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Water, Air Emissions, and Cost Impacts of Air-Cooled Microturbines for Combined Cooling, Heating, and Power Systems: A Case Study in the Atlanta Region

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ABSTRACT

The increasing pace of urbanization means that cities and global organizations are looking for ways to increase energy efficiency and reduce emissions. Combined cooling, heating, and power (CCHP) systems have the potential to improve the energy generation efficiency of a city or urban region by providing energy for heating, cooling, and electricity simultaneously. The purpose of this study is to estimate the water consumption for energy generation use, carbon dioxide (CO_2) and NO_x emissions, and economic impact of implementing CCHP systems for five generic building types within the Atlanta metropolitan region, under various operational scenarios following the building thermal (heating and cooling) demands. Operating the CCHP system to follow the hourly thermal demand reduces CO_2 emissions for most building types both with and without net metering. The system can be economically beneficial for all building types depending on the price of natural gas, the implementation of net metering, and the cost structure assumed for the CCHP system. The greatest reduction in water consumption for energy production and NO_x emissions occurs when there is net metering and when the system is operated to meet the maximum yearly thermal demand, although this scenario also results in an increase in greenhouse gas emissions and, in some cases, cost. CCHP systems are more economical for medium office, large office, and multifamily residential buildings.

1. Introduction

Cities are hubs for global economic activity and energy use. They are responsible for more than 70% of global energy use and approximately 50% of global greenhouse gas emissions [1]. In addition, the World Bank estimates that cities account for more than 80% of the global gross domestic product (GDP) [2]. By 2050, two-thirds of the global population will be city-dwellers, a shift that has prompted city governments to look for ways to reduce resource use and decrease environmental impacts [3]. There are three main challenges for cities with respect to continued growth: ① reducing energy demand, ② reducing water demand, and ③ reducing emissions. One of the critical issues in the provision of urban utilities is the energy-water nexus. It takes water to create energy and energy to treat and distribute water. Traditional energy generation systems typically have a high water footprint. Combined cooling, heating, and power (CCHP) systems have the potential to increase efficiency; alter the fuel mix of energy generation; and decrease primary energy use, water consumption, and emissions.

CCHP systems have greater energy efficiency than conventional energy generation systems. Instead of wasting heat, CCHP

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systems use the heat generated during the combustion process to partially (or fully) meet the heating and cooling requirements of the building [4]. Conventional energy systems for buildings (Fig. 1) are comprised of electricity from the central power grid and heat from a furnace or boiler [5,6]. Typical CCHP systems are composed of a microturbine and an absorption chiller (Fig. 1). The microturbine is the power-generating unit (PGU) of the system and generates electricity and heat, while the absorption chiller is able to convert the heat provided by the PGU in order to cool the building when required. The heat recovery unit (HRU) takes the exhaust heat provided by the PGUs and uses it to provide hot water and space heating. Increased efficiency translates into reduced carbon dioxide (CO_2) and NO_x emissions as well as reduced "water for energy" consumption. (From this point forward, "water for energy" refers to consumptive (evaporative) water demand for electricity generation.) Accordingly, the implementation of CCHP systems could have a tremendous impact at the urban scale due to the increased energy efficiency, lower water for energy footprint, lower emissions, and improved air quality.

The implementation of CCHP systems is of particular importance to cities or urban regions that currently, or might soon, face issues of water scarcity [7]. Atlanta is one such urban region. The Atlanta metropolitan region, located in the state of Georgia, is one of the fastest growing metropolitan regions in the US [8]. Georgia is located in the southeastern US and predominantly experiences a humid subtropical climate similar to the climate in southeastern Chinese cities such as Shenzhen. In Georgia, approximately 49% of the water withdrawal is for thermoelectric power [9]. With an estimated 55% of the state's population living within the Atlanta metropolitan region, a significant portion of the water for energy generation can be attributed to the metropolis [9,10]. The continued urban sprawl in Atlanta, combined with the inefficiencies and losses associated with traditional energy generation, will continue to increase energy and water demand and energy-related emissions [11]. Implementation of CCHP systems could increase the efficiency of the energy generation system and thereby reduce the CO_2 and NO_x emissions and the water for energy consumption of the region. Having a decentralized energy production system also increases the redundancy within the energy production system of a region, thereby increasing its resiliency.

There have been many studies on the benefits of CCHP systems and the most effective way to reduce cost, primary energy consumption, and carbon emissions [12,13]. CCHP systems can be designed to reduce the primary energy consumed [14–17], the cost [15] and carbon footprint of energy applications [12,18–20], or some combination thereof. Two strategies that have been widely used when modeling the operation of CCHP systems are: "following the electrical load" (FEL) [21] and "following the thermal load" (FTL). Most of the research on the use of CCHP systems has examined how the various load options mentioned above can best optimize the system to reduce cost, primary energy consumption, and carbon emissions. Previous studies have concluded that a "hybrid electric thermal" (HET) approach, which switches between FTL and FEL, and FTL are the best strategies to reduce the amount of excess heat and energy [22]. In some situations, the addition of thermal storage reduces costs by several percent [23]. Han et al. [24] modified the HET approach even further using a multi-objective optimization model. Knizley et al. [25] split the operation of the turbines into two components: One component meets a base load and the other component meets FEL or FTL.

Cho et al. [26] explored the operation of CCHP systems in different climatic conditions and the tradeoffs in cost and carbon emission reductions. The power to heat ratios—that is, the proportion of electrical energy to heat energy—of various building types also determine how effective combined heat and power (CHP) systems are in optimizing the reduction of energy consumption, cost of energy, and emissions [23]. The effects of energy management also impact the efficiency of the overall system and therefore the cost and number of units required [27]. The objective of this paper is to estimate the efficacy of implementing CCHP systems for five generic building types in the Atlanta region, looking at how the water for energy consumption, NO_x and CO_2 emissions, and costs are affected by various FTL options (e.g., hourly, daily, monthly, and yearly).

2. Material and methods

Our CCHP system consists of an air-cooled microturbine and an air-cooled absorption chiller (Fig. 1) used to meet the heating and cooling load of a building. For comparison, a conventional

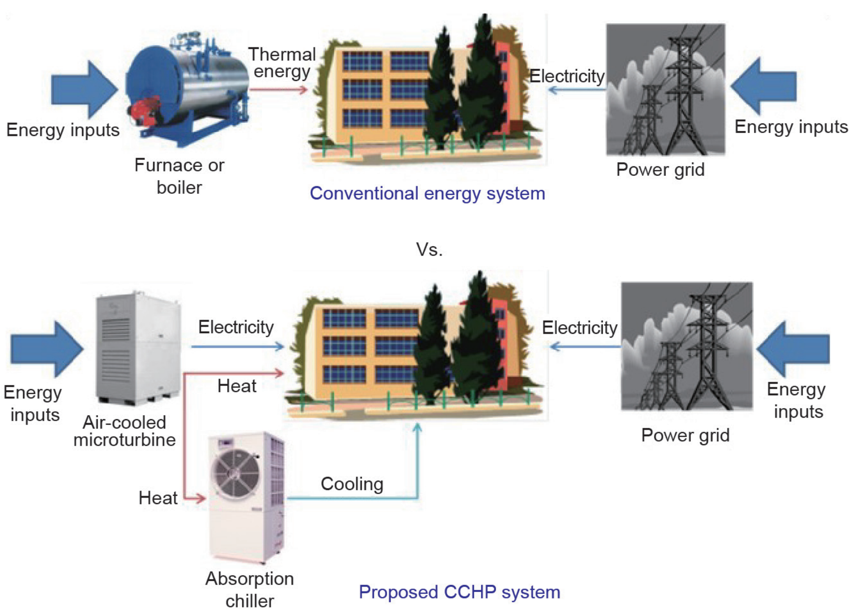

Fig. 1. A conventional building energy supply system versus a combined cooling, heating, and power (CCHP) system.

