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Effects of load-following operational methods on combined heat and power system efficiency

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HIGHLIGHTS

- We presented a hybrid method for operating CHP systems.
- The hybrid method either follows the facility thermal or the electric demand.
- Excess CHP system electrical or thermal energy is minimized with this method.
- We implemented the method for a large hotel building in 16 cities.
- The hybrid method results in a higher total CHP system efficiency.

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ABSTRACT

Combined heat and power (CHP) systems can be operated in partial loading situations when the maximum electrical and thermal output of the prime mover is not constantly required by the facility. Two basic load-following methods following the thermal load (FTL) and following the electric load (FEL), are compared with a hybrid method which either follows the thermal or the electric demand in a given time period, within a specified operating range, in order to minimize the amount of excess electrical or thermal energy produced by the CHP system. These methods are implemented on an hour by hour basis for a large hotel benchmark building which is modeled in 16 cities located in different climate zones using EnergyPlus building simulation software. The hybrid method results in a higher total CHP system efficiency than either the FTL or FEL methods, with CHP system efficiency values from 71% to 87%. The power-to-heat ratio of the building (PHR_b), which describes the relationship between electrical and thermal demand for the given facility, is found to predict the maximum possible CHP system efficiency using the hybrid method on an hourly basis. Buildings with lower PHR_b values, corresponding to higher relative thermal demands, have the highest possible CHP system efficiency values. The hybrid operational method is also implemented on a monthly basis, where the building's average monthly demands are used to set the operating condition of the prime mover for the entire month. The building is then simulated on an hour by hour basis to determine the system's performance with only monthly changes in the loading conditions. This monthly method produces similar results to the hybrid method when it is implemented on an hourly basis, with CHP system efficiency values from 74% to 86%.

1. Introduction

CHP systems, also known as cogeneration systems, provide both electricity and useful thermal energy from a single fuel source. By producing electricity near the site of use and capturing some of the heat produced from power generation which would otherwise be rejected, a CHP system can be an efficient way to meet a facility's energy needs. The facility receives electrical power and space heating or hot water heating, along with potential benefits such as reduced energy costs, increased power reliability, and reduced emissions associated with energy conversion. In the United States, 87% of CHP systems are located at industrial facilities, but the US Department of Energy [1] estimates the technical potential for new commercial and institutional facilities at 65 GW, including commercial buildings, multifamily residential buildings, hotels, hospitals, and university campuses. Industrial facilities typically have consistent loads over time, while commercial and residential buildings have loads which fluctuate seasonally, daily, and on short time scales (hourly or less). Therefore, prime mover sizing and selection of an appropriate operational strategy are critical for obtaining benefits from a CHP system [2,3]. One option is to size

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Nomenclature

CHP	combined heat and power
E_{grid}	electricity purchased from the grid
E_{max}	maximum electrical load for the PGU
E_{min}	minimum electrical load for the PGU
E_m	net electricity purchased from the grid, Egrid less any electricity exported
$E_{pgu,nom}$	rated capacity of the PGU
E_{pgu}	electricity generated by the PGU
$E_{pgu,opt}$	electricity produced when the PGU operates to meet a given thermal load
E_{req}	electricity required by the facility
FEL	following the electric load
FTL	following the thermal load
F_{boiler}	fuel consumed by the boiler
F_m	fuel purchased for both the CHP system and the building' boiler
F_{pgu}	fuel consumed by the PGU
OC	operating condition describing the loading condition of the PGU at a given time
OM	operational method used to determine PGU loading at each time step
PGU	power generation unit
Q_{boiler}	heat produced by the boiler
Q_{min}	heat recovered when PGU operates at E_{min}
Q_{req}	heat required to be supplied by the CHP system
Q_{pgu}	heat energy available from the PGU which was not converted to electricity
$Q_{rec,opt}$	heat recovered when the PGU operates to meet a given electrical load
Q_{rec}	heat recovered from the PGU
R_e	fraction of the total electric load, E_{req}, that is supplied by the CHP system
R_h	fraction of the total thermal load, Q_{req}, that is supplied by the CHP system
η_{chp}	CHP total system efficiency
η_{hc}	efficiency of the heating coil of the building's boiler
η_{hrs}	CHP heat recovery system efficiency
η_{pgu}	electrical efficiency of the PGU
ξ	factor that accounts for losses before thermal energy reaches the heat recovery system

