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MECHANICAL ENGINEERING | RESEARCH ARTICLE

Evaluation of the operational cost savings potential from a D-CHP system based on a monthly power-to-heat ratio analysis

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Abstract: This paper focuses on the analysis of a combined heat and power (CHP) system utilizing two power generation units operating simultaneously under differing operational strategies (D-CHP) on the basis of operational cost savings. A cost optimization metric, based on the facility monthly power-to-heat ratio (PHR), is presented in this paper. The PHR is defined as the ratio between the facility electric load and thermal load. Previous work in this field has suggested that D-CHP system performance may be improved by limiting operation of the system to months in which the PHR is relatively low. The focus of this paper is to illustrate how the facility PHR parameter could be used to establish the potential of a D-CHP system to reduce operational cost with respect to traditional CHP systems and conventional systems with separate heating and power. This paper analyzes the relationship between the PHR and the operational cost savings of eight different benchmark buildings. Achieving operational cost savings through optimal operation based on monthly PHR for these building types can enhance the implementation potential of D-CHP and CHP systems. Results indicate that the PHR parameter can be used to predict the potential for a D-CHP system to reduce the operational cost.

Subjects: Engineering Economics; Power & Energy; Renewable Energy; Energy & Fuels

Keywords: CHP; emissions reduction; dual CHP; energy sustainability

ABOUT THE AUTHORS

Alta Knizley is an instructor in the Mechanical Engineering Department at Mississippi State University (MSU) and James Tobermann is a recent graduate of the Mechanical Engineering Department at MSU who worked as an undergraduate researcher with the Micro-CHP and Biofuel Center at MSU. Pedro J. Mago is the Department Head and PACCAR Chair Professor for the Mechanical Engineering Department at MSU and Director of the Micro-CHP and Biofuel Center. This research group focuses on novel practices for sustainable, energy-efficient power generation strategies, and combined heat and power (CHP) optimization. The research reported in this paper can be utilized by industry and business owners to determine the viability of adopting a natural gas-fueled D-CHP implementation to reduce grid dependency while utilizing a widely available fuel source.

PUBLIC INTEREST STATEMENT

Combined heat and power (CHP) systems save energy by recovering waste heat from a power generation unit (PGU) and utilizing this heat to satisfy facility loads. CHP systems often increase the efficiency of energy production and lead to lower operational costs and carbon dioxide emission compared to separate heating and power (SHP). CHP systems can thus decrease grid dependency and provide a sustainable energy alternative to conventional SHP systems. This paper explores the cost saving potential of a CHP system with dual PGUs (D-CHP) with respect to an SHP system for various benchmark buildings. The authors find the potential of the D-CHP system to achieve cost savings is strongly linked to the monthly power-to-heat ratio (PHR). PHR is defined as the ratio of facility electrical demand to the facility heating demand. If the monthly PHR is below 3.0, the CHP system is highly likely to provide cost savings.

1. Introduction

Combined heat and power (CHP) systems utilize a power generation unit (PGU) to provide on-site electrical power while recovering waste heat from the PGU to satisfy the facility heating demand. CHP systems can be used to increase energy production efficiency and to provide a sustainable energy alternative through lowering grid dependency, often while achieving cost savings (Akorede, Hizam, & Pouresmaeil, 2010; Çakir, Çomakli, & Yüksel, 2012; Mago, Chamra, & Hueffed, 2009; Rosen, Le, & Dincer, 2005; Sun, 2008).

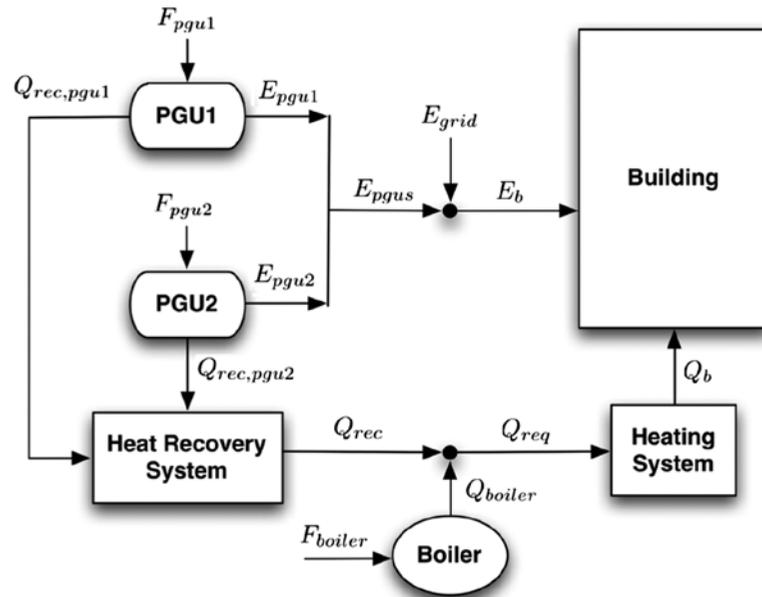
Typical operational strategies for CHP systems include following the electric load (FEL), following the thermal load (FTL), and base-loading (BL) (Cardona, Piacentino, & Cardona, 2006; Chicco & Mancarella, 2006; Fumo, Mago, & Smith, 2011; Hawkes & Leach, 2007; Hueffed & Mago, 2010; Kavvadias, Tosios, & Maroulis, 2010; Mago, Chamra, & Ramsay, 2010; Mago & Luck, 2013; Ren & Gao, 2010). When a CHP system operates FEL, the PGU electrical output varies depending on the building electrical demand, and the waste heat is used to satisfy part or all of the thermal demand of the facility. If the recovered heat is not sufficient to satisfy the thermal demand of the facility, a boiler can be used to supply the heat needed. On the other hand, if the recovered heat is more than that required by the facility, the excess heat could be stored or discarded. When the CHP system operates FTL, the PGU varies its power level depending on the building thermal demand, and the electricity generated is used to satisfy part or all the electric demand of the facility. If the electricity produced by the CHP system is not sufficient enough to meet the facility electric requirements, additional electricity must be purchased from the electric grid. On the other hand, if the electricity produced is more than the electricity needed by the facility, the excess can be stored or sold back to the electric grid. When a CHP system is operated BL, the PGU only provides a constant fraction of the electric demand of the building. In this case, electricity has to be imported from the electric grid to satisfy the electric demand of the facility. In addition, an auxiliary boiler can be used if the recovered heat is not sufficient to satisfy the facility thermal demand.

