Effects of a CHP System with Cooling on Carbon Dioxide Emissions In Full and Partial Cooling Load Applications

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ABSTRACT

Combined heat and power technology is one of the few market-proven power generation solutions for reducing energy usage and greenhouse gas emissions. This work assesses the net emissions reduction from installing a CHP system with absorption cooling (a CCHP system) as an alternative to a state of the art variable speed centrifugal chiller. A full load analysis is presented that examines the performance of the CCHP system installed as an alternative to a fully loaded centrifugal chiller. A part load analysis is presented that examines the performance of the same CCHP system installed as an alternative to the same chiller operating at part load. A sensitivity analysis was performed to compare the relative impact of cooling hours versus the local emissions coefficients to determine the factor that has the strongest effect on emissions reduction projects. The calculations and results of the analyses are presented and recommendations made as to the most effective designs and locations for installation of CCHP systems for reducing emissions.

INTRODUCTION

Ongoing concern over the effects that the contribution of greenhouse gases (GHG) may have on global warming and climate change has led to increased implementation of energy efficiency and emissions reduction projects by institutions and facilities around the United States. For example, many of the 40 largest cities in the world have joined the

Clinton Climate Initiative, which has the stated goal of reducing energy usage and GHG emissions (1). One of these cities is Chicago, which is developing the "Chicago Climate Action Plan" with the expected goal of cutting carbon dioxide emissions by 25% from 1990 levels once the plan is finalized (2). The savings are expected to come from transportation and fleet improvements as well as by increased efficiency in residential and commercial buildings. With the goal of paying for the cost of retrofits in these buildings through energy savings, a large portion of the work is likely to be awarded to energy service companies. One solution energy service companies can provide to generate large on-site energy savings and reduced emissions is combined heat and power (CHP) technology. Less sophisticated methods of reducing emissions, such as replacing old equipment, are typical. Municipal facilities are common sites for chilled water systems and typical replacement options include installing new chillers; possibly with variable speed compressors to further reduce energy use. This work assesses the net emissions reduction from installing a CHP system with absorption cooling as an alternative to a state of the art variable speed centrifugal chiller. That is, the emissions savings of a CCHP system above and beyond a new variable speed chiller are determined—not savings relative to existing equipment.

In a previous work the author detailed a preliminary method for quickly evaluating the net GHG emissions of a CHP system as a means of evaluating the feasibility of installing the system in a carbon dioxide emissions reduction project (3). The primary goal of that work was to demonstrate that retrofitting a traditional boiler plant with a CHP system can be a net negative GHG emissions measure. That work included the analysis of a natural gas internal combustion (IC) engine which generated electricity and hot water. That analysis was based on the emissions balance presented in Relation 1.

$$\text{Net GHG Emissions} = \text{GHG}_{\text{fuel}} - \text{GHG}_{\text{generation}} - \text{GHG}_{\text{boiler}} \tag{1}$$

In Relation 1, the terms on the right side of the equation represent the emissions associated with the fuel consumed by the prime mover, the utility-purchased kilowatt-hours offset by the generator, and the utility-purchased natural gas offset by recovering exhaust heat in a boiler.

The next level of complexity for a CHP system, beyond generating electricity and hot water, is to integrate the system with chilled water equipment to provide cooling. The present work describes methods for determining the net carbon dioxide emissions from installing the CHP system with cooling (CCHP system) in place of chillers that operate at full and part load. This revised analysis is based on Relation 2, a modified form of Relation 1.

$$\text{Net GHG Emissions} = \text{GHG}_{\text{fuel}} - \text{GHG}_{\text{generation}} - \text{GHG}_{\text{chiller}} \qquad (2)$$

In Relation 2, the terms on the right side of the equation represent the emissions associated with the fuel consumed by the prime mover, the utility-purchased kilowatt-hours offset by the generator, and the utility-purchased kilowatt-hours offset by replacing a mechanical chiller with an absorption chiller.