energy system is shown at the top of Fig. 1. In CCHP systems, the thermal load of the building consists of the sum of the energy required for space heating, cooling, and hot water. The CCHP system was designed to be an FTL model; systems of this type have been shown to have lower emissions and lower costs than those resulting from FEL of the building [22,28]. Five scenarios were tested to see which would most significantly decrease CO_2 and NO_x emissions, water for energy consumption, and cost. Each scenario is a variation of how the microturbine(s) was operated to meet the hourly, maximum daily, maximum monthly, and maximum yearly thermal demands of the buildings.

Capstone air-cooled microturbines were considered for this analysis, as they use air cooling rather than water cooling. Capstone currently manufactures 30 kW, 65 kW, and 200 kW air-cooled microturbines. Combinations of these turbines ranging from 95 kW to 2 MW were also evaluated. The combinations included differently sized turbines such as 95 kW (a combination of 65 kW and 30 kW turbines) and others. The thermal outputs of the turbines, running at various capacities, were determined using the technical manuals provided by the manufacturer [29]. In the case where multiple turbines are used, it is assumed that the largest turbine in the combination is ramped up first until it reaches 100% capacity. The process is repeated for each subsequent turbine added until the thermal demand is met. The thermal output for a given turbine corresponds to a given electrical output and fuel input requirements. The operating schedule of the turbines was simulated to meet the hourly, maximum daily, maximum monthly, and maximum yearly thermal loads of the five building types being considered (details are provided in Supplementary Information, Appendix A).

In each case, the turbine or combination of turbines was always able to meet the thermal load of the building. Therefore, the size of the turbine remained the same for a given building type, regardless of the operating scenario.

2.1. Reference buildings and energy supply options

Five building types were used in the analysis: three commercial and two residential buildings. The three commercial buildings ranged in size from small (5500 ft^2, 1 ft^2 = 0.092903 m^2) to large (500 000 ft^2), and the two residential buildings were a single-family house and a multifamily apartment building. Table 1 [30,31] contains some of the buildings' characteristics, specifications, and heating and cooling equipment used for conventional heating and cooling. The thermal load of a single-family building was too low for even the smallest sized turbine (30 kW). Calculation shows that a single 30 kW turbine would always be able to meet the thermal demand of five single-family buildings. This was calculated by dividing the maximum hourly thermal output of the turbine by the maximum hourly thermal output of the given building. All subsequent uses of "single-family" refer to five single-family buildings.

The building energy load profiles for Atlanta were obtained from the Open Energy Information (OpenEI) website [30]. The energy demands were generated from EnergyPlus simulations of the US Department of Energy commercial reference building models using the typical meteorological year 3 (TMY3) weather file for the Atlanta region [32]. The TMY weather file is used to describe a typical meteorological month that most closely represents the average meteorological month the (TMY) over a 30-year period [33].

We determined the buildings' heating, cooling, and electrical energy demands for the conventional energy system and the CCHP system using the OpenEI datasets for building energy demand. The building energy demand and input energy requirements for a small office building using a conventional and a CCHP system are shown in Fig. 2. The building electrical and thermal energy demands, when using the conventional energy system, were calculated using Eq. (1) and Eq. (2), respectively. For the conventional energy system, the building electrical demand must be met entirely by the electrical grid. The yearly energy input required by a building using the conventional energy system was determined by dividing the electrical load in Eq. (1) by the efficiency of the electrical grid and dividing the thermal load in Eq. (2) by the efficiency of the heating equipment. The yearly thermal and electrical energy inputs for a building using a conventional energy system were then added together to determine the total energy inputs required by the building. Energy supply for conventional operation is shown in Fig. 2(b).

$$\text{Electrical demand}_{\text{conventional}} = E_{\text{plug load}} + E_{\text{space cooling}} \tag{1}$$

$$\text{Thermal demand}_{\text{conventional}} = \text{Heating}_{\text{space}} + \text{Heating}_{\text{hot water}} \tag{2}$$

The building electrical and thermal energy demands for the CCHP system were determined using Eq. (3) and Eq. (4). The building electrical demand for the CCHP system is the plug load (Eq. (3)). The thermal load for a CCHP system is the sum of the energy required for space heating, hot water, and heat energy required for the absorption chiller for space cooling. The absorption chiller is able to convert heat energy into cooling energy. The heat energy required by the absorption chiller is determined using the ratio of coefficient of performance (COP) of the air conditioner and absorption chiller. It is assumed that the air conditioning

$$\text{Electrical demand}_{\text{CCHP}} = E_{\text{plug load}} \tag{3}$$

$$\begin{aligned}\text{Thermal demand}_{\text{CCHP}} = {} & \text{Heating}_{\text{space}} + \text{Heating}_{\text{hot water}} \\ & + (\text{COP}_{\text{air conditioner}}/\text{COP}_{\text{absorption chiller}}) \\ & \times E_{\text{space cooling}}\end{aligned} \tag{4}$$

Table 1
Characteristics of reference buildings and the conventional energy systems [30].

Building type	Size (ft^2)	Numbers of floors	Heating equipment (cost [31])	Cooling equipment (cost [31])	Yearly building electrical demand (kW·h·a^{-1})[a]	Yearly building thermal demand (kW·h·a^{-1})	Turbine size (kW)
Large office	500 000	12	Boiler ($9.85 ft^{-2})	Chiller, water-cooled-multi-zone ($9.85 ft^{-2})	6 963 487	419 346	2 000
Medium office	53 628	3	Boiler ($17.45 ft^{-2})	Packaged DX-multi-zone ($17.45 ft^{-2})	728 547	18 019	325
Small office	5 500	1	Furnace ($9.25 ft^{-2})	Packaged DX-single-zone ($9.25 ft^{-2})	68 171	7 447	30
Multifamily residential	33 740	4	Furnace ($6.39 ft^{-2})	Packaged DX-split system-single-zone($6.39 ft^{-2})	258 790	107 795	95
Single-family residential	2 546	1	Furnace ($6975)	Single packaged ($6975)	12 740	10 342	30 (for 5 buildings)

[a] cooling+plug load.