Although the strategies mentioned above are the most common strategies in CHP system operations, they may or may not guarantee the best performance of the system based on several parameters such as operational cost, carbon dioxide emissions (CDE) reduction, or primary energy consumption (PEC). Recently, Knizley and Mago (2012, 2013, 2014) and Mago, Luck, and Knizley (2014) have explored the feasibility of operating a CHP system with two PGUs simultaneously under differing operational strategies (D-CHP) to satisfy the electric and thermal demand of the facility. They determined that D-CHP systems can typically perform better than or comparably to traditional CHP systems operating under the most common operational strategies in terms of operational cost savings, PEC, and CDE. However, as with traditional CHP implementation, D-CHP systems performance is affected by the facility electric and thermal loads, climate conditions, relative costs of electricity and fuel, and other variables. Therefore, the objective of this paper is to establish a metric, based on the power-to-heat ratio (PHR) parameter, defined as the ratio between the facility electric load and the facility thermal load, for which a D-CHP system can potentially provide cost savings as compared with traditional CHP systems or with conventional systems with separate heating and power (SHP).

2. Methodology

In this paper, two PGUs are operated at the same time, where one PGU, PGU1, generates a constant base load while the other, PGU2, operates FEL. In this analysis, the two PGUs are sized to guarantee the highest operational cost savings. The facility fuel energy, F_b , and electricity, E_b , requirements are determined using EnergyPlus for each benchmark building, with weather data for Chicago, IL, presented hourly over the course of a year (U.S. Department of Energy, 2012). Figure 1 shows a schematic representation of the D-CHP configuration used in this paper. The PGUs simulated in this study are modeled as natural gas-fueled generators. The following equations are used to model the D-CHP system performance in terms of operational cost. The building fuel energy, F_b , and the corresponding building heating demand, Q_b , can be found using the building's heating system efficiency, η_h , as follows

Figure 1. Schematic of a D-CHP system.



$$Q_b = F_b \times \eta_h \tag{1}$$

For PGU1, that operates at BL, a constant minimum electrical output, E_{PGU1} , is considered, and consequently a constant efficiency, η_{PGU1} for that PGU can be assumed. E_{PGU1} is determined by the selected size of the PGU BL. The fuel energy needed to operate PGU1 can be found as

$$F_{PGU1} = \frac{E_{PGU1}}{\eta_{PGU1}} \tag{2}$$

The maximum heat that can be recovered from PGU1 is

$$Q_{rec, PGU1}^{max} = \xi(F_{PGU1} - E_{PGU1})\eta_{hrs} \tag{3}$$

where ξ is a factor accounting for PGU energy losses before entering the heat recovery system and η_{hrs} is the efficiency of the heat recovery system.

For PGU2, that operates FEL, the efficiency cannot be assumed constant since the PGU operates at different loads when it follows the electric load. Therefore, the fuel required to operate PGU2 can be determined through (Cho, Mago, Luck, & Chamra, 2009)

$$F_{PGU2} = a \times E_{PGU2} + b \tag{4}$$

where E_{PGU2} is the actual (hourly) output of PGU2 and a and b are engine-dependent constants that are determined from curve fitting of manufacturer's data of fuel usage versus engine output.

Thus, the efficiency of the PGU2 can be determined as

$$\eta_{PGU2} = \frac{E_{PGU2}}{a \times E_{PGU2} + b} \tag{5}$$

The maximum hourly output of the PGU FEL is determined by the selected size of PGU2 (F_{PGU2}^{max}), and PGU2 hourly operation is limited to the maximum output as well as to a minimum output of 25% of the maximum PGU2 output, in order to ensure operation within sufficient efficiency constraints.