This relation warrants some extra description to assure the reader that savings are not being counted twice. Consider an existing chiller plant with two or more mechanical chillers prior to a CCHP installation. The chiller plant uses some amount of electricity to power its chillers throughout the hours when cooling is required. If an absorber installed as part of the project replaces an existing chiller, all of the electrical usage associated with that chiller is removed (less the parasitic power requirements of the absorber) from the site load. Additionally, the electricity generated by the CHP system further decreases the site load. If the net power output of the engine generator is calculated with the parasitic power requirements of the absorber taken into account, then Relation 2 is accurate.

GHG EMISSIONS DATA

Continuing the procedure of the previous work, the first step in calculating the emissions associated with installing a CHP system is to determine which greenhouse gases are targeted for reduction. The second step is to establish the conversion coefficients that represent the amount of emissions per unit of energy.

This work will simulate a CCHP system being installed as part of a hypothetical carbon dioxide reduction project for the Chicago Climate Action Plan. The US Energy Information Administration publishes emissions data for various fuel types and locations and from this, the coefficients for electric and natural gas related carbon dioxide emissions in

Illinois were obtained (4, 5).

$$C_{kWh} = 1.16 \quad \frac{lb_{CO_2}}{kWh}$$

$$C_{therm} = 11.708 \quad \frac{lb_{CO_2}}{therm}$$

Once the coefficients for CO_2 emissions have been selected appropriately, the emissions balances are evaluated and the energy use associated with the chillers is calculated at full and part load.

FULL LOAD ANALYSIS

The following analysis determines the net CO_2 emissions of a CCHP system with a 300 ton steam fired double effect absorption chiller relative to a mechanical chiller which operates continuously at full load. The prime mover is assumed to be a natural-gas-fueled IC engine with the following performance specifications:

Fuel Consumption Rate = 130 therm/hr
Net Power Output = 1,200 kW
Exhaust Heat Recovery Rate = 3,500 Btu/kWh

It is assumed that the system is to be installed at a large correctional facility with a 2 MW base electrical demand and a central chiller plant that serves inmate housing facilities totaling approximately 275,000 ft^2. It is assumed that the existing chiller plant has three 300 ton centrifugal chillers (900 total tons of cooling capacity). Two chillers operate at full load throughout the year to cool and dehumidify areas that are constantly occupied by inmates. The third chiller follows its performance curve because it responds to weather related load fluctuations.

For this installation the new absorber will operate in place of one of the existing fully loaded centrifugal units. Leaving the centrifugal unit in place, if possible, provides redundancy for times when the CCHP system is offline for maintenance. It is assumed that the engine generator is available for operation during 90% of the annual operating hours and from these assumptions, based on 8,760 hr/yr, the engine is assumed to operate at full electrical output and heat recovery for 7,884 hr/yr. It is also assumed that the centrifugal chiller to be replaced currently stops operating 10 days/yr for maintenance. Based on 8,760 hr/yr, the existing centrifugal chiller is assumed to operate at full load for 8,520 hr/yr

The CO_2 emission balance for this scenario is presented in Relation 2.

$$\text{Net GHG Emissions} = GHG_{fuel} - GHG_{generation} - GHG_{chiller} \quad (2)$$

The method of evaluating the CO_2 emissions associated with the fuel usage of the prime mover is calculated in Relation 3.

$$GHG_{fuel} = (\text{Fuel Consumption Rate})(\text{Annual Operating Hours})(C_{therm}) \quad (3)$$

$$GHG_{fuel} = \left(130\frac{therm}{hr}\right)\left(7{,}884\frac{hr}{yr}\right)\left(11.708\frac{lb_{CO_2}}{therm}\right) \approx 11.99 \times 10^6\frac{lb_{CO_2}}{yr}$$

The method of evaluating the CO_2 emissions associated with the power generation of the prime mover is calculated in Relation 4.

$$GHG_{generation} = (\text{Net Power Output})(\text{Annual Operating Hours})(C_{kWh}) \quad (4)$$

$$GHG_{generation} = (1200\ kW)\left(7{,}884\frac{hr}{yr}\right)\left(1.16\frac{lb_{CO_2}}{kWh}\right) \approx 10.97 \times 10^6\frac{lb_{CO_2}}{yr}$$