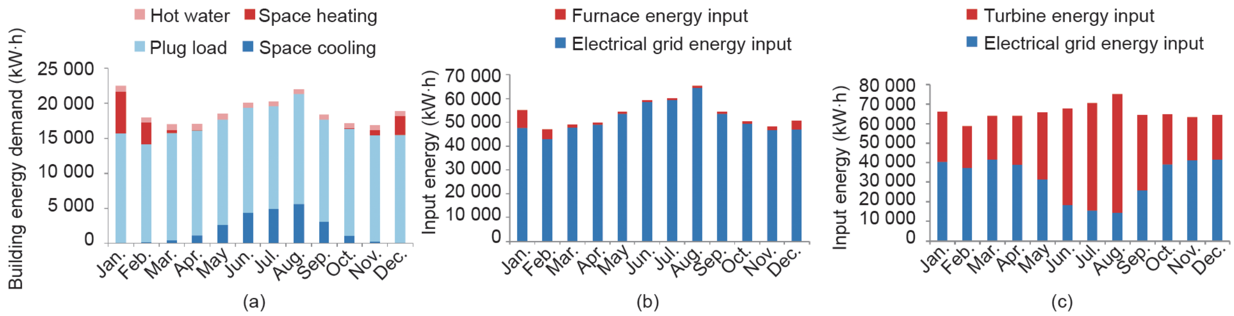

Fig. 2. Energy requirements of a small office building based on TMY3 weather files for the Atlanta region. (a) Small office building energy requirements; (b) input energy requirements of a small office building using a conventional energy generating and distribution system; (c) input energy requirements of a small office building on a CCHP system operated to meet the hourly thermal demand.

units use electricity and have a COP of 3.8, which corresponds to the minimum allowable seasonal energy efficiency ratio of 13. We assumed the COP of a commercially available single-effect absorption chiller to be 0.68 [34]. We also considered systems with a theoretical air-cooled double-effect absorption chiller, which has a COP of 1.42, similar to that found in literature [35–38]. The yearly energy input is the energy input that would be required from the electrical grid and the energy input required by the CCHP system. The input energy required by the CCHP system was determined using the manufacturer's technical documents, which provide turbine fuel requirements for turbines running at a given capacity. The electrical energy required from the grid is the electricity demand of the building minus the electricity produced by the turbine (Eq. (5)). The energy input required by the electrical grid system is the electricity required from the electrical grid divided by the efficiency of the grid generation and distribution system. The energy required for CCHP operation for a small office building is shown in Fig. 2(c).

$$\text{Electrical grid demand}_{\text{CCHP}} = \text{Electrical demand}_{\text{CCHP}} - \text{Turbine}_{\text{elec}} \tag{5}$$

2.2. CCHP system operation

Five alternate energy generation scenarios were evaluated for the buildings: ① no CCHP, ② turbines run to meet the hourly thermal demand, ③ turbines run to meet the maximum daily demand, ④ turbines run to meet the maximum monthly demand, and ⑤ turbines run at the yearly maximum thermal demand throughout the year. The hourly thermal load using a CCHP system was calculated by modifying the OpenEI dataset so that the heat required to produce space cooling (via an absorption chiller) was included in the thermal demand (Eq. (4)). The input data for Scenarios ③–⑤ were produced by altering the hourly thermal load of the building, from Eq. (4), to represent the maximum daily demand, maximum monthly demand, and maximum yearly demand. The maximum daily thermal demand was determined by finding the maximum thermal demand for every day in the hourly thermal dataset and setting this as the thermal demand of the building for the day. The maximum monthly and maximum yearly demands were determined in a similar fashion for a given month and for the year. Appendix A describes how the turbines were operated compared to the demand of the building and operation schedule. For each building type and scenario, the water for energy consumption, CO_2 emissions, NO_x emissions, and system costs were estimated. The turbines were modeled to ramp up and down to meet the demand profile required for the four scenarios that included a CCHP system. Turbine size was chosen based on the smallest sized turbine that was able to meet the maximum thermal load required by the building. Since the microturbine meets the entire thermal load, there is no need for a boiler or furnace if a CCHP system is used. All scenarios will require energy from the grid, but the amount will depend on how the turbines are operated. The absorption chiller for each building was sized to satisfy the cooling requirement of the building.

2.3. Water for energy, and emissions

The average CO_2 and NO_x emissions per kW·h from the Atlanta generation mix are shown in Table 2 [39–45], using 2012 and 2013 data. These emissions can be expected to change as newer power generation facilities replace older, less efficient plants. Choi and Thomas [46] have calculated that greenhouse gas emissions per kW·h in Georgia will fall over time as new nuclear power plants are completed and the planned retirements of coal-fired power plants occur. For this study, the CCHP emissions were compared to the emissions of the current Atlanta energy generation mix. Emissions from the furnace and from the microturbine were calculated using data provided by the manufacturer [39,40,47]. Water used for cooling in electricity production includes both water that is withdrawn and subsequently returned to the watershed (e.g., in once-through cooling systems) and water that is evaporated (e.g., in evaporative cooling). Water consumption (evaporative loss) for energy generation was calculated using the average consumption factor for the Georgia grid: 1.65 $\text{gal}\cdot(\text{kW}\cdot\text{h})^{-1}$. A secondary analysis compared the CCHP scenarios to one in which the energy required from the grid was met by a combined cycle natural gas plant using a factor of 0.2 $\text{gal}\cdot(\text{kW}\cdot\text{h})^{-1}$ [48],

Table 2
Emissions generation and water for energy consumption factors.

	CO_2e emissions ($\text{kg}\cdot(\text{kW}\cdot\text{h})^{-1}$)	NO_x emissions ($\text{g}\cdot(\text{kW}\cdot\text{h})^{-1}$)	Water for energy consumption ($\text{gal}\cdot(\text{kW}\cdot\text{h})^{-1}$)
Microturbine	0.768 [39]	0.290 [39]	—
Conventional electrical grid	0.570 [41]	0.408 [49]	1.65 [43]
Furnace	0.227	0.425 [40]	—
CCNG plant	0.515	0.300 [44]	0.20 [45]

CCNG: combined cycle natural gas.

which may be more typical of marginal consumption. Eq. (6) and Eq. (7) display factors that were included in the emissions for scenarios with CCHP versus those without.

$$\text{Emissions}_{\text{conventional net}} = \text{Emissions}_{\text{grid}} + \text{Emissions}_{\text{furnace}} \tag{6}$$

$$\text{Emissions}_{\text{CCHP net}} = \text{Emissions}_{\text{grid}} + \text{Emissions}_{\text{turbine}} \tag{7}$$

2.4. Cost estimates

The costs of the no-CCHP scenario, in which all the energy comes from the electrical grid and furnace, were calculated using the Georgia Power price of electricity [49] and the price of natural gas in Georgia for residential and commercial customers (Table 3) [42,50–52]. The cost of the CCHP systems was estimated using the range given in the literature, and the costs for the furnace and the heating, ventilation, and air conditioning (HVAC) system were estimated using the RSMeans dataset [31,53]. There may be installation costs over and above these values, which should be considered for individual project evaluation. The capital cost of the CCHP equipment was amortized for the yearly cost using a discount rate of 5% and a system lifetime of 10 years [29] (details are provided in Supplementary Information, Appendix B). The yearly HVAC systems cost was determined using a similar discount rate and a system lifetime of 15 years (details are provided in Appendix B). The capital cost of the absorption chiller was estimated using the range of values provided in the literature and an estimated lifespan of 20 years [52]. Two capital costs were calculated for the CCHP system using the minimum and maximum range of costs provided for the microturbine and absorption chiller. The total cost per year for each building in each scenario was estimated by summing the yearly fuel costs and the yearly capital costs for each system (Eq. (8) and Eq. (9)). The capital costs incurred by the utilities are incorporated in the per kW·h price paid for electricity generation. It is assumed that the buildings in the scenarios will be new, so the costs compare conventional technologies to that of the CCHP system. A secondary cost analysis also compared the cost of the CCHP systems under the premise that the price of natural gas used by the system was similar to the price paid by utilities.