The maximum heat that can be recovered from PGU2 is

$$Q_{\text{rec, PGU2}}^{\text{max}} = \xi(F_{\text{PGU2}} - E_{\text{PGU2}})\eta_{\text{hrs}} \quad (6)$$

If the total electricity generated by both PGUs, $E_{\text{PGUs}} = E_{\text{PGU1}} + E_{\text{PGU2}}$, is not sufficient to meet building electric load, electricity needs to be purchased from the grid, E_{grid} . Similarly, if the total heat recovered from both PGUs, Q_{rec} , is not sufficient to satisfy the building heating demand, then supplemental heat may be supplied by a boiler, Q_{boiler} . If a boiler is needed, the fuel energy required to operate the boiler can be found as

$$F_{\text{boiler}} = \frac{Q_{\text{boiler}}}{\eta_{\text{boiler}}} \quad (7)$$

where η_{boiler} is the boiler efficiency.

For a more detailed description of the D-CHP system model described in this paper, please refer to previous work from Knizley and Mago (2012, 2013, 2014) and Mago et al. (2014).

In this analysis, the performance of the D-CHP system is quantified in terms of operational cost savings over a reference case in which a traditional SHP system is employed. Operational cost for the reference case and for the D-CHP system case is estimated on an hourly basis and presented as both monthly and yearly summation totals. The metered electrical consumption, E_m , and metered fuel energy consumption, F_m , include any electrical power requirement provided by the grid (E_{grid}) and all fuel energy required to operate the PGUs and boiler, if applicable. Therefore, the cost for the D-CHP system and the SHP (reference case) operation are, respectively,

$$\text{Cost}_{\text{D-CHP}} = E_m \times \text{Cost}_e + F_m \times \text{Cost}_f \quad (8)$$

$$\text{Cost}_{\text{ref}} = E_b \times \text{Cost}_e + F_b \times \text{Cost}_f \quad (9)$$

where Cost_e and Cost_f are the costs of electricity and fuel, respectively. The difference between operating cost of the reference case and of the D-CHP system is used to determine if a D-CHP system can provide savings over the reference case, where a positive ΔCost indicates savings of D-CHP system over the reference case.

$$\Delta\text{Cost} = \text{Cost}_{\text{ref}} - \text{Cost}_{\text{D-CHP}} \quad (10)$$

Some results may be presented in terms of percentage variation of operating cost with respect to the reference case. In these situations, percent variation is defined by

$$\text{Variation \%} = \frac{\Delta\text{Cost}}{\text{Cost}_{\text{ref}}} \times 100 \quad (11)$$

After the operational cost of the D-CHP system is determined, the monthly PHR, is analyzed for each benchmark building and used as a metric for optimizing D-CHP performance when applicable. The PHR is defined as

$$\text{PHR} = E_b / Q_b \quad (12)$$

3. Results

In this paper, eight benchmark buildings were simulated and analyzed using a D-CHP system. The selected buildings include: full-service restaurant, large office, medium office, apartment, outpatient facility, supermarket, retail facility, and strip mall; and were simulated using the weather data for Chicago, IL. The cost of electricity and natural gas for the city of Chicago are determined from Target finder and eGRID data (U.S. Environmental Protection Agency, 2010; U.S. Environmental Protection Agency and the U.S. Department of Energy, 2013). Table 1 also shows the spark spread, or difference

between the cost of electricity and the cost of fuel (Smith, Fumo, & Mago, 2011). The assumed values of the efficiency for the components of the D-CHP system as well as the engine curve-fit parameters, a and b , determined from manufacturer’s data (Kohler, 2013), are presented in Table 2. In a previous study, Knizley and Mago (2012) reported that operating a D-CHP system only in months when the PHR is below 5.0 can potentially guarantee that the D-CHP system operational cost could be better than the SHP system. In that work, a full-service restaurant, a hospital, a large hotel, and a secondary school benchmark building were analyzed. The secondary school was the only building that did not produce cost savings while using a D-CHP system, and it was also the only building that had monthly PHR values exceeding 5.0. The work presented in this paper seeks to extend the work done by Knizley and Mago (2013), by analyzing different types of buildings to determine if the proposed maximum PHR value (PHR_{max}), or an optimum PHR_{max} , can be used for the additional building configurations. Table 3 lists building specifications and building load information for each of the benchmark buildings used in this paper.

The first step in this analysis was to find the PGU size combination (PGU1/PGU2) that yielded the best cost savings, or least additional cost, of a D-CHP system over the reference case. This was achieved by creating a mathematical model to simulate the D-CHP system performance. The model outputs changes in operational cost, CDE, and PEC based on the sizes of each PGU, electricity and fuel prices, and energy usage data obtained from EnergyPlus. Table 4 presents the PGU sizes and Δ Cost values for each building. In this table, negative values indicate that the D-CHP system operational

Table 1. Cost of electricity and natural gas in Chicago, IL (U.S. Environmental Protection Agency, 2010; U.S. Environmental Protection Agency and the U.S. Department of Energy, 2013)

Cost _e (\$/kW)	Cost _f (\$/kW)	Spark spread (\$/kW)
0.086	0.031	0.055

Note: Data taken in February 2014.

