



Supplementary Information for

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

Jean-Ann James^{a,b,*}, Valerie M. Thomas^{c,d}, Arka Pandit^{a,b}, Duo Li^e, John C. Crittenden^{a,b}

^a Brook Byers Institute for Sustainable Systems, Georgia Institute of Technology, Atlanta, GA 30332, USA

^b School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

^c H. Milton Stewart School of Industrial and Systems Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

^d School of Public Policy, Georgia Institute of Technology, Atlanta, GA 30332, USA

^e Crittenden and Associates, Beijing 100102, China

Appendix A

Fig. A1 in Appendix A shows the modified hourly thermal demand of a medium office building. This hourly thermal demand was used for the hourly thermal demand operating scenario (Fig. A2). Fig. A2 shows the combined cooling, heating, and power (CCHP) system

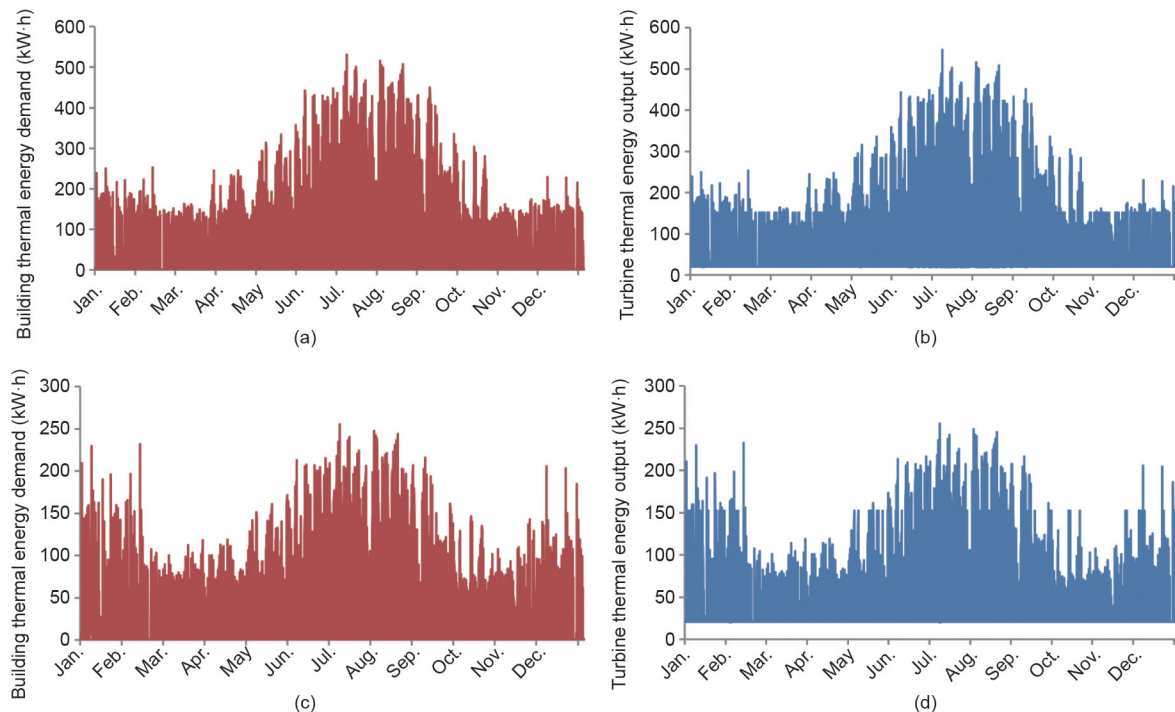


Fig. A1. Thermal (heating and cooling) demand of a medium office building and thermal output of the microturbine in the CCHP system when using a CCHP system with a single-effect and double-effect absorption chiller. (a) Hourly thermal demand of a medium office building with a single-effect absorption chiller; (b) thermal output of a 325 kW turbine operating to match the hourly thermal output of a medium office building with a single-effect absorption chiller; (c) hourly thermal demand of a medium office building with a double-effect absorption chiller; (d) thermal output of a 130 kW turbine operating to match the hourly thermal output of a medium office building with a double-effect absorption chiller.

