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# Evaluation of the performance of combined cooling, heating, and power systems with dual power generation units

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## HIGHLIGHTS

- We investigate benefits from using combined cooling, heating, and power systems.
- A dual power generation unit configuration is considered for CCHP and CHP.
- Spark spreads for cost, energy, and emissions correlate with potential savings.
- Thermal difference parameter helps to explain variations in potential savings.
- Carbon credits may increase cost savings where emissions savings are possible.

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## ABSTRACT

The benefits of using a combined cooling, heating, and power system with dual power generation units (D-CCHP) is examined in nine different U.S. locations. One power generation unit (PGU) is operated at base load while the other is operated following the electric load. The waste heat from both PGUs is used for heating and for cooling via an absorption chiller. The D-CCHP configuration is studied for a restaurant benchmark building, and its performance is quantified in terms of operational cost, primary energy consumption (PEC), and carbon dioxide emissions (CDE). Cost spark spread, PEC spark spread, and CDE spark spread are examined as performance indicators for the D-CCHP system. D-CCHP system performance correlates well with spark spreads, with higher spark spreads signifying greater savings through implementation of a D-CCHP system. A new parameter, thermal difference, is introduced to investigate the relative performance of a D-CCHP system compared to a dual PGU combined heat and power system (D-CHP). Thermal difference, together with spark spread, can explain the variation in savings of a D-CCHP system over a D-CHP system for each location. The effect of carbon credits on operational cost savings with respect to the reference case is shown for selected locations.

## 1. Introduction

Combined heat and power (CHP), or cogeneration, and combined cooling, heating, and power (CCHP), or trigeneration, systems are used to produce electricity on-site while making use of waste heat expelled from the power generation unit (PGU). The waste heat recovered from the PGU can be used to help meet building thermal demands. Typically, CHP and CCHP systems employ a single PGU operating in one of three modes: following the electric load (FEL), following the thermal load (FTL), or base-loaded (BL). Comprehensive reviews of CHP and CCHP systems have been prepared by Mago et al. (2009), Al-Sulaiman et al. (2011), and Wu and Wang (2006). Recently, Knizley and Mago (2012a, 2012b) proposed a CHP configuration where two PGUs operate simultaneously (D-CHP), with one PGU delivering power at a constant base load and the other PGU operated FEL. CHP and CCHP systems provide a potential for cost, primary energy consumption (PEC), and emissions savings over a traditional separate heating and power (SHP) configuration. Cho et al. (2009) examine CCHP systems on the bases of operating cost, PEC, and carbon dioxide emissions (CDE), using minimization functions to optimize the system operation based on each parameter. They determined that each optimization mode presents independent results. In other words, optimizing the CCHP system on the basis of cost minimization does not imply that PEC or CDE will also be minimized. Fumo and Chamra (2010) studied a CCHP system on the basis of PEC to define CCHP system operation conditions that can guarantee PEC savings. They determined that PEC savings cannot be guaranteed at all times, but that an analysis based on PEC can help