Table 2. System components efficiencies

Parameter	Symbol	Value
Building heating system efficiency	η_n	0.8
Efficiency of PGU1 (BL)	η_{PGU1}	0.3
PGU loss factor	ξ	0.95
Efficiency of heat recovery system	η_{hrs}	0.8
Engine curve-fit coefficient (Kohler, 2013)	a	2.3698
Engine curve-fit coefficient (Kohler, 2013)	b	$1.0322 \times E_{PGU2}^{max}$
Boiler efficiency	η_{boiler}	0.8

Table 3. Information of the selected benchmark buildings (U.S. Department of Energy, 2012)

Building	Area (m ²)	E_b (kW/year)	F_b (kW/year)	Q_b (kW/year)
Restaurant	511	314,713	544,085	435,268
Large office	46,320	5,997,309	1,484,035	1,187,228
Medium office	4,982	754,437	67,214	53,772
Apartment	3,135	234,403	229,848	183,878
Outpatient	3,804	1,359,779	902,318	721,854
Supermarket	4,181	1,661,349	942,965	754,372
Retail	2,319	320,300	282,364	225,891
Strip mall	2,090	288,661	293,019	234,416

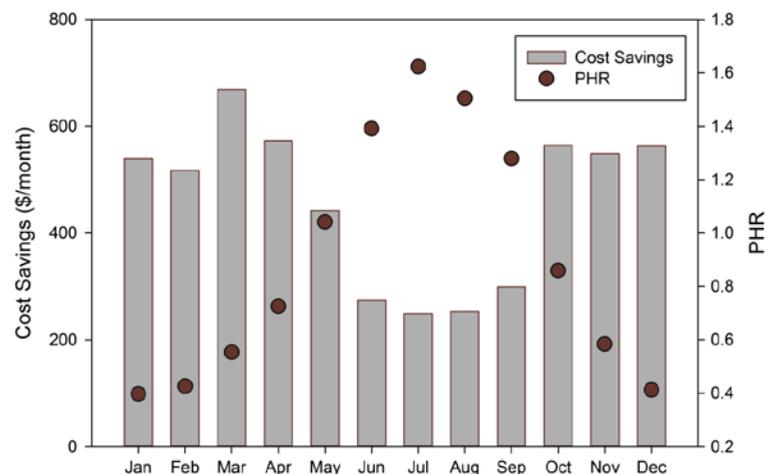
cost is higher than the operational cost of the reference building (SHP). As seen in Table 4, four of the eight evaluated buildings presented cost savings for D-CHP system operation over the reference case. The mid-size office and retail facility have comparable operational costs for the D-CHP system and the SHP system, while the large office and strip mall have significant increases in the operational cost when a D-CHP system is used.

After the monthly and yearly operational cost and cost savings were determined, the monthly PHR is examined for each facility to determine the relationship between the operational cost and the PHR for each month. In addition, the PHR was used to optimize the operation of applicable buildings. Figures 2 through 9 show the monthly PHR and monthly operational cost savings of a D-CHP system over the SHP reference case for all the evaluated buildings.

Aside from the outpatient building, the benchmark buildings present the same general trend, with rare anomalies, shown by Knizley and Mago (2012), where the D-CHP system operational cost savings increase as the monthly PHR decreases. The outpatient building (Figure 6) follows the opposite trend, however, which may be partially due to minimal variation of monthly PHR for that building. The monthly PHR for the outpatient facility is low each month, reaching a maximum of 2.98 in July and a minimum of 1.6 in December. As shown in Figures 2 and 6, for the restaurant and the outpatient facility, respectively, the D-CHP system is able to provide savings over the reference case nearly every month, so there is no reason to optimize the D-CHP system implementation for these two facilities. The monthly PHR for each of these buildings never exceeds the PHR_{max} value of 5.0, proposed in Knizley and Mago (2012), and, in fact, neither of these buildings exceeds a PHR of 3.0.

Table 4. PGU sizing and D-CHP system performance			
Building	PGU1 (kW)	PGU2 (kW)	ΔOpCost (\$/year)
Restaurant	10	30	5,486
Large office	85	5	-6,500
Medium office	5	5	-873
Apartment	15	5	1,463
Outpatient	60	5	15,005
Supermarket	85	30	1,971
Retail	5	35	-671
Strip mall	15	20	-1,215

Figure 2. Monthly cost savings and PHR for the full-service restaurant building.



Figures 3 and 4 show that nearly every month the use of a D-CHP system increases the operational cost for the large and medium office buildings, and it is therefore not beneficial to operate a D-CHP system during any portion of the year for those buildings. For the large office building, the months of January, February, and December have a monthly PHR below 3.0, but operational cost savings are still not achieved during those months. The PHR for other months is much higher, peaking at 161 in July. For the medium office building, no monthly PHR is below 3.0. The minimum monthly PHR for the medium office is 5.2 in January, and the maximum is 114 in July. Therefore, using the PHR_{max} value of 5.0, proposed in Knizley and Mago (2013), a conclusion that the operation of a D-CHP system in the large and medium office buildings is not beneficial would still have been valid.

Figures 5–9 illustrate the cost savings for an apartment building, a supermarket, a retail facility, and a strip mall. For these four buildings, it can be observed that during some months, the D-CHP system operation is not able to provide operational cost savings. It is interesting to observe that for these months the PHR is high. For the retail facility and the strip mall (Figures 8 and 9, respectively), the PHR in July is high. This is because in Chicago, July has the highest cooling demands of the year, and much electricity is used for air-conditioning. Additionally, heating demands in July are minimal, particularly in the retail facility and the strip mall (some buildings, such as the full-service restaurant building, require significant water heating, even in the summer). Because the PHR is the ratio of the electrical load to the thermal load, the retail facility and the strip mall have very high PHR values during July. The results presented in these figures, combined with the results presented in Figures 2 and 6, yield

Figure 3. Monthly cost savings and PHR for the large office building.