the CHP system for constant base load operation, but this limits the system's ability to respond to building demand and may limit the CHP system to providing a small percentage of the building's energy needs. Balance between the power to heat ratio of the PGU and the power to heat ratio of the building results in more favorable performance for a CHP system [4]. Partial load operation allows for system flexibility but introduces the problem of less efficient system operations [5], with transient periods having an additional negative impact on system efficiencies [6]. A more efficient CHP system has better potential to provide cost savings, reduced emissions, and reduced energy consumption over separate heating and power [7,8].

The sizing and operational method are critical factors for making the best use of the fuel energy input. Commonly investigated operational strategies include following the thermal load (FTL), also known as heat-led strategy or thermal demand management, and following the electric load (FEL), also known as electricity-led strategy or electrical demand management [9–11]. Yun et al. [12] showed that cost-optimized CHP system operation results in one of these strategies out of all possible loading conditions. Mago et al. [13] previously introduced a hybrid load-following method for combined cooling, heating and power (CCHP) systems which switches between FTL and FEL as needed to reduce operating costs, emissions, and primary energy consumption.

The energy-saving and cost-saving potential of a CHP system is sensitive to the local climate, which determines the number of heating-degree days and therefore affects the thermal demand of a given facility. In general, cold climates tend to show more advantages for CHP system installations than hot climates [14–17], with the greatest potential cost reductions during the colder seasons where heating demand is high [18]. Previous work has also demonstrated that other important factors for determining CHP system performance include: the percentage of recovered heat used and the percentages of the building's electrical and thermal needs met by the CHP system [19], and the power to heat ratio, or load ratio, of the facility [10,20].

This paper presents a method for using the modeled demand loads (electrical and thermal) of a large commercial building, along with information relating the fuel consumption to the electrical output of the prime mover, to assess the efficiency of the power generation unit (PGU) and of the CHP system when using a given operational strategy. For this paper, FTL and FEL methods were analyzed along with a hybrid method which aims to generally reduce the amount of excess energy produced (whether electrical or thermal) while allowing use of the CHP system whenever reasonably possible. This method is described and implemented using computer simulations along with the strict FEL and FTL methods. The partial loading situations can be advantageous when the maximum electrical and thermal output from the prime mover is not constantly required by the facility. The effects on efficiency of the CHP system are investigated.

Next, this operational method is employed based on monthly data, so that the operation of the prime mover is adjusted only once per month. This simple method is then simulated for the hotel building using hourly demand data in order to compare the performance results against the hourly-adjusted operational method. The selection of an operational method based on only the monthly demand data provides additional benefits in addition to energy efficiency potential. Ebrahimi and Keshavarz [20], in a recent study on prime mover sizing for CCHP, found that it was impractical to use a monthly hybrid operational method for residential building applications due to difficulties with prime mover sizing and reduced efficiencies associated with partial loading conditions. However, it is demonstrated here that for a large commercial building, an engine which has a nominal power output below the average power demand for the building can be operated at partial capacity for 9 or more months of the year, resulting in system efficiency values of 74% or greater for the year, depending on the local heating demand. Rezvan et al. [21] found that for a simulated CCHP system serving a hospital in Tehran, Iran, increasing uncertainty in hourly building demand loads would reduce the optimal selection of CHP capacity and increase operating costs. The monthly implementation of the hybrid method proposed in this paper reduces the impact of hour-to-hour load uncertainty on the selection of operational method for the prime mover. Verda and Baccino [22] found that for a natural gas microturbine power system, the control system affected the efficiency performance of the prime mover and the operational costs, particularly in transient operation. The