* Corresponding author.

E-mail address: jjames@gatech.edu

thermal output to match the hourly demand for a medium office building. Fig. A2(a) illustrates the hourly demand profile (red) and the thermal output of the CCHP system (purple) for the month of June. Fig. A2(b) is a snapshot of how the CCHP system operates to meet the hourly demand for one day in the month of June. In all the figures, red represents the hourly thermal demand, green represents the thermal demand of the specified operating scenario, and purple represents the turbine output to meet the demand of the given operating scenario. The turbines have a minimum capacity at which they can be operated before they switch off. This is the lowest operating mode of the turbines, and can be seen in Fig. A2. Since the turbines cannot be turned on and then instantaneously meet a thermal demand, their output is assumed to never fall below the minimum operating capacity. Fig. A3 represents the maximum daily demand operating scenario for the month of June. The green line represents the maximum daily demand of the building, and the purple line represents the turbine output for the operating scenario. Similarly, Figs. A4(a) and (b) represent the maximum monthly and maximum annual thermal demand, respectively.

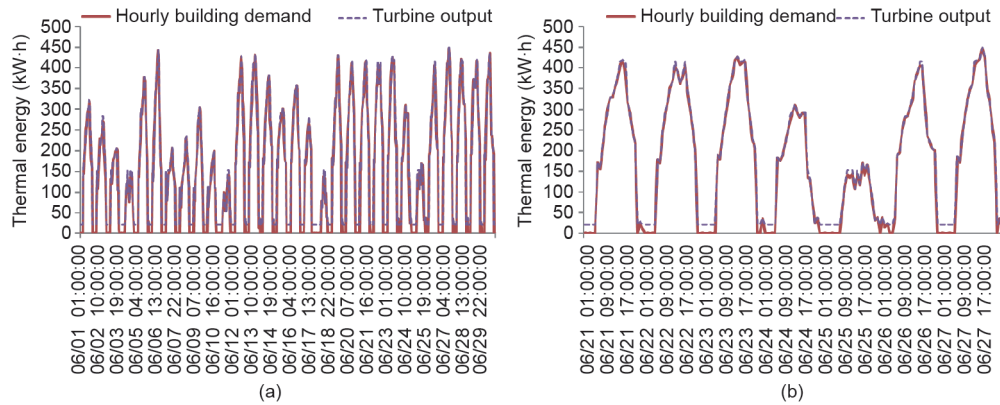


Fig. A2. Thermal energy output of the CCHP system operated to meet the hourly thermal load of a medium office building. (a) A comparison of the thermal demand of the building and the thermal output of the building over the month of June; (b) a comparison of the thermal demand of the building and thermal output of the building over a day in June.

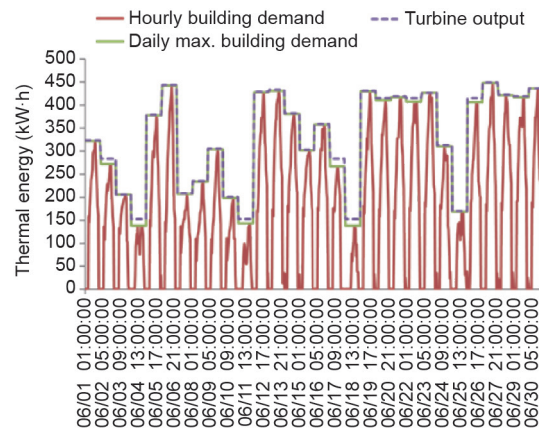


Fig. A3. Thermal energy output of the CCHP system operated to meet the daily thermal load of a medium office building in the month of June.