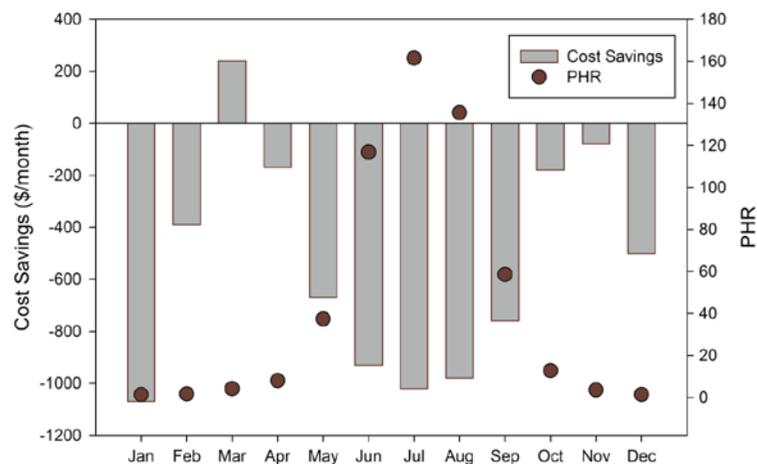


Figure 4. Monthly cost savings and PHR for the medium office building.

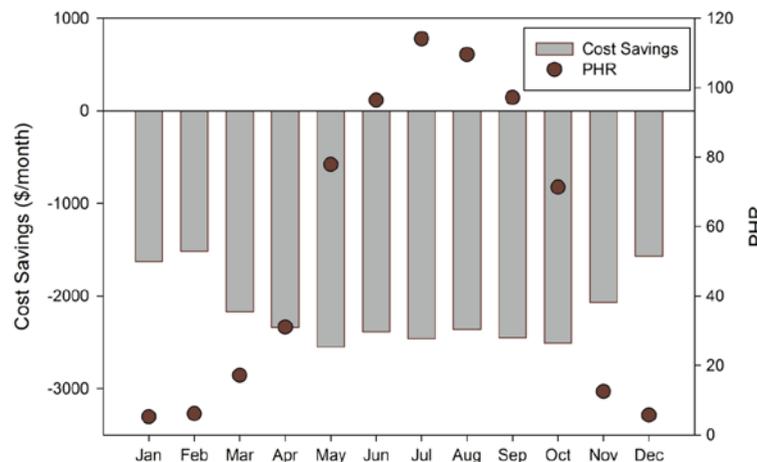


Figure 5. Monthly cost savings and PHR for the apartment building.

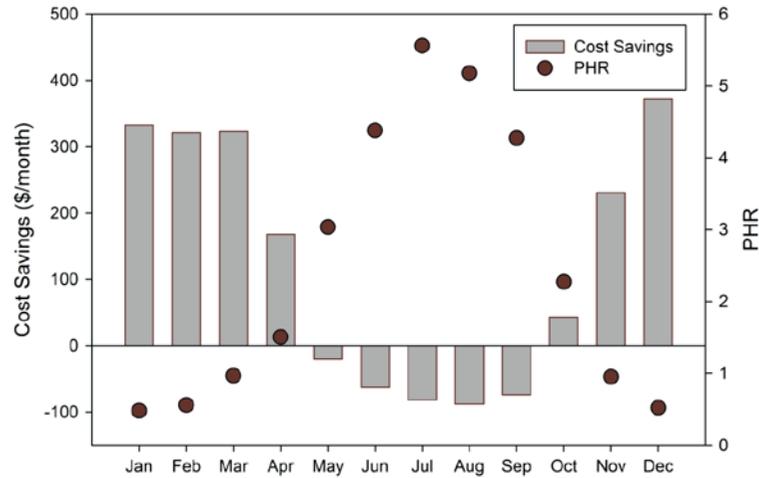


Figure 6. Monthly cost savings and PHR for the outpatient building.

