located in Atlanta, GA, is used as a case study for performing the analysis.

An integral part of uncertainty analysis is the definition of the input uncertainties. This paper presents novel approaches to estimating the uncertainty in several of the input parameters. The uncertainty that underlies the variation of the thermal load, for example, is expected to be an important factor contributing to the overall uncertainty, and previous studies have not given a full and adequate characterization of the factors that contribute to these uncertainties. The variation in the weather conditions is the main source of uncertainty in the thermal load. Macdonald and Strachan [11] accounted for uncertainties in the weather conditions by using a fixed uncertainty range for basic weather parameters (e.g. temperature, radiation, wind speed, etc.). Corrado and Mechri [12] used a similar approach except only monthly averages of a few weather parameters (e.g. temperature, solar radiation, and wind speed) are used. However, since the amount of variation in weather conditions that can be expected is not constant throughout the year, this method does not adequately characterize the uncertainty in the thermal load. Additionally, these studies greatly over simplify the problem since many relevant weather parameters are ignored and the interactions between the factors are not considered. In the current study, a practical approach is presented for estimating the uncertainty in the thermal load.

Other key input parameters whose uncertainty is difficult to characterize are the engine performance, the cost of electricity purchased from the grid, and the cost of natural gas. For example, engine performance uncertainty can be difficult to characterize because of the nonlinearity of engine efficiency curves. Therefore, a practical approach to estimating the uncertainty in engine performance is presented in the current study. Additionally, Houwing et al. [13] have presented uncertainties in energy prices that result from implementation of CHP systems. For example, they consider uncertainty in factors such as energy provider policy and government policy (e.g. taxes and tariffs). However, these factors are hard to characterize a priori and require extensive knowledge of the policies that apply to specific areas. This approach is difficult to implement in the modeling process and the assumptions required are extensive. Therefore, a more pragmatic approach is presented for estimating the uncertainty in the cost of electricity, and the cost of natural gas.

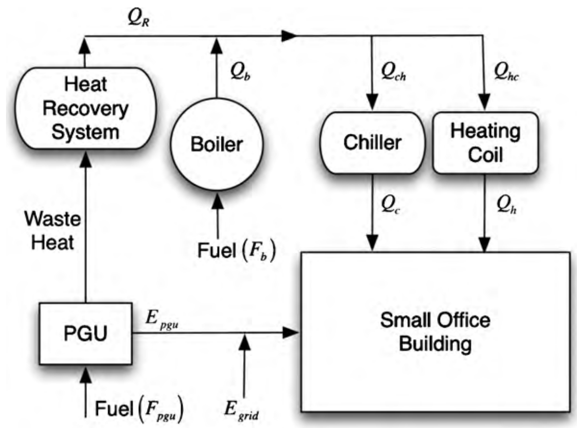

Fig. 1. Schematic of a CCHP system.

2. Analysis

The CCHP system performance is evaluated according to three factors: primary energy consumption, cost, and carbon dioxide emissions. To study and evaluate the performance of CCHP systems operating under different strategies, thermodynamic models of the different components have been developed. Although the analysis of simplified thermodynamic models generally leads only to qualitative conclusions about the system performance, these models allow the evaluation of how changes in operating parameters affect the actual system performance. A schematic of the CCHP system analyzed in this paper is shown in Fig. 1. The building model, energy loads, and basic modeling equations that are used to model the system are defined in Section 2.1. The fuel and electricity requirements for the electric and thermal load following strategies are presented in Sections 2.2 and 2.3, respectively. The ultimate goal in these sections is to define the fuel and grid electricity needs so that the three performance factors listed above can be used to evaluate the two operation strategies.

2.1. Building model, energy loads, and basic CCHP system model equations

The U.S. Department of Energy has developed several commercial building benchmark models. These building models provide standard values of parameters such as floor area, occupancy schedule, equipment and lighting schedule and thermostat schedule for different building types and locations. The main benefit of the standardized benchmark models is that they form a common point of comparison between research projects [14]. The current study focuses on a new small office benchmark building with a 511 m^2 floor area that is located in Atlanta, GA. The air distribution is a single zone constant volume. The reference building was simulated using the software, EnergyPlus [15], to obtain hourly site energy load data.