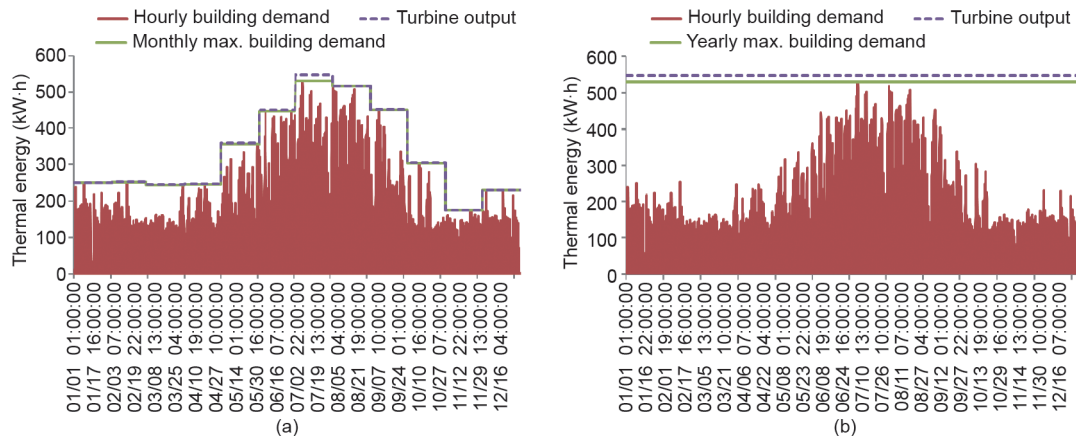


Fig. A4. Operational scenarios of a CCHP system against the thermal demand when a CCHP system is used. (a) CCHP system operated to meet the hourly load of a medium office building; (b) CCHP system operated to meet the maximum annual demand of a medium office building.

Appendix B

Equations used to calculate the annual cost of the heating and cooling systems.

$$P_{\text{furnace annual}} = \frac{P_{\text{furnace}} \times i}{1 - (1 + i)^{-n}}$$

$$P_{\text{AC annual}} = \frac{P_{\text{AC}} \times i}{1 - (1 + i)^{-n}}$$

$$P_{\text{turbine annual}} = \frac{P_{\text{turbine}} \times i}{1 - (1 + i)^{-n}} + \text{Cost}_{\text{O\&M}}$$

$$P_{\text{chiller annual}} = \frac{P_{\text{chiller}} \times i}{1 - (1 + i)^{-n}} + \text{Cost}_{\text{O\&M}}$$

Appendix C

Per square foot water consumption for energy generation of all building types, operation scenarios, and grid technologies.