The method of evaluating the CO_2 emissions associated with replacing the centrifugal chiller with an absorption unit versus the variable speed unit is calculated according to Relation 5 using the variable speed chiller manufacturer's published efficiency at 100% load.

$$GHG_{chiller} = (\text{Chiller Capacity})(\text{Chiller Efficiency})(\text{Annual Operating Hours})(C_{kWh}) \quad (5)$$

$$GHG_{chiller} = (300\ Tons)\left(0.57\frac{kW}{ton}\right)\left(8{,}520\frac{hr}{yr}\right)\left(1.16\frac{lb_{CO_2}}{kWh}\right) \approx 1.69 \times 10^6\frac{lb_{CO_2}}{yr}$$

These values are substituted into Relation 2 to determine the net CO_2 output of the CCHP system relative to the variable speed chiller.

$$\text{Net GHG Emissions} = \text{GHG}_{\text{fuel}} - \text{GHG}_{\text{generation}} - \text{GHG}_{\text{chiller}} \tag{2}$$

$$\text{Net GHG Emissions} = 11.99 \times 10^{6}\frac{\text{lb CO}_2}{\text{yr}} - 10.97 \times 10^{6}\frac{\text{lb CO}_2}{\text{yr}} - 1.69 \times 10^{6}\frac{\text{lb CO}_2}{\text{yr}}$$

$$\text{Net GHG Emissions} = -\,0.67 \times 10^{6} \quad \frac{\text{lb}_{\text{CO}_2}}{\text{yr}}$$

$$\text{Net GHG Emissions} = -\,335 \ \frac{\text{ton}_{\text{CO}_2}}{\text{yr}}$$

The result of the full load analysis is that a CCHP system operating in such a scenario can be shown to reduce net CO_2 emissions on the order of hundreds of tons annually over a late model chiller with modern performance levels.

PART LOAD ANALYSIS

The second analysis determines the net CO_2 emissions resulting from a CCHP application with the same double effect absorption chiller as an alternative to the variable speed mechanical chiller operating at part load. The prime mover is assumed to be the same natural-gas-fueled internal combustion engine from the previous analysis:

Fuel Consumption Rate = 130 therm/hr
Net Power Output = 1200 kW
Exhaust Heat Recovery Rate = 3,500 Btu/kWh

The method of evaluating the CO_2 emissions associated with replacing the partially loaded chiller with an absorption unit, as opposed to the variable speed unit, can be calculated by at least four methods that account for varying loads and site-specific weather data. Weather data required include the bin data for the installation site, cooling design temperature, and facility balance point temperature. An assumption has to be made about how the cooling load fluctuates with temperature and, in this analysis, it is assumed that the cooling load varies linearly from 100% to 0% as the temperature varies from the design cooling temperature (88°F at Chicago O'Hare) to the balance point (assumed to be 63°F such that no cooling is required in the 60-65°F bin). For Chicago O'Hare there are 2,342 hours in this range, based on TMY-2 weather data, during which it is assumed cooling is required.

The CO_2 emission balance for this scenario is presented in Relation 6.

$$\text{Net GHG Emissions} = GHG_{fuel} - GHG_{generation} - GHG_{chiller} - GHG_{HW_1} \quad (6)$$

Relation 6 introduces the new term GHG_{hw_1}. To maximize the amount of heat recovered from the CCHP system on an annual basis, the recommendation could be made that an additional shell-and-tube heat exchanger be installed downstream of the absorption chiller. During times of partial cooling load, this would allow any steam in excess of the absorber demand to reject heat in a useful manner, to the heating or domestic hot water (HW) system. Using a heat exchanger also allows the steam loop to remain closed. For the purpose of this analysis, it is assumed that the steam condensate returns to the engine generator in the same state regardless of site cooling load by rejecting energy in excess of absorber needs to a natural-gas-fired HW system through a heat exchanger at 80% thermal efficiency. The CO_2 emissions associated with the HW system are reduced proportionally to the amount of heat recovered from the steam loop.