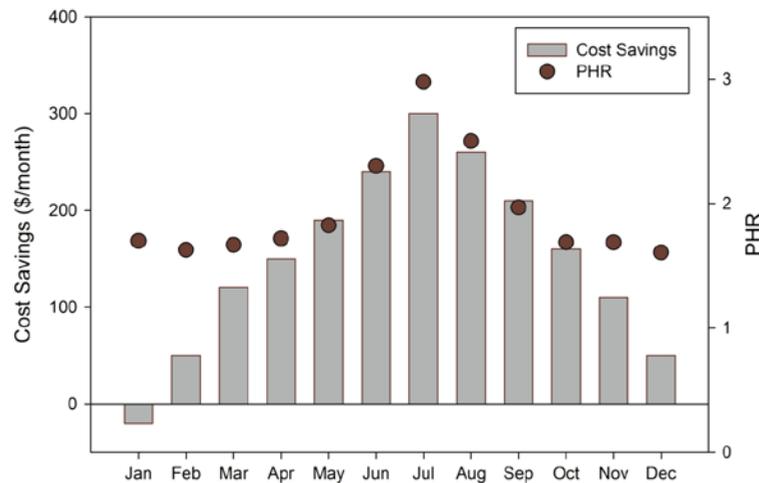
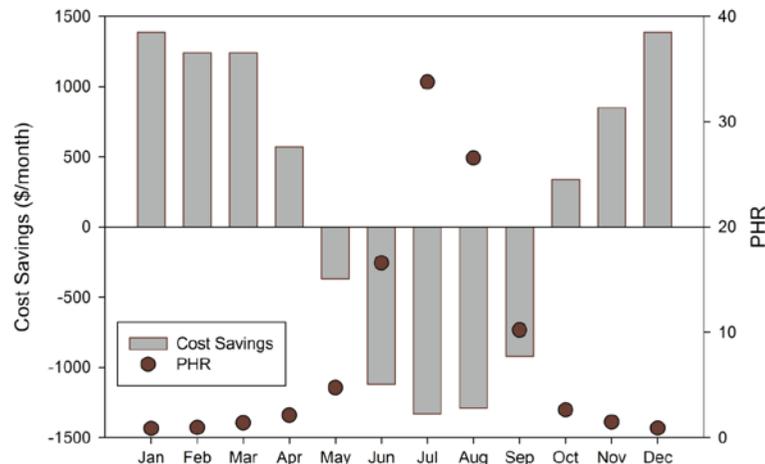


Figure 7. Monthly cost savings and PHR for the supermarket building.



the conclusion that a PHR below 3.0 can be used as indicative that the D-CHP system operation can potentially provide cost savings. If this threshold is used, $PHR_{max} = 3.0$, for the apartment building, the D-CHP system should not be operated from May to September. Similarly, for the supermarket, the D-CHP system should not be operated from May to September. The results of the optimized D-CHP

Figure 8. Monthly cost savings and PHR for the retail building.

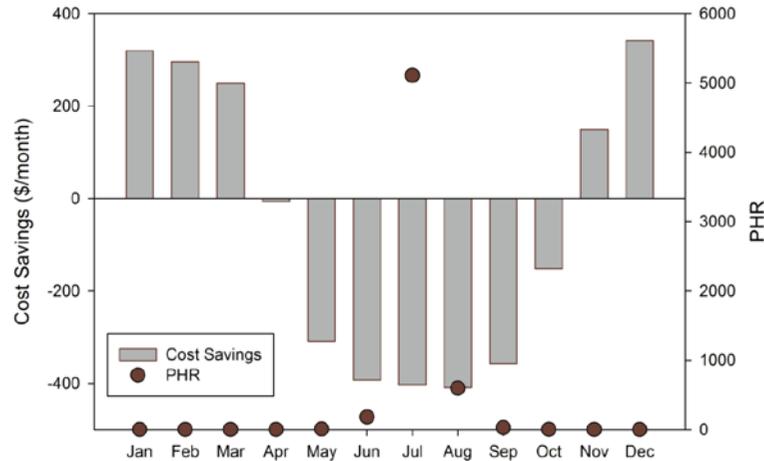
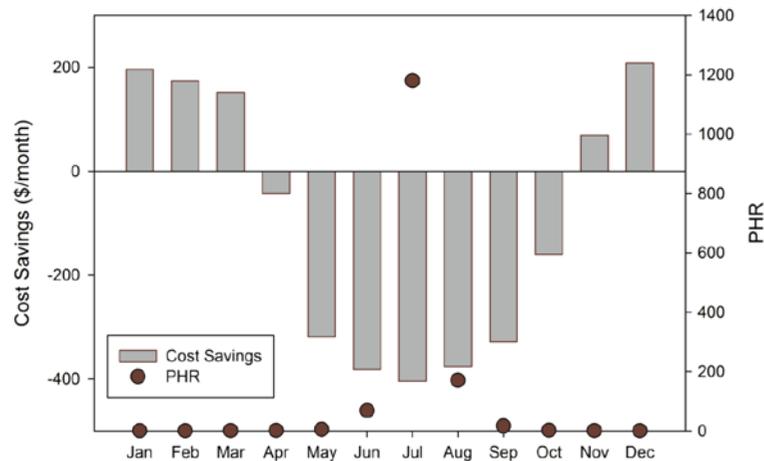


Figure 9. Monthly cost savings and PHR for the strip mall building.



system operation are presented in Figure 10 for the apartment and in Figure 11 for the supermarket. Both figures present the optimized case using the PHR_{max} value of 5.0, proposed in Knizley and Mago (2013), and the new PHR_{max} value of 3.0 suggested in this paper. For the apartment building, a non-optimized D-CHP system has an operational cost 5.37% less than the reference case. Furthermore, cost savings of 5.99 and 6.56% can be obtained when the D-CHP system is optimized based on PHR_{max} of 5.0 and 3.0, respectively. For the supermarket building, a non-optimized D-CHP system has operational cost savings of 1.16% over the reference case. When the system is optimized, savings of 3.86 and 4.08% can be obtained for a PHR_{max} of 5.0 and 3.0, respectively.