$$\text{Cost}_{\text{conventional net}} = (\text{Elec}_{\text{used}} \times P_{\text{elec}}) + (\text{Nat gas}_{\text{used}} \times P_{\text{nat gas}}) + P_{\text{AC yearly}} + P_{\text{furnace yearly}} \tag{8}$$

$$\text{Cost}_{\text{CCHP}} = (\text{Elec}_{\text{used}} \times P_{\text{elec}}) + (\text{Nat gas}_{\text{used}} \times P_{\text{nat gas}}) + P_{\text{turbine yearly}} + P_{\text{chiller yearly}} \tag{9}$$

2.5. Net metering

Within each of the five scenarios, the impact of a net metering policy on the system was evaluated. Net metering is the ability to sell excess electricity generated to the grid. Net metering policies in the state of Georgia limit system capacities to 10 kW and 100 kW, respectively, for residential and nonresidential sectors, and do not currently include CHP systems as an eligible technology [54]. In this study, we assume that the net metering policy in Georgia is similar to that of New York, which includes CHP systems in the technology portfolio, and which has a maximum system capacity of 2 MW [54]. For scenarios with net metering, the electricity available to sell back to the grid was determined by finding the difference between the electricity generated by the CCHP system and the electricity demand of the building. Excess electricity is generated when, at any given hour, the electricity produced by the turbine surpasses the electricity required by the building. The water consumed during energy production for the CCHP system and for traditional systems was calculated using the estimates listed in Table 2. As stated previously, the microturbine is air-cooled and therefore does not consume any water. It is assumed that, when a net metering policy is implemented, the water consumed for energy produced by the power grid is mitigated, since a portion of the electricity will be provided by the CCHP system.

Table 3
Costs of CCHP system components and fuels.

Cost type	Cost description	Cost range ($ USD)
Microturbine	Capital ($\$\cdot\text{kW}^{-1}$)	700–1100 [52]
	O&M ($\$\cdot(\text{kW}\cdot\text{h})^{-1}$)	0.005–0.016 [52]
Absorption chiller	Capital ($\$\cdot\text{kW}^{-1}$)	140–290 [51]
	O&M ($\$\cdot(\text{kW}\cdot\text{a})^{-1}$)	4.5–9 [51]
Natural gas	Residential ($\$\cdot(\text{kW}\cdot\text{h})^{-1}$)	0.049815 [42]
	Commercial ($\$\cdot(\text{kW}\cdot\text{h})^{-1}$)	0.032 [42]
	Utility ($\$\cdot(\text{kW}\cdot\text{h})^{-1}$)	0.015 [42]
Grid electricity	Residential ($\$\cdot(\text{kW}\cdot\text{h})^{-1}$)	0.1255 [50]
	Commercial ($\$\cdot(\text{kW}\cdot\text{h})^{-1}$)	0.1044 [50]

O&M: operation and maintenance.

3. Results and discussion

The CCHP system, which has a single-effect absorption chiller, cannot reduce the primary energy input, regardless of the operational strategy. Double-effect chillers are common in industry and have a COP of 1.42 [35–38]; however, they are not air-cooled systems. According to manufacturers, air-cooled double-effect absorption chillers are possible, but are currently cost prohibitive based on customer demand. We therefore considered the impact on the input energy of a system with a double-effect chiller (with a minimum COP of 1.42). In this case, a CCHP system (with a double-effect chiller) operated to meet the hourly thermal load would reduce the amount of input energy required by 3%, 12%, and 20%, respectively, for the multifamily, medium office, and large office buildings, as shown by a comparison of the first two bars for each building type in Fig. 3(b). Moreover, there is a tradeoff in the input energy requirement when CCHP is used: More electricity is produced per unit of energy input and the building requires less electricity from the grid. This tradeoff is shown in the medium and large office buildings in Fig. 3(b).

However, for smaller buildings, CCHP systems can increase the input energy use even with a double-effect absorption chiller. For the small office building, the peak thermal energy demand is approximately 35% of the maximum turbine thermal energy output when a double-effect absorption chiller is used. Therefore, to maximize the benefits, we assumed that two small office buildings would be able to function on one CCHP system, assuming the use of a double-effect absorption chiller. In this scenario, the overall energy consumption increases by 53% in the case of the small office building with a CCHP system that has a double-effect absorption chiller being run to meet the hourly building thermal requirements, as shown in Fig. 3(b). All other operational strategies would further increase the input energy use. Similarly, there is a 20% increase in the input energy for the single-family building complex when a CCHP system with a double-effect chiller is operated to meet the hourly thermal demand. In these cases, even when the CCHP system was running at its lowest capacity, it was still producing more thermal energy than the building required. Fig. 4 shows that even operating the turbine at its lowest capacity produces more thermal energy than is required by the thermal demand of two small office buildings. In comparison, the excess thermal energy production is much smaller for a medium office building when either a single-effect or a double-effect absorption chiller is used (Appendix A, Fig. A1). The increased efficiency of the CCHP system was not significant enough to offset the excess input energy required when the system was overproducing thermal energy.

3.1. Energy and "water for energy" savings

In all scenarios, and for all building types, there was a significant reduction in electricity required from the grid as compared to the centralized system. The operating scenarios that require the turbines to operate consistently at higher outputs reduce the building's dependence on the electrical grid as the turbines generate more electricity. This is because the turbine is able to meet most or all of the building's electrical demand. The excess electricity generated can be sold to the grid.

Fig. 5 displays the water consumption for energy production for a medium office building under all operating scenarios (FTL) with and without net metering, assuming: ① the average water demand for Georgia electrical power production, and ② that all grid energy was met using combined cycle natural gas plants. The water for energy demand is reduced to zero in the maximum monthly and maximum yearly thermal demand operating scenarios. This result was expected, because the CCHP is producing excess heat while producing more electricity, translating to no energy being required from the grid. No consumption of grid electricity means that there is no water for energy consumption. The water for energy results were similar for all other buildings (Table 4). The water for energy consumption for all buildings and scenarios with a CCHP system is less than that of the central grid scenario, and is zero in all cases when the CCHP system is operated to meet the maximum monthly or maximum yearly thermal demand (see Supplementary Information, Appendix C, Fig. C1(a) and (b) for details).