The CCHP system output is evaluated during the 2,342 cooling-hour period. The method of evaluating the CO_2 emissions associated with the fuel usage and power generation of the prime mover are unchanged and calculated by Relations 3 and 4, respectively.

$$GHG_{fuel} = (\text{Fuel Consumption Rate})(\text{Annual Operating Hours})(C_{therm}) \quad (3)$$

$$GHG_{fuel} = \left(130\frac{\text{therm}}{\text{hr}}\right)\left(2{,}342\frac{\text{hr}}{\text{yr}}\right)\left(11.708\frac{\text{lb}_{CO_2}}{\text{therm}}\right) \approx 3.56 \times 10^6\frac{\text{lb}_{CO_2}}{\text{yr}}$$

$$GHG_{generation} = (\text{Net Power Output})(\text{Annual Operating Hours})(C_{kWh}) \quad (4)$$

$$GHG_{generation} = (1200\ \text{kW})\left(2{,}342\frac{\text{hr}}{\text{yr}}\right)\left(1.16\frac{\text{lb}_{CO_2}}{\text{kWh}}\right) \approx 3.26 \times 10^6\frac{\text{lb}_{CO_2}}{\text{yr}}$$

METHOD 1

The first method of evaluating the CO_2 emissions of the absorption unit relative to the variable speed chiller is based on the non-standard part load value (NPLV) for chiller efficiency. This value is provided by the manufacturer and represents an estimate of the efficiency at off design conditions. This method calculates the emissions associated with the variable speed chiller operation according to Relation 7.

$$GHG_{chiller} = (\text{Chiller Energy Usage})(C_{kWh}) \qquad (7)$$

In Relation 7, the chiller energy usage is calculated for each temperature bin, as shown in Relation 8.

$$\text{Chiller Energy Usage} = (\text{Chiller Load})(\text{NPLV})(\text{Hours in Bin}) \qquad (8)$$

For example, in the temperature bin from 80-85°F the chiller is loaded to 78% of capacity (234 tons) and there are 347 hours in this temperature range. These values are substituted into Relation 8 to calculate chiller energy usage.

$$\text{Chiller Energy Usage} = (\text{Chiller Load})(\text{NPLV})(\text{Hours in Bin}) \qquad (8)$$

$$\text{Chiller Energy Usage} = (234 \text{ Tons})\left(0.38\,\frac{\text{kW}}{\text{Ton}}\right)\left(347\frac{\text{hr}}{\text{yr}}\right)$$

$$\text{Chiller Energy Usage} = 30{,}855 \quad \frac{\text{kWh}}{\text{Yr}}$$

The results of this calculation were repeated for each of the temperature ranges during which cooling is required and is tabulated in Table 1.

The sum of the annual chiller energy usage in each temperature range is then substituted into Relation 7 to determine the annual carbon dioxide emissions associated with the variable speed chiller.

$$GHG_{chiller} = \left(136{,}526\frac{\text{kW}}{\text{yr}}\right)\left(1.16\frac{\text{lb}_{CO_2}}{\text{kWh}}\right) \approx 0.158 \text{ x } 10^6\frac{\text{lb}_{CO_2}}{\text{yr}} \qquad (7)$$

This method represents a simple way to achieve a savings estimate for part load operation. This method does not mirror the published performance curve of the chiller, nor does it exactly match the actually efficiency of the machine that will be installed in the field.

Finally, the HW system emissions offset by the remaining energy

Table 1. Annual chiller energy usage for a 300-ton variable speed centrifugal chiller in Chicago, Illinois operating at the NPLV efficiency

Percent Temperature Range (°F)	Cooling Load (%)	Cooling Load (tons)	NPLV (kW/ton)	Chiller Hours in Range (hr/yr)	Energy Usage (kWh/yr)
95 to 100	100	300	0.38	1	114
90 to 95	100	300	0.38	47	5,358
85 to 90	98	294	0.38	119	13,295
80 to 85	78	234	0.38	347	30,855
75 to 80	58	174	0.38	576	38,085
70 to 75	38	114	0.38	658	28,505
65 to 70	30	90	0.38	594	20,315
60 to 65	0	0			
				2,342	136,526

in the steam loop are calculated by Relation 9.

