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Analysis and optimization of CCHP systems based on energy, economical, and environmental considerations

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ABSTRACT

Analysis of combined cooling, heating, and power (CCHP) systems is frequently based on reduction of operating cost without measuring the actual energy use and emissions reduction. CCHP systems can be optimized based on different optimization criterion such as: energy savings, operation cost reduction or minimum environmental impact. In this study, CCHP systems operated following the electric load (FEL) and the thermal load (FTL) strategies are evaluated and optimized based on: primary energy consumption (PEC), operation cost, and carbon dioxide emissions (CDE). This study also includes the analysis and evaluation of an optimized operational strategy in which a CCHP system follows a hybrid electric–thermal load (HETS) during its operation. Results show that CCHP systems operating using any of the optimization criteria have better performance than CCHP systems operating without any optimization criteria. For the evaluated city, the optimum PEC and cost reduction are 7.5% and 4.4%, respectively, for CCHP-FTL, while the optimum CDE reduction is 14.8% for CCHP-FEL. Results also show that the HETS is a good alternative for CCHP systems operation since it gives good reduction of PEC, cost, and CDE. This optimized operation strategy provides a good balance among all the variables considered in this paper.

1. Introduction

The term CCHP (combined cooling, heating, and power) describes all electrical power generation systems that utilize recoverable waste heat for space heating, cooling, and domestic hot water purposes. The main difference between CCHP systems and the typical methods of electric generation is the utilization of the waste heat rejected from the prime mover in order to satisfy the thermal demand of a facility (cooling, heating, or hot water needs). One of the most basic goals of CCHP systems is to ensure that it is a more attractive option than traditional power supply. The end goals of CCHP systems are to ensure reduction of primary energy, cost, emissions, or a combination of all of them. To achieve these goals, CCHP are usually operated using two basic strategies: following the electric load (FEL) and following the thermal load (FTL). However, in addition to the operation strategies it is necessary to apply optimization criteria to guarantee the benefits of CCHP systems over conventional technologies. The CCHP operation strategy will dictate the loading and fuel consumption of the prime mover and thus the energy consumption profile of the CCHP system. In the case of FEL operation strategy, the prime mover is loaded in order to satisfy the electric demand of the facility through the generator that is part of the power generation set. The waste heat from this loading is then recovered in order to satisfy the thermal load of the facility. For this operation strategy, if the recovered thermal energy is not enough to handle the thermal load (cooling or heating) of the facility, additional heat has to be provided by the auxiliary boiler of the CCHP system. For FTL strategy, the prime mover is loaded such that the recovered waste heat will be adequate to supply the facility with the necessary thermal energy to satisfy the heating and cooling requirements. For this operation strategy the amount of electricity produced may or may not be enough to provide the electricity required by the building. Therefore, if the electricity produced is not enough to handle the electric load additional electricity has to be imported from the grid. Some researchers such as Cardona and Piacentino [1,2], Jalalzadeh-Azar [3], and Mago et al. [4] among others have investigated the operation of CCHP systems under these two operation strategies. Cardona and Piacentino [1] refer to these two styles as electric demand management (EDM) and thermal demand management (TDM) strategies. The choice between EDM and TDM is usually governed by the loading of the prime mover as well as a few extraneous circumstances including the ability to sell back electricity to the grid or store it on site for later use via some battery system. In addition, the price of fuel versus that of electricity purchased from a traditional source can affect the

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Nomenclature

CDE	carbon dioxide emissions reduction (tons)
CCHP	combined cooling, heating and power
CHP	combined heating and power
COP	coefficient of performance
Cost	cost ($ or $/kWh)
E	electric energy (kWh)
ECF_{CDE}	emission conversion factor for electricity (tons/year-kWh)
ECF_{PEC}	site-to-primary energy conversion factor for electricity
E_m	electric energy registered at the meter (kWh)
E_{pgu}	PGU electricity (kWh)
F_m	fuel energy registered at the meter (kWh)
F_{pgu}	PGU fuel energy consumption (kWh)
F_{boiler}	boiler fuel energy consumption (kWh)
FEL	following the electric load
FTL	following the thermal load
FCF_{CDE}	emission conversion factor for fuel (tons/year-kWh)
FCF_{PEC}	site-to-primary energy conversion factor for fuel
HETS	hybrid electric–thermal load operation
PFI	performance factor indicator
PEC	primary energy consumption (kWh)
PGU	power generation unit
Q_{boiler}	heat that has to be provided by the boiler (kWh)
Q_R	recovered waste heat (kWh)
Q_{ch}	heat required by the absorption chiller to handle the cooling load (kWh)
Q_c	building cooling load (kWh)
Q_{hc}	heat required to handle the heating load (kWh)
Q_h	building heating load (kWh)