3.2. Emission reductions

The maximum reduction in CO_2 emissions for a medium office building is 3% when a CCHP system with a single-effect absorption chiller is operated to meet the hourly thermal demand of the building (Table 4). All other operating scenarios result in CO_2 emissions that are higher than those of the no-CCHP scenario, as shown in Fig. 6(a). The single-family, multifamily, and small office buildings have a reduction in CO_2 emissions if the CCHP system is operated to meet the hourly thermal demand (Table 4; also see Supplementary Information, Appendix D, Fig. D1). We found that there was a 13% increase in CO_2 emissions for the large office building (Table 4).

However, if a CCHP system has a double-effect absorption chiller, then the CO_2 emissions for the medium office building can be reduced by 20%, when the CCHP system is operated to meet the hourly thermal demand. For a medium office building, the system can be operated to meet the daily demand and still have lower CO_2 emissions than the no-CCHP scenario. However, if the system is operated at the maximum monthly or maximum yearly demand, the emissions from the CCHP system are greater than those from the conventional system, because too much heat is

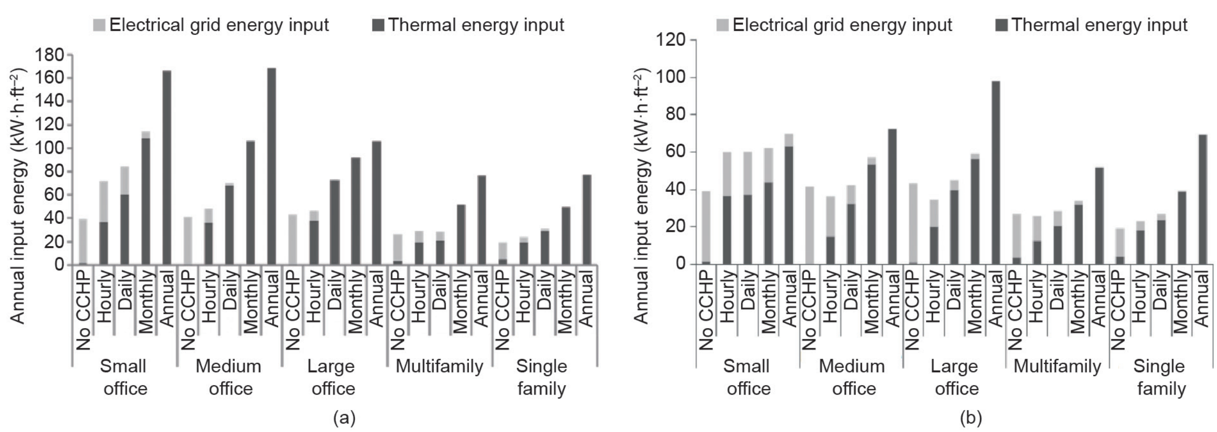

Fig. 3. Input energy for all building types in all scenarios. (a) Input energy needed when using a single-effect absorption chiller with a COP of 0.68; (b) input energy needed when using a double-effect absorption chiller with a COP of 1.42.

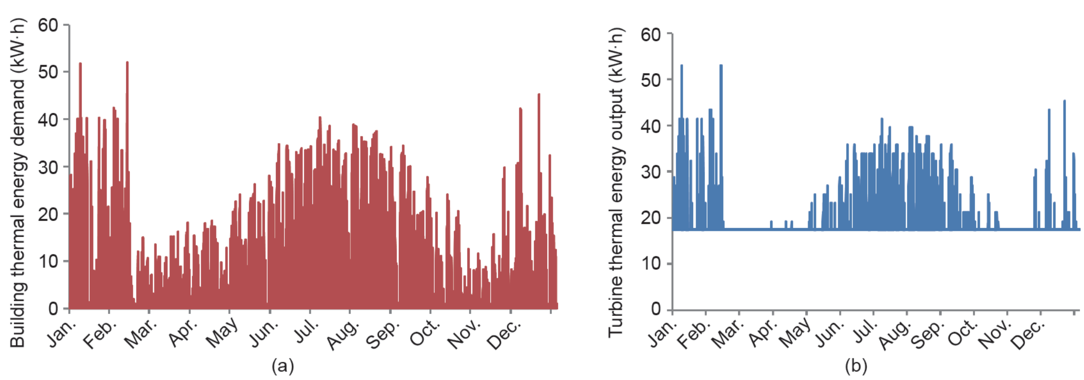

Fig. 4. Thermal demand of two small office buildings when a CCHP system with a double-effect absorption chiller is used, and the thermal output of the microturbine in the CCHP system. (a) Hourly thermal demand of a small office building; (b) thermal output of a 30 kW turbine operating to match the hourly thermal output of a small office building.

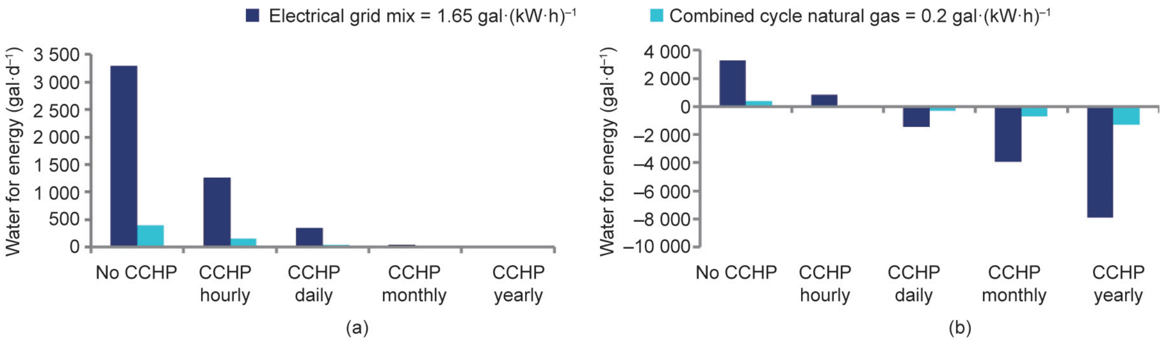

Fig. 5. Water for energy consumption for a medium office building, comparing the consumption factor of the Georgia grid with the consumption factor of a combined cycle natural gas plant. (a) Water for energy consumption of a medium office building with a CCHP system and no net metering; (b) water for energy consumption of a medium office building with a CCHP system and net metering. Negative water for energy consumption is the water consumption mitigated by the grid because it is generating less electricity. (Note: In these figures, the term "hourly" refers to meeting the hourly demand, and the terms "daily," "monthly," and "yearly" refer to meeting the maximum daily, monthly, or yearly demand, respectively.)

Table 4
Percent change in water for energy, CO_2 emissions, and NO_x emissions for all buildings and all operating scenarios, compared with the no-CCHP scenario when a single-effect absorption chiller is used.