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**Nomenclature**

| | |
|---|---|
| CHP | combined heat and power |
| CCHP | combined cooling, heating, and power |
| PGU | power generation unit |
| FEL | following the electric load |
| FTL | following the thermal load |
| BL | base-loaded |
| D-CHP | dual-PGU CHP system configuration |
| SHP | separate heating and power |
| PEC | primary energy consumption |
| CDE | carbon dioxide emissions |
| HETS | hybrid electric-thermal load |
| D-CCHP | dual-PGU CCHP system configurations |
| $Q_b$ | building heating demand (hourly) |
| $E_b$ | building electric demand, CCHP (hourly) |
| $E_{\text{fac}}$ | facility electric demand, SHP (hourly) |
| $E_{\text{cool}}$ | cooling electric demand (hourly) |
| $Q_{\text{cool}}$ | cooling thermal demand (hourly) |
| $F_{\text{fac}}$ | facility fuel energy requirement (hourly) |
| $\eta_h$ | heating system efficiency, SHP |
| $\text{COP}_{\text{vc}}$ | vapor compression system coefficient of performance, SHP |
| $Q_{\text{req}}$ | thermal load required to meet building demand, CCHP |
| $Q_{\text{req,heat}}$ | thermal load required to meet building heating demand, CCHP |
| $Q_{\text{req,cool}}$ | thermal load required to meet building cooling demand, CCHP |
| $\eta_{h,\text{CCHP}}$ | efficiency of heating coil, CCHP |
| $\text{COP}_{\text{chill}}$ | chiller coefficient of performance, CCHP |
| $E_{\text{pgu1}}$, $E_{\text{pgu2}}$ | respective electrical energy output of PGU1 and PGU2 |
| $E_{\text{pgus}}$ | combined electrical output from both PGUs |
| $Q_{\text{rec,pgu1}}$ | heat recovered from PGU1 |
| $Q_{\text{rec,pgu2}}$ | heat recovered from PGU2 |
| $Q_{\text{rec}}$ | total heat recovered from combined PGUs |
| $Q_{\text{boiler}}$ | auxiliary heat provided by boiler |
| $E_{\text{grid}}$ | auxiliary electricity provided by grid |
| $\eta_{\text{pgu1}}$, $\eta_{\text{pgu2}}$ | respective efficiencies of PGU1 and PGU2 |
| $F_{\text{pgu1}}$, $F_{\text{pgu2}}$ | respective fuel energy requirement of PGU1 and PGU2 |
| $E^{\max}_{\text{pgu2}}$ | maximum electrical energy output capability of PGU2 |
| $E^{\min}_{\text{pgu2}}$ | minimum electrical energy output for PGU2 to operate |
| $Q^{\max}_{\text{rec,pgu1}}$ | maximum heat that can be recovered from PGU1 |
| $Q^{\max}_{\text{rec,pgu2}}$ | maximum heat that can be recovered from PGU2 |
| $\xi$ | PGU energy loss factor |
| $\eta_{\text{hrs}}$ | efficiency of heat recovery system |
| $F_{\text{boiler}}$ | fuel needed to operate boiler |
| $\eta_{\text{boiler}}$ | boiler efficiency |
| $F_{\text{pgus}}$ | combined fuel energy requirement from both PGUs |
| $F_m$ | metered fuel consumption |
| $E_m$ | metered electrical energy |
| $\text{Cost}_e$ | cost of electricity ($/kW h) |
| $\text{Cost}_f$ | cost of fuel ($/kW h) |
| $\text{PECF}_e$ | primary energy conversion factor (electricity) |
| $\text{PECF}_f$ | primary energy conversion factor (fuel) |
| $\text{CDEF}_e$ | carbon dioxide emissions factor (electricity) |
| $\text{CDEF}_f$ | carbon dioxide emissions factor (fuel) |
| $OpCost_{\text{DCCHP}}$ | operational cost of D-CCHP system |
| $OpCost_{\text{ref}}$ | operational cost of SHP system |
| $\text{PEC}_{\text{DCCHP}}$ | PEC of D-CCHP system |
| $\text{PEC}_{\text{ref}}$ | PEC of SHP system |
| $\text{CDE}_{\text{DCCHP}}$ | CDE of D-CCHP system |
| $\text{CDE}_{\text{ref}}$ | CDE of SHP system |
| $\Delta\text{CDE}$ | CDE difference between SHP and D-CCHP |
| $OpCost^{\text{CC}}_{\text{DCCHP}}$ | operational cost of D-CCHP system with carbon credits considered |
| $OpCost_{\text{savings}}$ | operational cost savings of D-CCHP over SHP |
| $\text{PEC}_{\text{savings}}$ | PEC savings of D-CCHP over SHP |
| $\text{CDE}_{\text{savings}}$ | CDE savings of D-CCHP over SHP |
| $Q_{\text{thermal}}$ | total thermal load required for building, CCHP |
| $R_{\text{cool}}$ | ratio of cooling load to total thermal requirement, CCHP |
| $R_{\text{heat}}$ | ratio of heating load to total thermal requirement, CCHP |
| $TD$ | thermal difference |

determine operational strategies that yield the smallest amount of undesired PEC. From these authors, we note that, even if a CCHP system does not prove beneficial in terms of operational cost savings, it can still be worthwhile to examine the system with regard to PEC savings and CDE savings.

Kong et al. (2004) also explored the economic impact of a CCHP configuration in which the PGU is considered to be a Stirling engine. They focused on energy savings and economic feasibility in terms of cost and payback to conclude that the natural gas-based Stirling engine-driven CCHP system can save more than 33% of PEC as compared to a conventional, SHP system. They also noted that the performance of the chiller used in CCHP has a significant impact on the energetic efficiency of the CCHP system. Finally, they concluded that the price of natural gas, used to fuel the Stirling engine, was an important parameter influencing the economic performance of the CCHP system.

Several authors have analyzed CCHP and CHP systems operational strategies (Mago et al., 2009; Mago and Chamra, 2009; Espirito Santo, 2012; Fang et al., 2012a, 2012b; Wang et al., 2011; Smith et al., 2010; Liu et al., 2012; Jalalzadeh-Azar, 2004). Mago et al. (2009) compared CHP and CCHP systems operated FEL and FTL on the bases of PEC, operating cost, and CDE. For systems operated FEL, they determined that CCHP reduced the PEC, operating cost, and CDE compared to the CHP configuration for the four locations examined. The CCHP system also outperformed the CHP system for most cases when operated FTL. In another study, Mago and Chamra (2009) looked at CCHP systems operated FEL and FTL to evaluate and optimize each strategy in terms of PEC, operating cost, and CDE. Additionally, they introduced a hybrid electric-thermal load operational scheme (HETS). They determined that optimization based on PEC was most favorable for the location examined and that HETS can be a viable alternative to a CCHP system operating FEL or FTL. Espirito Santo (2012) evaluated the performance of an IC engine-driven CCHP system on the basis of energy utilization factor, exergetic efficiency, and PEC savings for two different operational strategies. They found that the energy utilization factor can be between 65% and 81% for the given strategies, with efficiencies between 35% and 38.4%. Fang et al. (2012a, 2012b) proposed an integrated performance criterion to optimize CCHP operational strategies FEL or FTL on the bases of PEC, operating cost, and CDE. Wang et al. (2011) compared CCHP systems operating FEL and FTL against a SHP system on the bases of PEC savings, exergetic efficiencies, and CDE reduction. They determined that cooling load to electric demand and heating load to electric demand ratios can be indicative of CCHP performance. Smith et al. (2010) included model data uncertainty in the analysis of different CCHP operating strategies. They concluded that both FEL and FTL operations have minimal CDE and PEC uncertainties, with no uncertainty specified corresponding to CDE and PEC uncertainties, but that uncertainty involved in operating cost

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