

Are high penetrations of commercial cogeneration good for society?

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Abstract

Low natural gas prices, market reports and evidence from New York State suggest that the number of commercial combined heat and power (CHP) installations in the United States will increase by 7-9% annually over the next decade. We investigate how increasing commercial CHP penetrations may affect net emissions, the distribution network, and total system energy costs. We constructed an integrated planning and operations model that maximizes owner profit through sizing and operation of CHP on a realistic distribution feeder in New York. We find that a greater penetration of CHP reduces both total system energy costs and network congestion. Commercial buildings often have low and inconsistent heat loads, which can cause low fuel utilization efficiencies, low CHP rates-of-return and diminishing avoided emissions as CHP penetration increases. Low emission CHP installations can be encouraged with incentives that promote CHP operation only during times of high heat loads. Time-varying rates are one option. In contrast, natural gas rate discounts, a common incentive for industrial CHP in some states, can encourage CHP operation during low heat loads and thus increase emissions. Policies aimed at reducing emissions should encourage small commercial CHP operation only during times of high heat loads.

1. Introduction

Combined heat and power (CHP) systems can achieve higher fuel utilization efficiencies than conventional power plants. CHP contributes approximately 7% of US generation capacity with 97% of this capacity found in the electrical power and industrial sectors [1]. Low natural gas prices may encourage more commercial CHP in commercial and institutional settings. Schools, hospitals, nursing homes, laundromats, prisons, and other buildings with hot water needs are likely to benefit from commercial CHP [2, 3]. Already, the majority of CHP sizes in New York are less than 1 MW [4] (Supplementary Material, Figure S8) and US market forecasts predict annual growth rates of between 7-9% or about 70 GW over the next five years [5, 6]. If these forecasts are accurate, CHP may have a large effect on the environment, and on electric distribution grids.

Research on high penetrations of CHP in commercial buildings is limited. There is considerable research examining the economic feasibility and optimal sizing of CHP [7, 8, 9], but this work often focuses on universities and hospitals rather than on small commercial buildings such as apartments. Studying these smaller commercial buildings is important because they tend to have large daytime heat loads only in the winter and low heat loads during other times, but CHP could still be attractive for these customers at low natural gas prices. Inconstant commercial building heat loads may lead to wasted heat and low fuel utilization efficiencies if the CHP is operated during times of low heat loads [10, 11, 12]. To mitigate this problem, Smith *et al* [11] recommend oversizing water tanks (where space permits) to allow more heat storage and consequent emission reductions. Mago *et al* [12] suggest operating CHP at small offices only during office hours. These authors did not, however, assess the capability of commercial CHP to reduce regional emissions in high penetration scenarios. Even though the overall fuel efficiency for heat and power can be high, small CHP have electrical efficiencies as low as 25%, so CHP

placed at buildings with low heat loads could produce higher emissions than the bulk power grid. Finally, we are not aware of any research that examines the effect of commercial CHP on the local distribution network. Commercial CHP operation is dependent on building heat loads and will have a unique effect on the network losses, congestion and power flows. We examine stakeholder costs and benefits, emissions, and network effects of high penetrations of commercial CHP. Because the details and emission consequences of how commercial CHP is operated may also be dependent on who owns the CHP, we compare utility and customer ownership.

We have constructed an integrated planning and operations model that maximizes owner profit through sizing and operation of commercial CHP on a realistic distribution feeder in New York. In the following section we describe our model. Customer and utility ownership models are used to explore how the benefits of CHP vary. We then discuss results that show CHP in commercial buildings reduces electric distribution system costs but that policies aimed at reducing emissions should encourage CHP operation only during times of high heat loads.

2. Combined heat and power model

Our model compares the CHP benefits accrued when operated by a utility and by a customer. These ownership models reflect current opposing viewpoints on who should own distributed energy resources (DER). For example, the American Council for an Energy Efficient Economy (ACEEE) has recently reported on the benefits of utility owned CHP [13] while the New York Reforming Energy Vision (REV) process currently prohibits utility ownership of DER [14].

An overview of the model is shown in Figure 1 and details are in Section A of the Supplementary Material. A radial distribution feeder is modeled with hourly time-varying electrical and heat loads; these are derived from the GridLab-D feeder taxonomy [15] and the US Department of Energy (DOE) commercial reference building model [16, 17], respectively. CHP

that are installed at commercial buildings on the feeder can be used to supplement grid power and heat from pre-existing boilers (Supplementary Material Figure S1) and thus avoid energy costs, but at the expense of additional capital and operations & maintenance (O&M) costs. So, the model places CHP in commercial buildings only if the resulting cash flow yields a rate-of-return greater than 10%. The units are sized to maximize the net present value (Supplementary Material Figure S2). Next, the CHP are operated for one year (using observed heat loads and power prices) and the economic, environmental, and network benefits are computed. The primary difference between the owners is that the customer-owners are subject to a flat rate tariff (prices do not vary with hour or season) and a demand charge. The utility is an investor owned deregulated utility that does not own generation and buys power on the wholesale market at time-varying locational marginal prices (LMPs). Additionally, the utility must offer the customer a power purchase agreement (PPA) to compensate for the opportunity cost foregone by not renting the space the CHP occupies; the utility can afford to do this because CHP reduces the utility's wholesale power purchase costs. We define a PPA similarly to the SolarCity PPA, where the customer earns a fixed rate for each kWh produced by the CHP. All modeling parameters were based on representative values from the northeastern United States (Supplementary Material, Section C).