Building type	Water for energy consumption				CO_2 emissions				NO_x emissions			
	Hourly	Daily	Monthly	Yearly	Hourly	Daily	Monthly	Yearly	Hourly	Daily	Monthly	Yearly
Small office	–62%	–90%	–99%	–100%	–3%	+53%	+134%	+278%	–54%	–68%	–63%	–42%
Medium office	–45%	–56%	–77%	–100%	–3%	+12%	+55%	+165%	–45%	–51%	–62%	–65%
Large office	–80%	–99%	–100%	–100%	+13%	+82%	+129%	+160%	–68%	–73%	–67%	–63%
Multifamily residential	–57%	–78%	–98%	–100%	–9%	+34%	+95%	+95%	–63%	–70%	–74%	–62%
Single-family residential	–72%	–86%	–100%	–100%	–26%	+25%	+149%	+149%	–65%	–49%	–6%	+60%

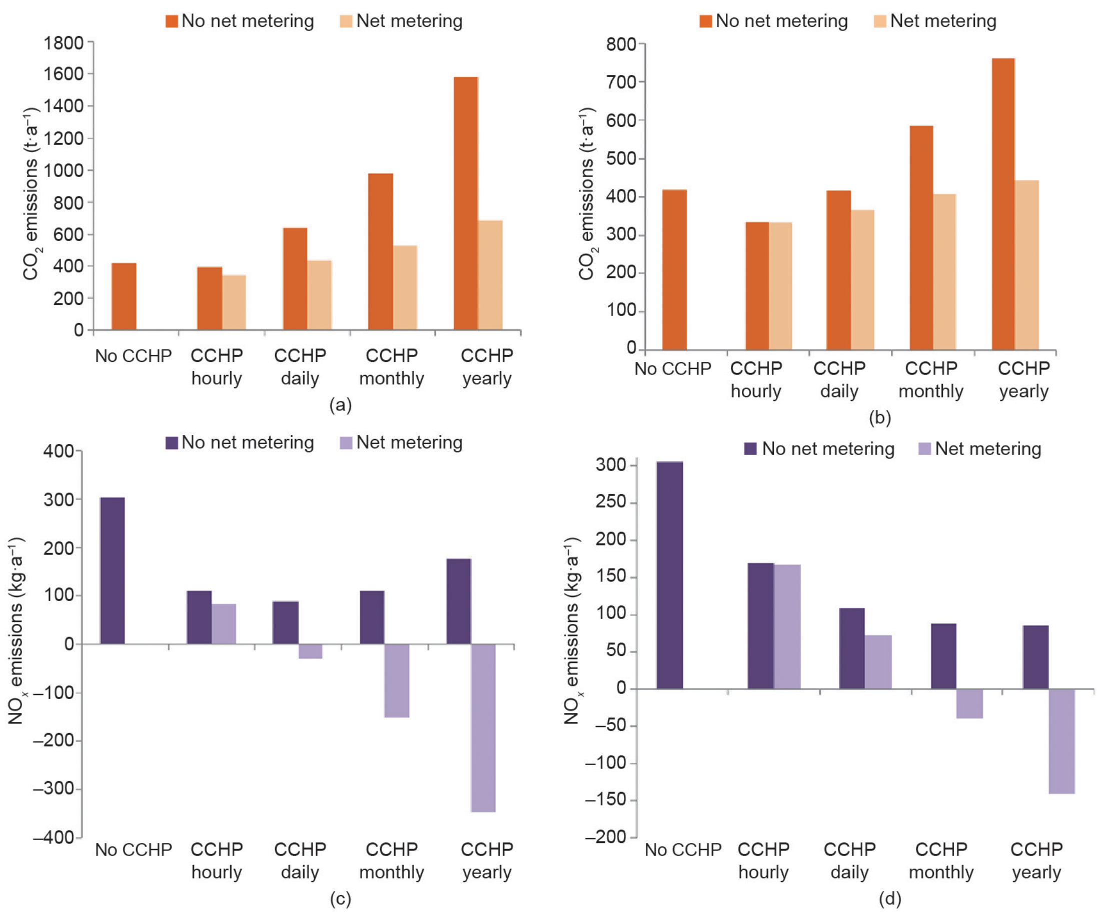

Fig. 6. Yearly emissions for a medium office building operating under varying CCHP operations. (a) CO_2 emissions for a medium office building when a single-effect absorption chiller is used (COP: 0.68); (b) CO_2 emissions for a medium office building when a double-effect absorption chiller is used (COP: 1.42); (c) NO_x emissions for a medium office building when a single-effect absorption chiller is used (COP: 0.68); (d) NO_x emissions for a medium office building when a double-effect absorption chiller is used (COP: 1.42). Negative emissions are the emissions mitigated, because over the year the grid is generating less electricity. (Note: In these figures, the term "hourly" refers to meeting the hourly demand, and the terms "daily," "monthly," and "yearly" refer to meeting the maximum daily, monthly, or yearly demand, respectively.)

wasted. All buildings have the lowest CO_2 emissions when the system is run to meet the hourly thermal demand (see Appendix D, Fig. D2(a) for details). The single-family buildings have the highest emission reduction, 38%, while the small office, large office, and multifamily buildings have decreases in emissions of 12%, 28%, and 29%, respectively.

NO_x emissions are reduced for the medium office building under all CCHP system operation scenarios with a single-effect absorption chiller. However, the greatest reduction is 68% and occurs when the system is operated to meet the maximum daily demand, as shown in Fig. 6(c). Similarly, although NO_x emissions are reduced for all the buildings when a CCHP system is used, the best-case scenario for NO_x reductions depends on the building type and the operating scenario (Table 4). Compared to the medium office building, the multifamily and large office buildings have higher NO_x reduction potentials of 74% and 73%, respectively, if the system is operated to meet the monthly and daily thermal demand. The small office building has a maximum 68% reduction if the system is operated to meet the daily thermal demand. The single-family buildings see a maximum NO_x reduction of 65% when the CCHP system is operated to meet the hourly demand; these are the only buildings that have an increase above the no-CCHP scenario when the system is operated at maximum yearly thermal demand. The difference in maximum achievable NO_x reduction for different buildings is attributable to the tradeoff between the wasted thermal energy and the reduced energy demand from the grid.

A double-effect chiller will also reduce all the NO_x emissions for the medium office building for all operating strategies. The greatest reduction occurs when the system is operated to meet the maximum yearly thermal demand. However, when a double-effect chiller is used, the reduction potential is not as great as with a single-effect chiller, as shown in Fig. 6(c) and (d). This result is attributable to the fact that when a single-effect absorption chiller is used, the hourly thermal demand is higher than when a double-effect absorption chiller is used. An increased thermal demand translates to a need for a larger turbine—325 kW versus 130 kW for single-effect and double-effect systems, respectively. A larger microturbine and a higher thermal demand lead to more electricity production, thereby reducing electricity demand from the grid. Less grid electricity reduces the overall NO_x emissions.

3.3. Cost

The medium office building is the most economical when the CCHP system meets the hourly thermal demand of the building; this building could have an yearly cost reduction of 14% (Fig. 7). For all other operational strategies, the costs are higher than those of the no-CCHP scenario. If the price of natural gas being charged is comparable to the price faced by utilities, the cost will be lower than the no-CCHP strategy in all operating strategies. The greatest reduction is approximately 50% and occurs if the system is operated to meet the hourly thermal demand (Fig. 7). When considering utility-priced natural gas, the hourly thermal demand operating strategy has the lowest cost for all buildings except the small office building, as shown in Fig. 8(a) and (b).