As shown in Figures 12 and 13, for the retail facility and the strip mall, there is no difference between a PHR_{max} of 5.0 or 3.0, as when the PHR is sufficiently low, it is below 3.0. However, for each of these buildings, optimizing the D-CHP system with $PHR_{max} = 3.0$ or 5.0 will provide savings when a non-optimized D-CHP system does not. For the retail facility, a non-optimized D-CHP system has an operational cost 1.85% higher than the reference case, while an optimized D-CHP system provides 3.30% savings over the reference case. For the strip mall, a non-optimized D-CHP system has an operational cost 3.58% higher than the reference case, while optimizing the D-CHP system provides 1.76% savings over the reference case.

These results signify that monthly PHR is a useful parameter that can provide an initial indication of the potential for operational cost savings with a D-CHP system. As the results demonstrate, for the group of benchmark buildings examined in this paper, using a threshold of $PHR_{max} = 3.0$ leads to the

Figure 10. Savings of D-CHP system over the reference case for the apartment building with no optimization, optimization based on $PHR_{max} = 5.0$, and optimization based on $PHR_{max} = 3.0$.

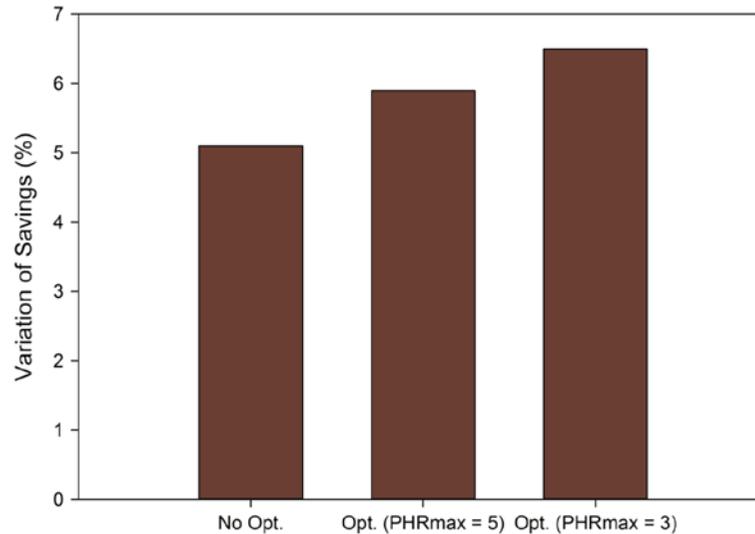
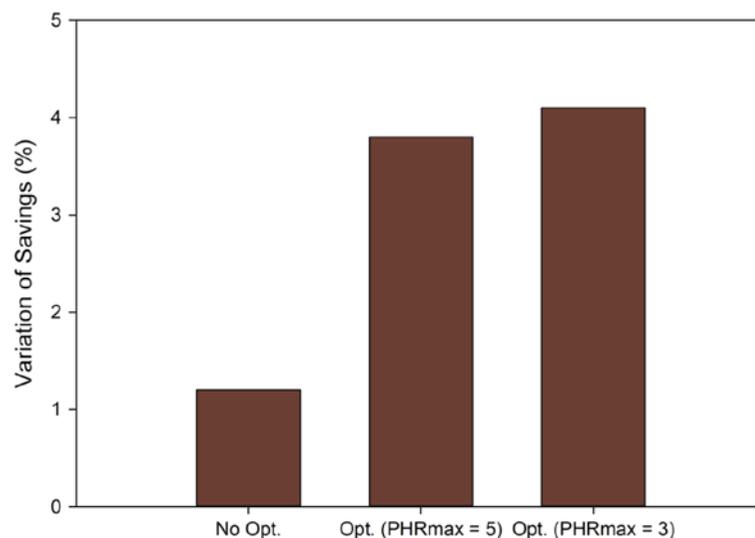


Figure 11. Savings of D-CHP system over the reference case for the supermarket benchmark building with no optimization, optimization based on $PHR_{max} = 5.0$, and optimization based on $PHR_{max} = 3.0$.



highest overall cost savings. This paper examines a larger group of buildings than previously examined by Knizley and Mago (2013), and the buildings examined in this paper exhibit more varied behavior. In previous work by Knizley and Mago, the only building with monthly PHR values exceeding 5.0 was the secondary school; in this paper, some of the examined buildings, such as the apartment and supermarket, present higher cost savings when using a PHR threshold of 3.0 rather than 5.0.

4. Conclusions

For the buildings analyzed in this paper, it was established that a PHR below approximately 3.0 is an indication that the D-CHP system could potentially provide cost savings for that particular month. The only building that did not meet this condition was the large office building, in which the PHR was close to 3.0 for three months of the year, and savings were not achieved. Based on this threshold, it was shown that two of the eight buildings needed no optimization, with each month having a PHR below 3.0. For these two buildings, the restaurant and the outpatient facility, the D-CHP system provides cost savings each month. On the other hand, the mid-size and large office buildings present high PHR values most months of the year, and therefore could not be optimized to produce any savings over the reference case. For the four remaining buildings, the apartment facility, the supermarket, the retail facility, and the strip mall, the D-CHP system operation produced overall yearly

Figure 12. Savings of D-CHP system over the reference case for the retail benchmark building with no optimization, optimization based on $PHR_{max} = 5.0$, and optimization based on $PHR_{max} = 3.0$.