Symbols

η	efficiency level, ratio between useful output and input amount

Subscripts

boiler	boiler
building	building
ch	absorption Chiller
conventional	reference building
electricity	electricity
excess	excess electricity
fuel	fuel
grid	electricity required from the grid
hc	heating coil
pgu	power generation unit
rec	recovered heat
req	required

management of a plant [2]. Jalalzadeh-Azar [3] performed a non-dimensional analysis of energy cost and primary energy consumption of CCHP systems utilizing a gas fired micro-turbine in three varying climates. In his analysis, the two main operational strategies were evaluated in the three differing climes. The results yielded an 11% reduction in total energy consumption when the CCHP operates FTL versus that of FEL. Mago et al. [4] studied the performance of CCHP and CHP (combined heating and power) systems operating FEL and FTL, based on primary energy consumption, operation cost, and emissions for different climate conditions. Their results showed that CCHP and CHP systems operated FTL reduce the PEC for all the evaluated cities. On the other hand, CHP systems operated FEL always increases the PEC. In their study, the only operation mode that reduces PEC and CDE while reducing the cost is CHP-FTL.

The operational strategy of a CCHP system can be described as overriding management philosophies used to determine the manner in which a CCHP facility operates. The CCHP strategy used strongly depends on the specific goal to be obtained from the CCHP operation. However, in addition to the operational strategies, optimization techniques have to be employed to guarantee the lowest cost of operation, reduction of the PEC, and/or reduction of CDE. It is also possible for the goal behind an operating strategy to be a combination of the above listed goals with a balance being sought between two or more. Several researchers have investigated different optimized operational strategies for CCHP systems. Some of them are: Cardona and Piacentino [5], Li et al. [6], Chicco and Mancarella [7], Sun et al. [8], Zogg et al. [9], and Fumo et al. [10]. Cardona and Piacentino [5] investigated a strategy to ensure primary energy savings (PES). They found that the operation of a CCHP plant under this PES strategy allowed the engine to run at full load for almost 2800 h per year thus increasing thermal energy produced. This increase in thermal energy production falls in line with the benefits of increased thermal production outlined by Moran et al. [11]. Li et al. [6] used a technique called fuel energy savings ratio (FESR) which gives the ratio of primary energy consumption of a CCHP system versus the separate production case. They reported that the heating and power mode is very efficient when evaluated with FESR while the cooling and power mode is usually a loss comparing to separate production using FESR. This point emphasizes the need to operate under a proper management strategy in order to ensure the best possible energy efficiency at all times during CCHP operation. Chicco and Mancarella [7] further the evaluation method of primary energy and applied it specifically to trigeneration. They introduced a new performance assessing indicator, called trigeneration primary energy saving (TPES). This indicator evaluates the fuel energy savings obtained in a trigeneration plant as compared with separate, conventional production. Using this indicator, it was determined that nearly 70% rate of energy savings can be obtained with the use of trigeneration. Sun et al. [8] utilized a primary energy rate (PER) to compare the energetic efficiency of a combined system for cooling and heating to that of separate production. They defined the PER as the ratio of required output to primary energy demand where a higher PER is more favorable. Their analysis points to the possibility of 35% greater efficiency than a separate production case. Zogg et al. [9] found that CCHP has the ability to achieve primary energy savings in two ways. First, if the CCHP system generates electricity at an efficiency higher than the grid and secondly, if the CCHP system cannot generate electricity at an efficiency better than the grid then energy savings depend upon the extent to which waste heat can be used to supply space heating and/or space cooling. Fumo at el. [10] introduced the definition of building primary energy ratio (BPER) as a parameter to evaluate CCHP energy performance. The BPER measured the variation of the building primary energy when the building is operated without a CCHP system versus the building primary energy when a CCHP system is used. Their results showed that using the thermal efficiency alone is not the best approach to describe CCHP system energy performance and that using the BPER provides a more comprehensive CCHP evaluation.

As a result of the worldwide concern about global warming, consideration of greenhouse gas emissions has gained a lot of interest in the analysis of energy systems. Several researchers have