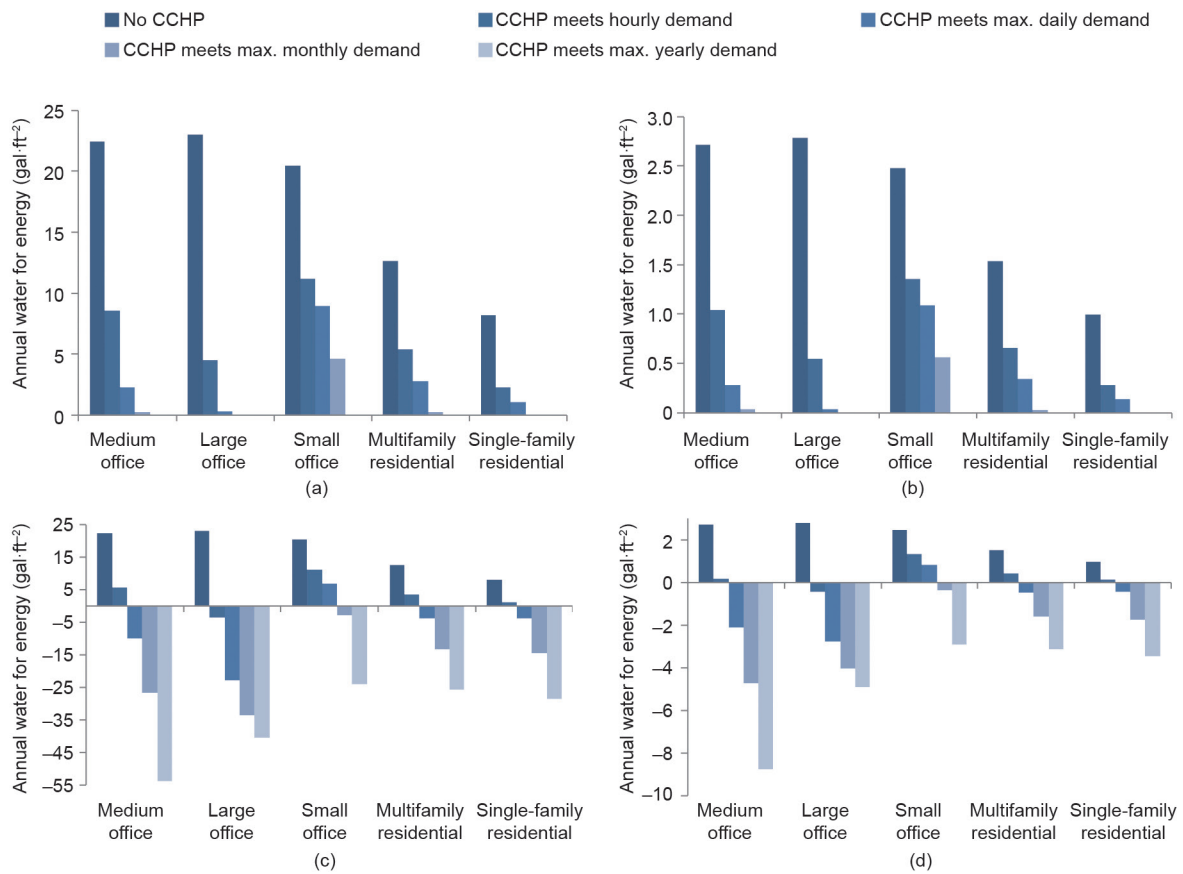


Fig. C1. Water for energy consumption for five building types operating under five CCHP scenarios. (a) Water for energy consumption using a consumption factor of 1.65 gal·(kW-h)⁻¹ and no net metering; (b) water for energy consumption using a consumption factor of 0.2 gal·(kW-h)⁻¹ and no net metering; (c) water for energy consumption using a consumption factor of 1.65 gal·(kW-h)⁻¹ and net metering; (d) water for energy consumption using a consumption factor of 0.2 gal·(kW-h)⁻¹ and net metering. Water for energy consumption is negative in the net metering scenarios because it is mitigated by the grid producing less electricity.

Appendix D

Per square foot CO₂ emissions for all building types, operation strategies, grid technology composition, and net metering policy. Fig. D1 assumes the current technology of a single-effect air-cooled absorption chiller while Fig. D2 shows the impact of a double-effect chiller.