$$GHG_{HW_1} = (\text{HW Energy Offset})(C_{\text{Therm}}) \tag{9}$$

In Relation 9, the HW system energy usage is calculated for each temperature bin, as shown in Relation 10.

$$\begin{matrix}\text{HW}\\ \text{Energy}\\ \text{Offset}\end{matrix} = \left(\frac{\text{Chiller Capacity}-\text{Chiller Load}}{\text{Chiller COP}}\right)\left(12\frac{\text{kBtu}}{\text{Ton}}\right)\left(\frac{1\text{ therm}}{100\text{ kBtu}}\right)(\eta_{HX,HW})(\text{Hours in Bin}) \tag{10}$$

For example, in the temperature bin from 80-85°F, the chiller is loaded to 78% of capacity (234 tons), and there are 347 hours in this temperature range. The absorption chiller manufacturer's published coefficient of performance (COP) is 1.19. These values are substituted into Relation 10 to calculate heat rejected to the HW system.

$$\begin{matrix}\text{HW}\\ \text{Energy}\\ \text{Offset}\end{matrix} = \left(\frac{300\text{ Tons} - 234\text{ Tons}}{1.19}\right)\left(12\frac{\text{kBtu}}{\text{Ton}}\right)\left(\frac{1\text{ therm}}{100\text{ kBtu}}\right)(0.8)\left(347\frac{\text{hr}}{\text{yr}}\right) \tag{10}$$

$$\begin{matrix}\text{HW}\\ \text{Energy}\\ \text{Offset}\end{matrix} = 1{,}848\ \frac{\text{therm}}{\text{yr}}$$

The results of the HW energy offset calculation were repeated for each of the temperature ranges during which cooling is required and is tabulated in Table 2.

Table 2. Hot water system energy offset by recovering heat from the absorption steam loop during times of partial cooling load

Percent Temperature Range (°F)	Cooling Load (%)	Heat Cooling Load (tons)	Exchanger Efficiency (%)	Hw Hours in Range (hr/yr)	Energy Offset (therms/yr)
95 to 100	100	300	80	1	0
90 to 95	100	300	80	47	0
85 to 90	98	294	80	119	58
80 to 85	78	234	80	347	1,848
75 to 80	58	174	80	576	5,855
70 to 75	38	114	80	658	9,873
65 to 70	30	90	80	594	10,063
60 to 65	0	0	80	0	0
				2,342	27,696

The sum of the annual HW energy offset in each temperature range is then substituted into Relation 9 to determine the avoided annual carbon dioxide emissions associated with the additional heat recovery. Note that this value is the same for all methods of evaluating chiller emissions usage because it is based on cooling load, which is imposed independently of equipment performance.

$$GHG_{HW_1} = \left(27,696\frac{\text{therm}}{\text{yr}}\right)\left(11.708\frac{\text{lb}_{CO_2}}{\text{therm}}\right) \approx 0.324 \times 10^6 \frac{\text{lb}_{CO_2}}{\text{yr}} \qquad (9)$$

METHOD 2

The second method of evaluating the CO_2 emissions associated with the chiller replacement is based on the manufacturer's published performance curve. Four points on this curve are provided by the manufacturer and represent the chiller efficiency at 25%, 50%, 75%, and 100% load, as tested according to ARI standard 550/590-2003. Based on these points, a curve fit can be performed and an equation generated that interpolates the chiller efficiency between 25% and 100% load. This performance curve is then used in place of the NPLV with local climactic weather data to approximate site specific energy usage. This second method represents a more advanced way to analyze how energy usage varies with chiller performance and local weather. This method does not reflect the actual performance of the installed chiller, which will differ from testing conditions, and uses weather data averaged over many years.

METHOD 3

The third method of determining the existing chiller energy usage would utilize data acquired from the physical chiller to be replaced. These data would be acquired by mapping chiller performance in the field by artificially loading and unloading the compressor and measuring the kW draw. Similar data would be collected for the proposed chiller from a factory test. Based on these data, a curve fit that accurately represents the particular chillers could be developed and the energy usage calculated similarly to Method 2. This method would reflect the actual performance of the chillers but would still rely on long term average weather data.