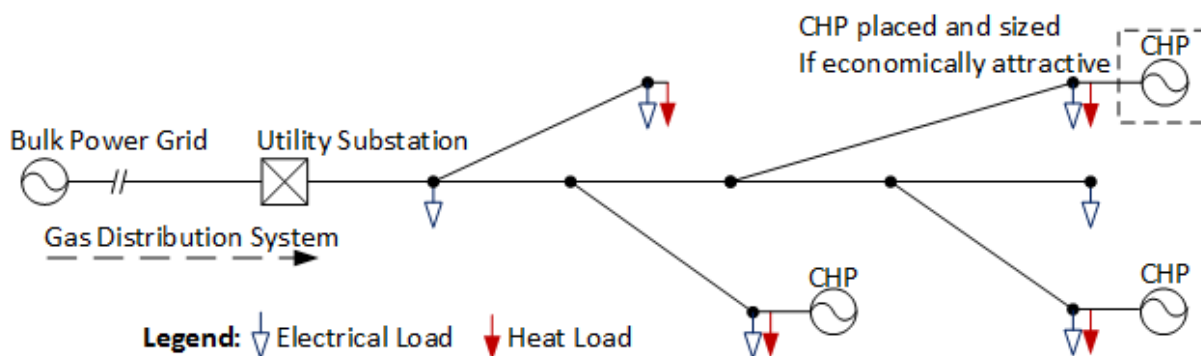


Figure 1. A simplified version of the integrated planning and operations model is shown.

Economically attractive CHP are placed on a distribution feeder with time varying electrical and heating loads. The CHP are operated by a customer, subject to a flat tariff, and a utility subject to time varying locational marginal prices. The effect of each owner's planning and operating strategy on the CHP economics, environmental benefits and network benefits are recorded and compared. Statistics for the full model are shown in Table S7 of the Supplementary Material. The full model has over 700 nodes and a lower penetration of CHP than shown here.

Annual metrics for the distribution network effects, relative CHP emissions, and allocation of economic benefits were collected. Distribution network effects were examined through the loading on all the network components such as transformers. We used regional marginal emission factors (MEFs) for the bulk power generation grid to compare the CHP emissions with marginal emissions on the bulk power grid. The MEFs estimate the emissions of the power plants that the CHP are most likely to replace at the time of day and year the CHP is producing power. We used three metrics for the allocation of economic benefits: System savings compare the cost of energy (i.e. LMP) and transmission & distribution (T&D) costs needed to deliver power to the loads against the cost of delivering that power with CHP (including fuel, O&M, and capital expenses). Customer savings depend on the ownership model and describes the final reduction in the customers' bills accounting for tariff structure (e.g. the energy charge and demand charges), capital costs, O&M costs, and power purchase agreement. Utility savings also depend on the ownership model, and compares avoided LMP costs, with loss of revenue through PPA costs, reduced demand charges, capital costs, O&M costs, and lost sales. Details are in Section B of the Supplementary Material.

3. Results

We find that the benefits of commercial CHP depend on the penetration level and how the CHP fleets are operated. Customer ownership leads to higher CHP penetration, which has benefits for the grid. However, lower CHP penetration and less CHP operation at night and in the summer leads to lower relative CO₂ and NO_x emissions in the utility ownership scenario.

We first discuss in what kinds of buildings CHP is profitable under the two ownership models. In our model, customer CHP owners install more CHP than utility owners on a greater variety of buildings (Table 1). The reason for the difference is that customers benefit from reduced demand charges under both ownership models and utilities must share revenue through a PPA.

Table 1. Planning Results. Customer CHP owners install more CHP on a greater number and variety of buildings.

Owner	Commercial Buildings															Penetration	Total (kW)		
	Large Office	Supermarket	Primary School	Secondary School	Strip Mall	Warehouse	Quick-Service Rest.	Stand-Alone Retail	Small Office	Hospital	Medium Office	Full Service Rest.	Small Hotel	Midrise Apt	Outpatient			Large Hotel	
Customer	Total [kW]	513	76	62	600	69	85	0	94	7	425	2	0	30	15	50	250	13.4%	2278
Utility	Total [kW]	10	25	0	20	0	45	0	0	0	135	0	0	20	0	85	250	3.4%	590

In many cases it is not necessary for the utility to offer a PPA, because the customer's avoided demand charges are greater than the opportunity cost foregone by not renting the space the CHP occupies. Figure S14 of the Supplementary Material shows the range of PPAs that the utility could offer to the host customer of each load.