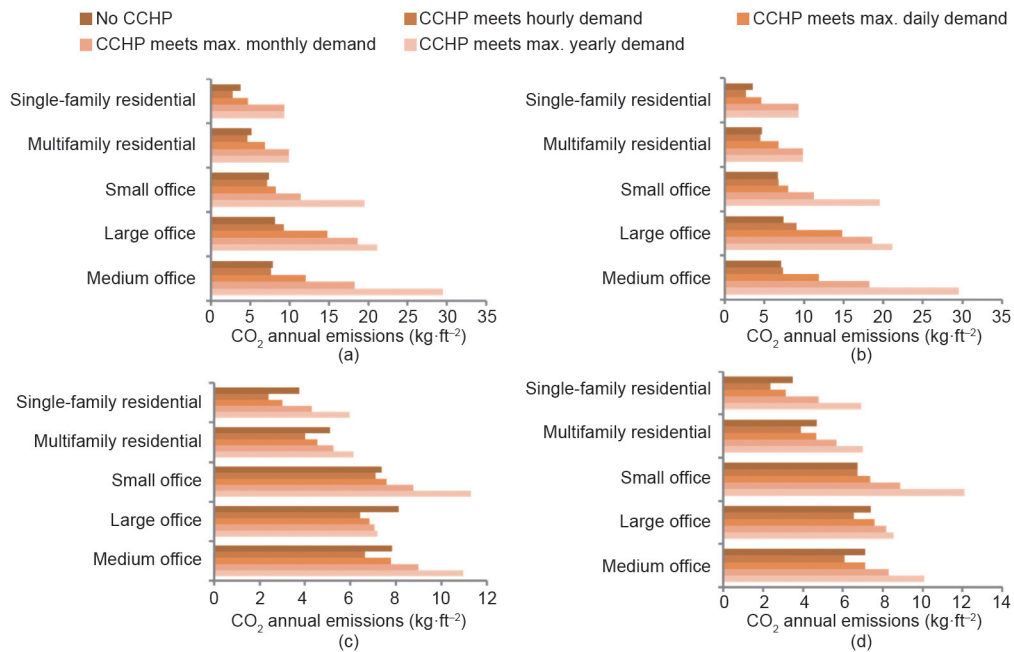


Fig. D1. Per square foot CO₂ emissions of all building types under all operation scenarios with a single-effect air-cooled absorption chiller (COP: 0.68). (a) CO₂ emissions with a CCHP system and no net metering, assuming emissions from CCHP system and grid mix; (b) CO₂ emissions with a CCHP system and no net metering, assuming emissions from grid are those of a combined cycle natural gas (CCNG) plant; (c) CO₂ emissions with a CCHP system with net metering, assuming emissions from CCHP system and grid mix; (d) CO₂ emissions with a CCHP system with net metering, assuming emissions from grid are those of a CCNG plant.

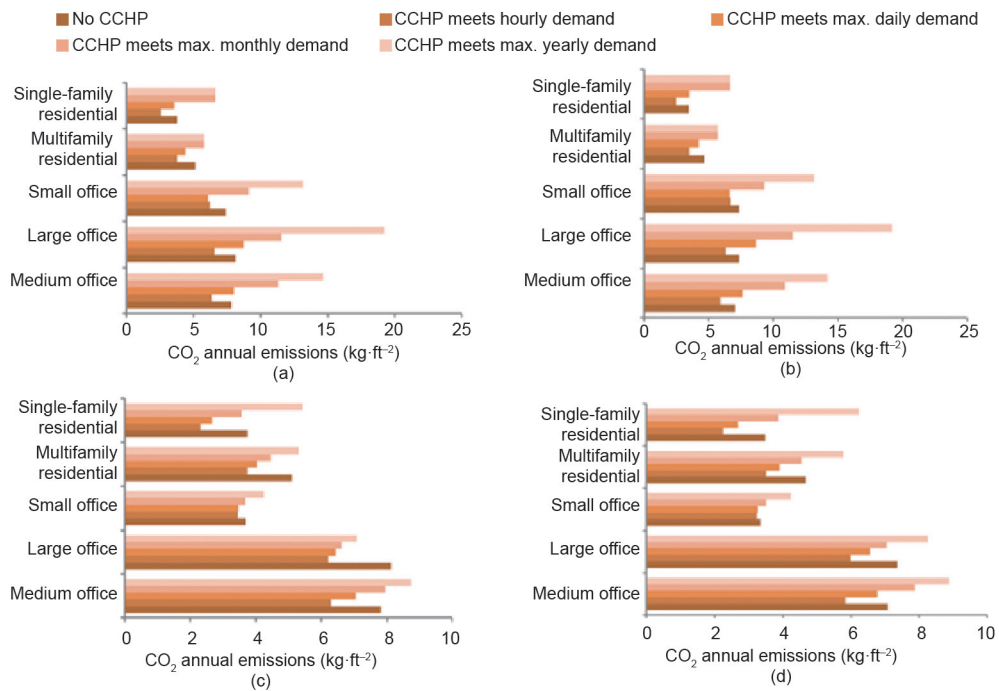


Fig. D2. Per square foot CO₂ emissions of all building types under all operation scenarios with a double-effect absorption chiller. (a) CO₂ emissions with a CCHP system and no net metering, assuming emissions from CCHP system and grid mix; (b) CO₂ emissions with a CCHP system and no net metering, assuming emissions from grid are those of a CCNG plant; (c) CO₂ emissions with a CCHP system with net metering, assuming emissions from CCHP system and grid mix; (d) CO₂ emissions with a CCHP system with net metering, assuming emissions from grid are those of a CCNG plant.

Appendix E

Additional per square foot cost estimates with commercial and residential natural gas prices and utility-priced natural gas.