METHOD 4

The fourth method of determining chiller energy usage would be from extracting the data from an existing energy management system that has a recorded trend of chiller kW draw, load, and other relevant historical information such as the corresponding outdoor air temperatures. This method would be the most accurate because it would reflect both actual chiller performance and simultaneously recorded weather data. This information is often unavailable.

PART LOAD ANALYSIS RESULTS

Based on the methods of part load analysis described previously, the quantities of CO_2 associated with the energy use of the variable speed chiller are substituted into Relation 6 to determine the net emissions of the CCHP system. Method 2 is not presented in this study because the results do not differ appreciably from the results of Method 1 (approximately 1% difference). Methods 3 and 4 were not calculated in this study because of the limited availability of data.

Net GHG Emissions =

$$GHG_{fuel} - GHG_{generation} - GHG_{chiller} - GHG_{HW_1} \tag{6}$$

$$\text{Net GHG Emissions} = 3.56 \times 10^6 \frac{lb_{co_2}}{yr} - 3.26 \times 10^6 \frac{lb_{co_2}}{yr} - 0.158 \times 10^6 \frac{lb_{co_2}}{yr} - 0.324 \times 10^6 \frac{lb_{co_2}}{yr}$$

$$\text{Net GHG Emissions} = -\ 0.18 \times 10^6 \ \frac{lb_{co_2}}{yr}$$

$$\text{Net GHG Emissions} = -\ 89 \ \frac{ton_{co_2}}{yr}$$

The final result is that installing a CCHP system as an alternative to the variable speed centrifugal chiller can provide an additional decrease in CO_2 emissions during the cooling season in Chicago. It should be noted that the auxiliary HW heat recovery is the factor that drives the emissions reduction. Offsetting chiller emissions with the absorption system alone would not reduce onsite CO_2 emissions.

SENSITIVITY ANALYSIS

The results discussed thus far came from analyzing the performance of a CCHP system in Chicago, Illinois designed to replace a chiller operating at part load. Accordingly, the results are strongly linked to the Chicago climate; which affects cooling load, chiller efficiency, and energy usage. Emissions are proportional to this energy usage and the proportionality is based on the mix of electric utility fuel sources in Illinois. The results of this study lead to questions about the relative influence of the weather data versus coefficients for CO_2 emissions on CCHP system performance.

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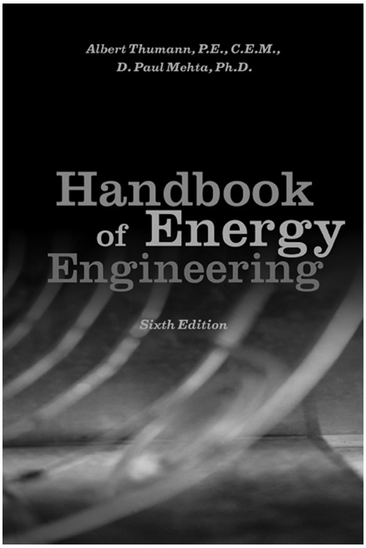

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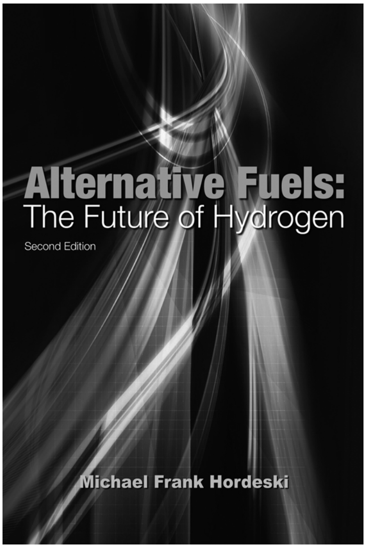

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To investigate these effects, a similar part load analysis was also completed for Phoenix, Arizona and South Bend, Indiana. Phoenix was chosen because it has more than double the cooling hours of Chicago and a similar coefficient for utility generated CO_2 emissions. South Bend was chosen because it has roughly the same number of cooling hours as Chicago but a coefficient for utility generated CO_2 emissions that is nearly twice as high as that in Illinois.