Fig. 8 and Fig. E1 (Appendix E, Supplementary Information), display the potential cost reductions for all building types and operating scenarios, assuming the maximum and minimum cost of the CCHP system. If we assume the maximum system cost, the cost is reduced in the case of the medium office, large office, and multifamily buildings (14%, 6%, and 9%, respectively) when the system is operated to meet the hourly thermal demand (Appendix E, Fig. E1). The small office building and the single-family residential buildings are the two building types in which having a CCHP system is more expensive than not having one, no matter how the system is operated. If we assume the minimum system cost, which is presented in Table 3, the medium office, large office, and multifamily buildings have a reduced energy cost but greater reductions: 29%, 20%, and 22%, respectively.

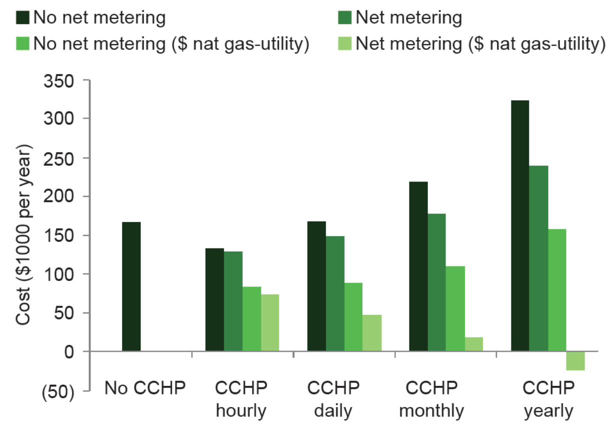

Fig. 7. Cost of implementing CCHP systems operating at various capacities, with and without net metering, and comparing the residential and commercial natural gas pricing rates to those of utilities for a medium office building. (Note: In these figures, the term "hourly" refers to meeting the hourly demand, and the terms "daily," "monthly," and "yearly" refer to meeting the maximum daily, monthly, or yearly demand, respectively.)

If we assume that utility-priced natural gas is used, the cost for all buildings operating under the hourly thermal demand strategy is lower than that of the no-CCHP scenario, when the minimum system cost is assumed (Fig. 8). The cost will also be lower for all buildings except the small office building when the maximum system cost is assumed. Fuel cost is the primary factor that determines whether CCHP systems will be economically beneficial. For example, in the case of the medium office building (Fig. 7), when the price paid for natural gas is similar to that charged to utilities, the cost of all scenarios is reduced by 23%–45%. This finding also means that the cost of the CCHP systems could be greatly affected by the cost of natural gas, with lower natural gas prices making CCHP systems more economically viable under all operating scenarios.

3.4. Impact of net metering

Net metering can result in significant reductions in water for energy consumption, CO_2 emissions, NO_x emissions, and the cost of all buildings and all operating scenarios of the CCHP system. Under a net metering policy, operating the CCHP systems to meet the yearly thermal demand provides the maximum reduction in water for energy and NO_x emissions for the medium office building, as shown in Fig. 5(b) and Fig. 6(c). The best operating strategy to reduce CO_2 emissions is still that of operating the system to meet the hourly thermal demand for the medium office building, which yields a reduction of 15% (Table 5). However, the CCHP system for the medium office building can be operated to meet the maximum yearly demand and still produce 1% less CO_2 emissions than the no-CCHP scenario. Operating the system to meet the hourly thermal demand is the best operating strategy for all the buildings to reduce CO_2 emissions (Table 5). Unlike the no-net-metering case, other operating strategies also reduce CO_2 emissions. Single-family residential, multifamily residential, large office, and small office buildings also have the greatest reduction (36%, 21%, 21%, and 4%, respectively) in CO_2 emissions when the CCHP system is operated to meet the hourly thermal demand of the building (Table 5).

All building types have the highest reductions in water for energy consumption and NO_x emissions when the CCHP system is operated to meet the maximum yearly demand (see Supplementary Information, Appendix C, Fig. C1(c) and (d), and Appendix F, Fig. F1(b) for more information). Water for energy consumption and NO_x emissions are greater than 100% in some operating scenarios because, over the entire year, the CCHP system produces more electricity than what is needed by the building (Table 5). With net metering in effect, this excess electricity is sold back to the grid, offsetting a portion of the grid electricity. Reduced production of grid electricity reduces water for energy consumption and NO_x emission, reductions that are entirely attributed to the demand of one building. The water for energy and NO_x reduction potentials are greater with a single-effect absorption chiller than with a double-effect absorption chiller because more electricity is generated by the CCHP system. The system generates more electricity because more thermal energy has to be generated in order to meet the thermal demand of the building.

The cost of CCHP systems for all building types, except for the single-family residential building, and for all operating scenarios is reduced when there is a net metering policy (Appendix E, Fig. E1). This means that the CCHP system can be operated at a higher capacity while still having a lower yearly cost than the no-CCHP scenario. In the case of the single-family building, implementing a CCHP system increases the cost by 47% if the system is operated to meet the hourly thermal load. Increasing the operating capacity of the system further increases costs, up to four times those of