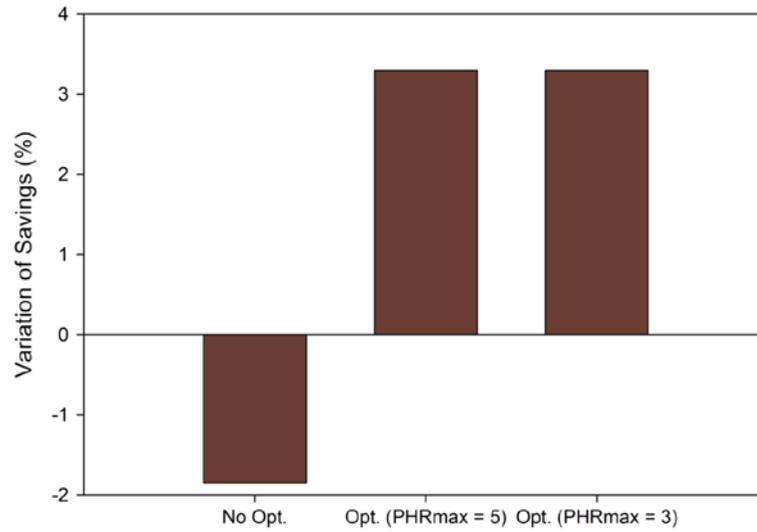
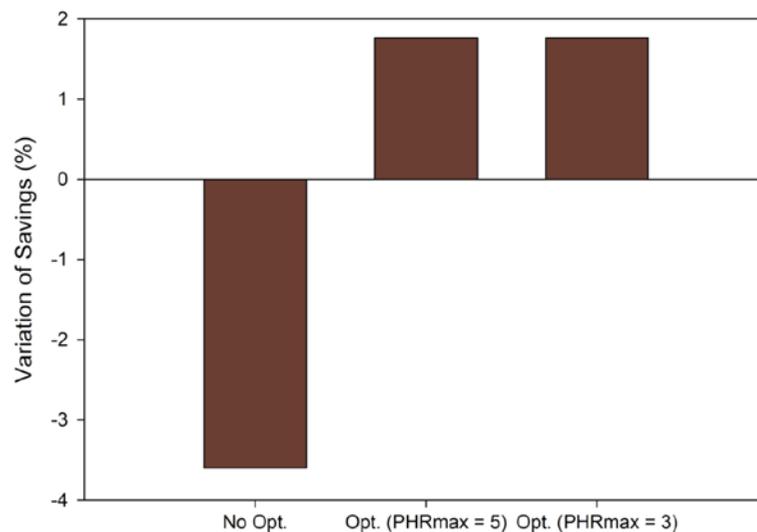


Figure 13. Savings of D-CHP system over the reference case for the strip mall benchmark building with no optimization, optimization based on $PHR_{max} = 5.0$, and optimization based on $PHR_{max} = 3.0$.



cost savings but was not beneficial during certain months of the year with high PHRs. For each of these buildings, optimizing the D-CHP system operation for months with PHR below 3.0 produces the greatest cost savings over the reference case. Therefore, for the buildings analyzed in this paper, several months having PHR values below 3.0 would be an indication that the implementation of a D-CHP system could potentially reduce the operational cost savings and provide justification to perform more detailed analysis on the feasibility of D-CHP implementation. In contrast, for buildings with monthly PHR consistently exceeding 3.0, it is unlikely that the implementation of a D-CHP system would produce significant operational cost savings. The monthly PHR can thus be used as an initial indicating parameter for the potential of a D-CHP system to provide operational cost savings. However, it is not a replacement for a complete, detailed analysis; as noted earlier, some buildings present an anomaly and do not follow the established trend.

Nomenclature

CHP	combined heat and power
D-CHP	dual-PGU CHP system configuration
SHP	separate heating and power

PGU	power generation unit
PHR	power-to-heat ratio
FEL	following the electric load
FTL	following the thermal load
BL	base loading
E_b	hourly electrical energy requirement of building
F_b	hourly fuel energy requirement of building
η_{PGU1}, η_{PGU2}	respective efficiencies of PGU1 and PGU2
η_h	heating system efficiency
η_{hrs}	efficiency of heat recovery system
η_{boiler}	boiler efficiency
ξ	PGU energy loss factor
$Cost_e$	cost of electrical energy (\$/kW) for Chicago, IL
$Cost_f$	cost of natural gas (\$/kW) for Chicago, IL
E_{PGU1}, E_{PGU2}	respective electrical energy output of PGU1 and PGU2
E_{PGU2}^{max}	maximum output (size) of PGU2
F_{PGU1}, F_{PGU2}	respective fuel energy requirement of PGU1 and PGU2
$Q_{rec,PGU1}^{max}$	maximum heat that can be recovered from PGU1
$Q_{rec,PGU2}^{max}$	maximum heat that can be recovered from PGU2
Q_b	heat required by the building
Q_{req}	overall heat input needed for combined heating systems
Q_{rec}	total heat recovered from combined PGUs
Q_{boiler}	auxiliary heat provided by boiler
E_{grid}	auxiliary electricity purchased
E_{PGUs}	combined electrical output from both PGUs
F_{PGUs}	combined fuel energy requirement from both PGUs
E_m	metered electrical energy
F_m	metered fuel consumption
F_{boiler}	fuel needed to operate boiler
Cost	operational cost
PEC	primary energy consumption
CDE	carbon dioxide emissions
Δ	difference between CHP and reference case

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