The sensitivity analysis was based on the ASHRAE design cooling temperatures for each city and a constant facility balance point of 63°F. The assumption that steam in excess of absorber needs during partial cooling loads rejects heat to a HW system was upheld. It is also assumed that during all non-cooling hours, the facility has a demand for hot water at a rate that exceeds the amount that can be generated by recovering heat from the engine. During these hours, all of the recoverable energy in the exhaust is used to offset the natural gas usage of the HW system. These assumptions normalize the sensitivity analysis by assessing annual CCHP system performance instead of performance only during specific cooling hours. For each city the avoided emissions associated with heat rejected during the non-cooling hours is calculated by Relation 11.

$$\begin{aligned} GHG_{HW_2} = {} & (\text{Exhaust Heat Rate})(\text{Power Output})(\eta_{HX})(8{,}760 \\ & - \text{Cooling Hours})(C_{therm}) \end{aligned} \tag{11}$$

As an example, the non-cooling season heat rejection is presented for Chicago (which has 2,342 cooling hours).

$$\begin{aligned} GHG_{HW_2} = {} & \left(3{,}500\frac{\text{Btu}}{\text{kWh}}\right)(1200\text{ kW})(0.8)\left(8760-2342\frac{\text{hr}}{\text{yr}}\right) \\ & \left(\frac{1\text{ therm}}{100{,}000\text{ Btu}}\right)\left(11.708\frac{\text{lb}\ CO_2}{\text{therm}}\right) \approx 2.53 \times 10^6\frac{\text{lb}\ CO_2}{\text{yr}} \end{aligned} \tag{11}$$

Table 3 presents important terms from the analyses of the same CCHP system in these three cities and the net emissions in each scenario. The HW term in Table 3 is the sum of heat rejected to the HW system during the cooling and non-cooling hours. Relation 12 presents the summation for Chicago.

$$GHG_{HW_{1+2}} = GHG_{HW_1} + GHG_{HW_2} \tag{12}$$

$$GHG_{HW_{1+2}} = 0.324 \times 10^6 \ \frac{lb_{CO_2}}{yr} + 2.53 \times 10^6 \ \frac{lb_{CO_2}}{yr}$$

$$GHG_{HW_{1+2}} = 2.85 \times 10^6 \ \frac{lb_{CO_2}}{yr}$$

Table 3. Results of the comparison of CO_2 emission factors associated with a CCHP system operating in different locations

Location	C_{kWh}	Annual Cooling Hours	GHG_{fuel}	$GHG_{generation}$	$GHG_{chiller}$	$GHG_{HW_{1+2}}$	Net CO_2 Emissions
	$\frac{lb_{CO_2}}{kWh}$	$\frac{hr}{yr}$	$\frac{lb_{CO_2}}{yr}$	$\frac{lb_{CO_2}}{yr}$	$\frac{lb_{CO_2}}{yr}$	$\frac{lb_{CO_2}}{yr}$	$\frac{ton_{CO_2}}{yr}$
Chicago, IL	1.16	2,342	11.99×10^6	10.97×10^6	0.158×10^6	2.85×10^6	−991
Phoenix, AZ	1.05	5,489	11.99×10^6	9.93×10^6	0.330×10^6	2.06×10^6	−163
South Bend, IN	2.08	2,428	11.99×10^6	19.68×10^6	0.300×10^6	2.82×10^6	−5,400

In Table 3, although Phoenix has over twice the cooling hours of Chicago and South Bend, the net CO_2 emissions reduction is actually an order of magnitude less than in both of the other cities. The more than doubled number of cooling hours in Phoenix versus the other cities is reflected in the slightly more than doubled CO_2 emissions reduction from offsetting the chiller energy usage. However, the larger reduction from offsetting chiller energy usage comes at the expense of fewer HW therms offset because of the reduced amount of non-cooling hours. It appears that the increased chiller emissions offset is the term that contributes least to the overall emissions reduction.