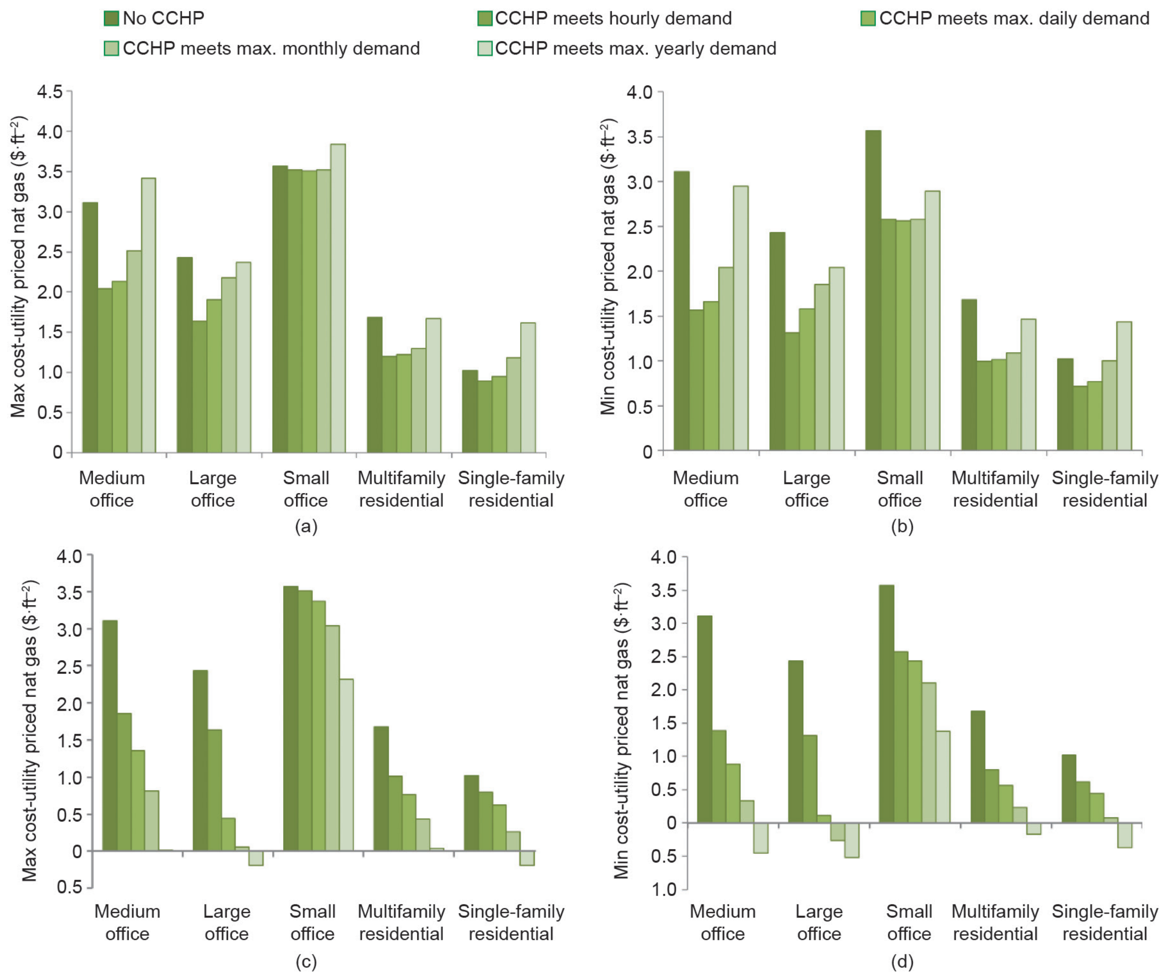

Fig. 8. Per square foot cost estimates of CCHP systems compared to the cost of energy in the no-CCHP scenario for all five building types. (a) Maximum CCHP system cost estimates with no net metering; (b) minimum CCHP system cost estimates with net metering; (c) maximum CCHP system cost estimates with no net metering, and assuming that the price of natural gas is equal to what utilities pay; (d) minimum CCHP system cost estimates with net metering, and assuming that the price of natural gas is equal to what utilities pay.

Table 5
Percent change in water for energy consumption, CO_2 emissions, and NO_x emissions for all buildings and all operating scenarios compared with the no-CCHP scenario, when there is a net metering policy and when a single-effect absorption chiller is used.

Building type	Water for energy consumption				CO_2 emissions				NO_x emissions			
	Hourly	Daily	Monthly	Yearly	Hourly	Daily	Monthly	Yearly	Hourly	Daily	Monthly	Yearly
Small office	−46%	−66%	−115%	−217%	−4%	+3%	+19%	+53%	−45%	−60%	−96%	−170%
Medium office	−74%	−144%	−219%	−340%	−15%	−1%	+15%	+40%	−66%	−121%	−180%	−276%
Large office	−115%	−199%	−246%	−276%	−21%	−16%	−13%	−12%	−101%	−168%	−205%	−229%
Multifamily residential	−72%	−130%	−205%	−304%	−21%	−11%	+3%	+21%	−73%	−107%	−149%	−205%
Single-family residential	−84%	−146%	−278%	−450%	−36%	−20%	+15%	+60%	−72%	−81%	−102%	−129%

the no-CCHP scenario. The yearly costs of the medium office, large office, and multifamily buildings can be reduced by 19%, 6%, and 12%, respectively, when the maximum cost of the CCHP system is used and the system is operated to meet the hourly thermal demand (Appendix E, Fig. E1). Using the minimum yearly costs and operating the system to meet the hourly thermal demand reduces the costs of the medium office, large office, small office, and multifamily buildings by 34%, 20%, 9%, and 25%, respectively. For these buildings, the maximum cost reduction occurs when the CCHP system is operated to meet the hourly thermal demand of the building (Appendix E, Fig. E1). The economic feasibility of the small office building varies depending on the cost structure that is assumed. If the cost of the natural gas used in the building is the same as what utilities pay, the yearly costs can be reduced to 18%–50% compared with the no-CCHP costs. In the case of the medium office and single-family buildings, net metering and utility-priced natural gas result in negative system costs, as shown in Fig. 8(c) and (d). This means that the system can make money for the owners, rather than cost them money.

4. Conclusions

CCHP systems can be very effective in reducing water consumption for energy generation, NO_x and CO_2 emissions, and the cost of energy generation in Atlanta, depending on: ① the operational strategy of the system, ② whether or not there is a net metering policy, and ③ the cost of natural gas. For the single-family, multifamily, medium office and small office buildings, CO_2 emissions are lower with a CCHP system when it is operated to meet the hourly thermal demand. All buildings have lower CO_2 emissions if there is a net metering policy, with the lowest emissions coming from the hourly thermal demand operating strategy. Net metering scenarios mean that CCHP systems can be run under other operational strategies while still reducing CO_2 emissions when compared with the no-CCHP scenario. The water consumption for energy generation of all building types decreases when the CCHP system is operated at higher capacities. This is because the excess energy produced by the CCHP system is sent to the grid so the energy grid needs to produce less electricity, resulting in avoided water consumption for energy generation for all buildings. Therefore, increasing the operational capacity of the turbine consistently results in lower water for consumption for energy generation. NO_x emissions are also reduced when a CCHP system is used, but the optimum operating strategy varies depending on the building type. When a net metering policy is in place, NO_x emissions are always lowest when the CCHP system is operated to meet the maximum yearly thermal demand, as the system produces more electricity than the building needs and is therefore able to reduce the emissions from the grid. The best operational strategy from a cost perspective varies depending on the cost structure used, on net metering, and on the price of natural gas. These systems become more economical as the price of natural gas decreases.

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Compliance with ethics guidelines

Jean-Ann James, Valerie M. Thomas, Arka Pandit, Duo Li, and John C. Crittenden declare that they have no conflict of interest or financial conflicts to disclose.

Nomenclature

CCHP combined cooling, heating, and power
CHP combined heat and power
COP coefficient of performance
$Cost_{CCHP\ net}$ sum of the yearly costs of electricity required from the grid, fuel for operating the microturbine, and debt service of the CCHP system
$Cost_{conventional\ net}$ sum of the yearly costs of electricity required from the grid, furnace/boiler fuel, and debt service of the heating and cooling systems
$E_{plug\ load}$ electricity required to meet the plug loads
$E_{space\ cooling}$ electricity required for space cooling
$Emissions_{CCHP\ net}$ net emissions from the CCHP system
$Emissions_{conventional\ net}$ net emissions from the conventional energy generation system
$Emissions_{furnace}$ emissions from furnace/boiler heat generation
$Emissions_{grid}$ emissions from the production of grid electricity
$Emissions_{turbine}$ emissions from the production of electricity from the microturbine
FEL follow the electric load
FTL follow the thermal load
$Heating_{hot\ water}$ heat energy required for hot water
$Heating_{space}$ heat required for space heating
HET hybrid electric thermal
HRU heat recovery unit
HVAC heating, ventilation, and air conditioning
OpenEI Open Energy Information
PGU power-generating unit
TMY typical meteorological year

Supplementary Information

http://engineering.org.cn/EN/10.1016/J.ENG.2016.04.008
Appendixes A to F

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