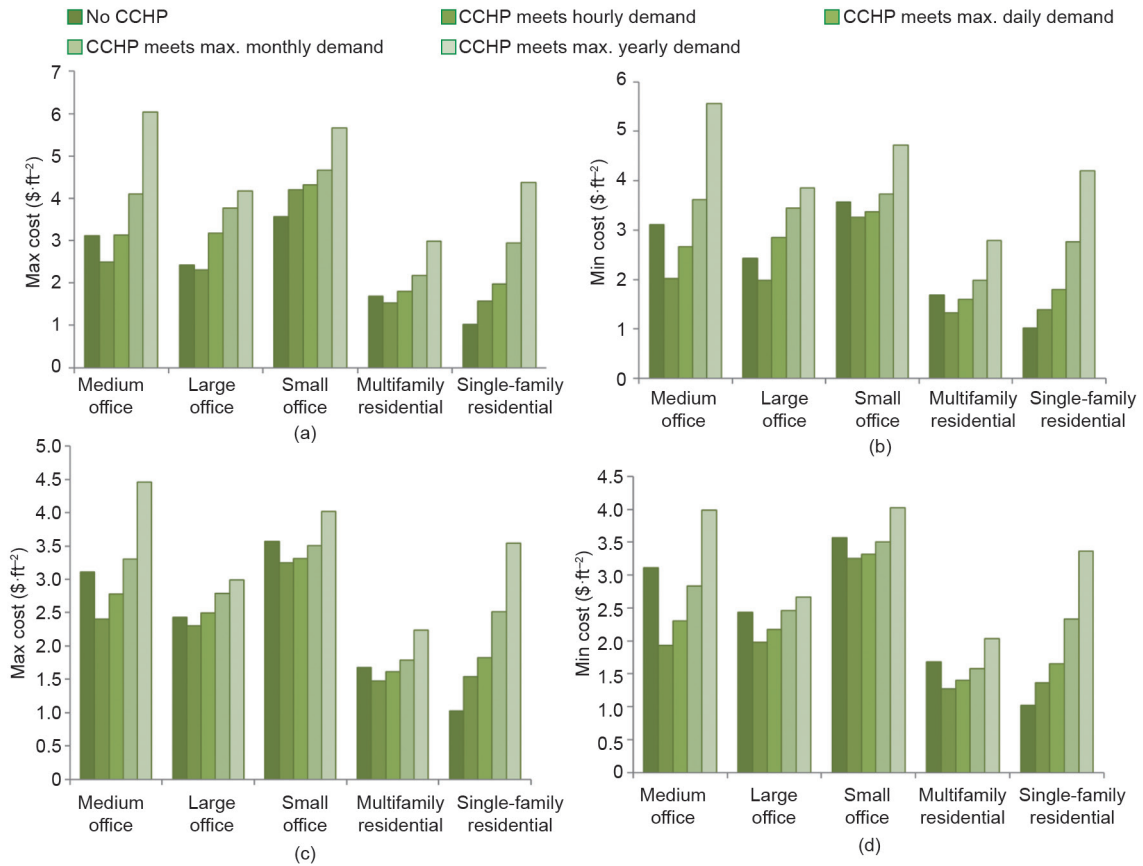


Fig. E1. Per square foot cost estimates of CCHP systems compared to the cost of energy in the no-CCHP scenario for all five building types. (a) Maximum CCHP system cost estimates with no net metering; (b) minimum CCHP system cost estimates with no net metering; (c) maximum CCHP system cost estimates with net metering; (d) minimum CCHP system cost estimates with net metering.

Appendix F

Per square foot NO_x emissions of all buildings types and operational scenarios, assuming the emissions from the grid mix of technologies or a CCNG plant.