South Bend has a coefficient for utility generated emissions that is nearly twice as large as those in the other states. This impacts the analysis in both of the two terms associated with electrical power. This doubled emissions coefficient is reflected in the approximately doubled CO_2 emissions offset from the power generation. The fact that the emissions offset by power generation is larger than the emissions associated with engine fuel consumption indicates that the natural-gas-fired CHP system would, in fact, reduce on-site CO_2 emissions without utilizing any waste heat. The reason for this is that Indiana is a state that generates a significant amount of electricity at coal-fired power plants, and a CHP system that uses natural gas as its fuel, by design, will have fewer CO_2 emissions than the state average.

The result of this comparison between cities is that the coefficients of CO_2 emissions for electrical power have a stronger effect on net CO_2 emissions than weather effects. Also, the emissions reduction from offsetting chiller energy provides the smallest contribution to the emissions balance for each city.

CONCLUSIONS

This work was undertaken to expand on the premise that the implementation of a CHP system can result in a net reduction of on-site GHG emissions. In this work, the CHP system considered for analysis consisted of an internal combustion engine generator with waste heat recovered in an absorption chiller to be installed in a hypothetical carbon dioxide reduction project as part of the "Chicago Climate Action Plan."

The full load analysis examined the performance of the CCHP system as an alternative to a fully loaded centrifugal chiller. The results of the analysis indicate that a CCHP system replacing a chiller operating continuously at full load can reduce on-site carbon dioxide emissions by hundreds of tons annually over the reduction provided by a variable speed chiller.

The part load analysis examined the performance of the same CCHP system as an alternative to a partially loaded variable speed centrifugal chiller. Four methods were described for evaluating the results of the installation including the use of local weather data with the manufacturer supplied NPLV value, with manufacturer supplied performance curves, with equipment specific performance maps, and performance trend data as logged by an energy management system. The results of the analysis indicate that a CCHP system can further reduce on-site carbon dioxide emissions relative to the variable speed chiller; but the full utilization of exhaust heat, through an additional heat exchanger to a hot water system or otherwise, is critical to achieving an emissions reduction.

To account for the fact that typical chiller operation does not necessarily occur during a majority of operating hours, a sensitivity analysis was performed to compare the relative impact of cooling hours versus the emissions coefficients for electricity generated in different states. Table 3 shows that, for the same system analyzed in three cities, the results indicate that CCHP systems can outperform modern chiller technology in reducing on-site CO_2 emissions. Results indicate that emissions coefficients weigh much more heavily on the net effects of CCHP systems than do the cooling hours at the location of installation. This suggests that the cost of installing the system will have greater returns in states with higher emissions coefficients and less cooling hours than in states with lower emissions coefficients and more cooling hours. Furthermore, this finding suggests that financial incentives for installing CHP systems in states with higher emissions coefficients would result in a greater emissions reduction per incentive dollar. Five states with the highest emissions coefficients for electricity are: Indiana, Kentucky, New Mexico, North Dakota, and Wyoming.

The maximization of heat recovery is typically the major factor in the success or failure of a CHP system in achieving project goals. The analyses in this study were based conveniently around a hypothetical facility with electric and thermal loads safely in excess of equipment output capability to the extent that hot and chilled water can be generated and used simultaneously. This permits the investigation of CCHP system designs that can continuously generate heat and power at maximum output to maximize savings independent of weather conditions. This scenario is possible at facilities with large and consistent domestic hot water loads.

CCHP designs for facilities that fulfill only HVAC thermal demands must be developed more carefully, with a useful sink for excess exhaust energy generated during off-design cooling loads, to ensure that emissions are being reduced and a minimal amount of exhaust heat is vented to the atmosphere. This is the result of the notable difference between hot and chilled water heat recovery systems—the former has one stage of heat exchange and the latter has two. Both transfer heat from exhaust gas to water, but the absorption chiller also transfers heat from the water to the working fluids. The irreversibilities associated with the transfer of heat from water to working fluids in the absorption chiller represents energy that could possibly have been better used to offset emissions.

The methodologies presented in this work can be used as calculation tools for engineers and points of reference for facility managers and owners who are tasked with developing emission reduction projects. This will enable engineers to assess the feasibility of achieving a targeted reduction with CHP applications that involve cooling in both full and part load applications.

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