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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

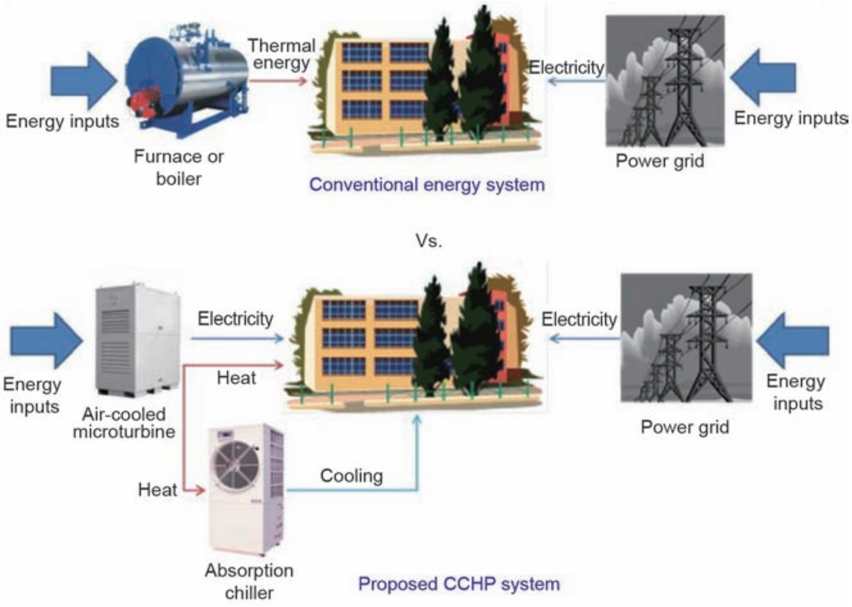

Fig. 1. A conventional building energy supply system versus a combined cooling, heating, and power (CCHP) system.