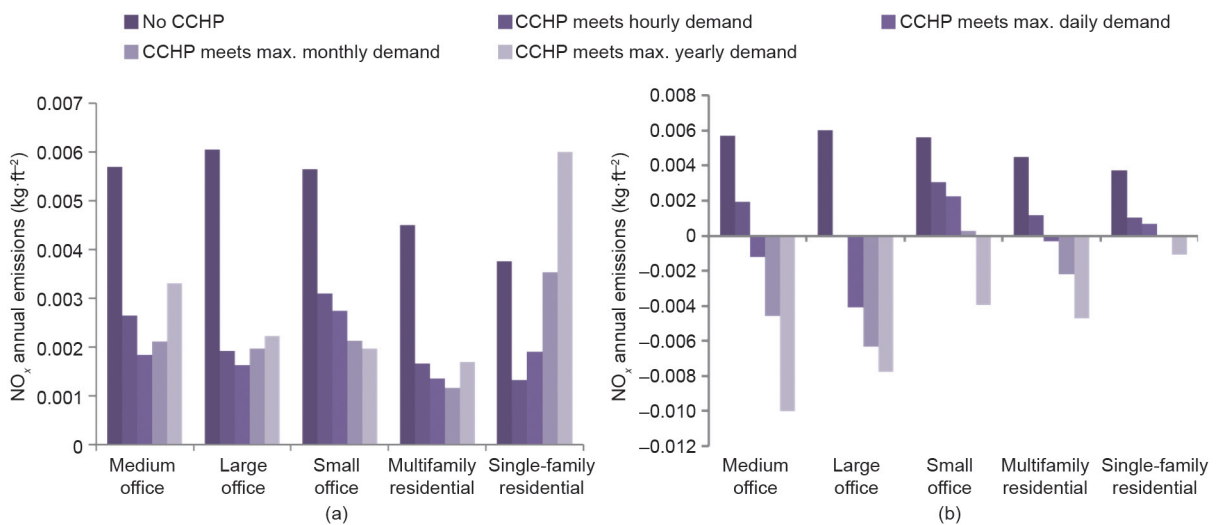


Fig. F1. Per square foot NO_x emissions of all building types under all operation scenarios, assuming grid emissions are based on the grid mix. (a) NO_x emissions without net metering; (b) NO_x emissions with net metering.

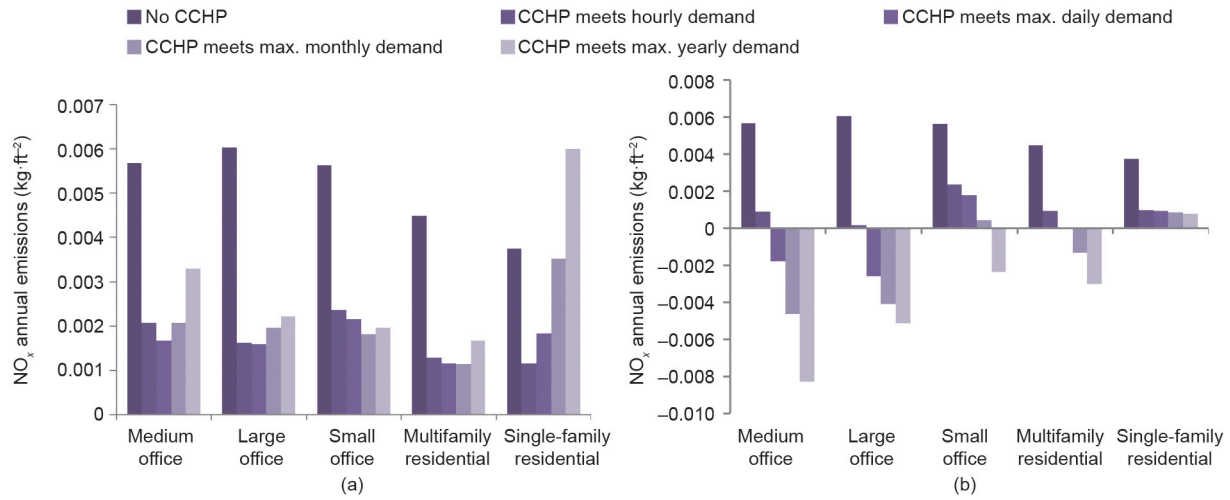


Fig. F2. Per square foot NO_x emissions of all building types under all operation scenarios, assuming grid emissions are from a CCNG. (a) NO_x emissions without net metering; (b) NO_x emissions with net metering.