We next discuss network energy losses, thermal violations (i.e. equipment overloading) and voltage violations (e.g. over voltages) for each ownership model (Supplementary Material Section B). Resistive energy losses in the distribution network equipment account for approximately 1% of network demand without CHP and were reduced to 0.9% and 0.8% under utility and customer ownership, respectively. If these losses are monetized using the New York 2014 LMPs, savings would be \$6-8/kW-year, a small amount relative to CHP capital costs (~2%). The distribution network in this analysis is representative of many Northeastern feeders and is loaded to 60% of its capacity. It is likely that greater value could be obtained from reduced losses

through CHP placed on more heavily loaded feeders.

System benefits can also be produced by CHP that defers capital investments needed for the distribution network infrastructure. On networks with more congestion or high load growth, customer ownership would be more effective than utility ownership in deferring capacity investments (Supplementary Material Figure S15). We did not observe thermal violations or voltage violations that were caused or reduced by the commercial CHP.

A potential challenge with using commercial CHP to defer capacity investments for electrical distribution networks is that congestion will be shifted from the electricity network to the gas distribution network. Commercial CHP increased the yearly natural gas consumption for the sum of the buildings on the feeder by 46% and 400% under the utility and customer ownership scenario, respectively. Thus, high penetration commercial CHP scenarios are likely to require investments in natural gas distribution infrastructure. These investments, however, may not raise natural gas distribution costs since the CHP fleets increased natural gas load factors from 11% to 15% and 36% under customer and utility ownership, respectively.

4. Emissions

The relative CO₂, SO₂ and NO_x emissions of each CHP owner compared to the NPCC bulk power grid are shown in Figure 2. CHP decreases CO₂ and SO₂ emissions, but NO_x emissions increase. We find that utility owned CHP CO₂ and NO_x emissions are lower than those of customer owned CHP, despite having less installed CHP capacity. There are two reasons that the customer owned fleet of CHP has higher emissions. First, the customer owner is subject to a flat electricity tariff and operates the CHP more than the utility owner does during the night when heat loads are low and excess heat is wasted. This behavior is illustrated in Figure 3 for a supermarket. The utility sees lower LMPs at night, so will turn the CHP off at night and waste less heat. For similar

reasons, the customer owner will operate the CHP more during the summer when heat loads are low. Buildings that have consistent heat loads, like hospitals, are less sensitive to time-varying rates and show less variation in emissions between owners.

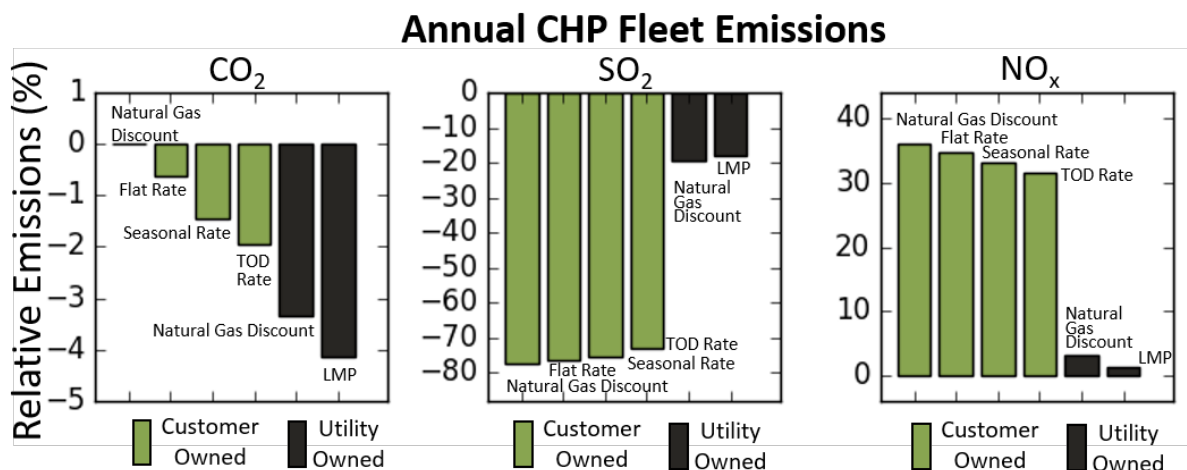


Figure 2. Utility and customer CHP emissions relative to the NPCC bulk power grid. Utility owned CHP reduces CO₂ and NO_x emissions more than customer owned CHP despite having less installed CHP capacity. Customer owned CHP emissions are higher because the customer's flat rate incentivizes continuous operation even when heat loads are low, and because the customer fleet contains more CHP with higher emissions. Time-varying rates, shown in the Time-of-Day (TOD) and Seasonal Rate scenario, reduce customer emissions by incentivizing the owner to reduce CHP operation during times of high heat loads. In contrast, a natural gas discount will encourage more operation of the CHP and increases emissions

CHP Dispatch at a Supermarket in September

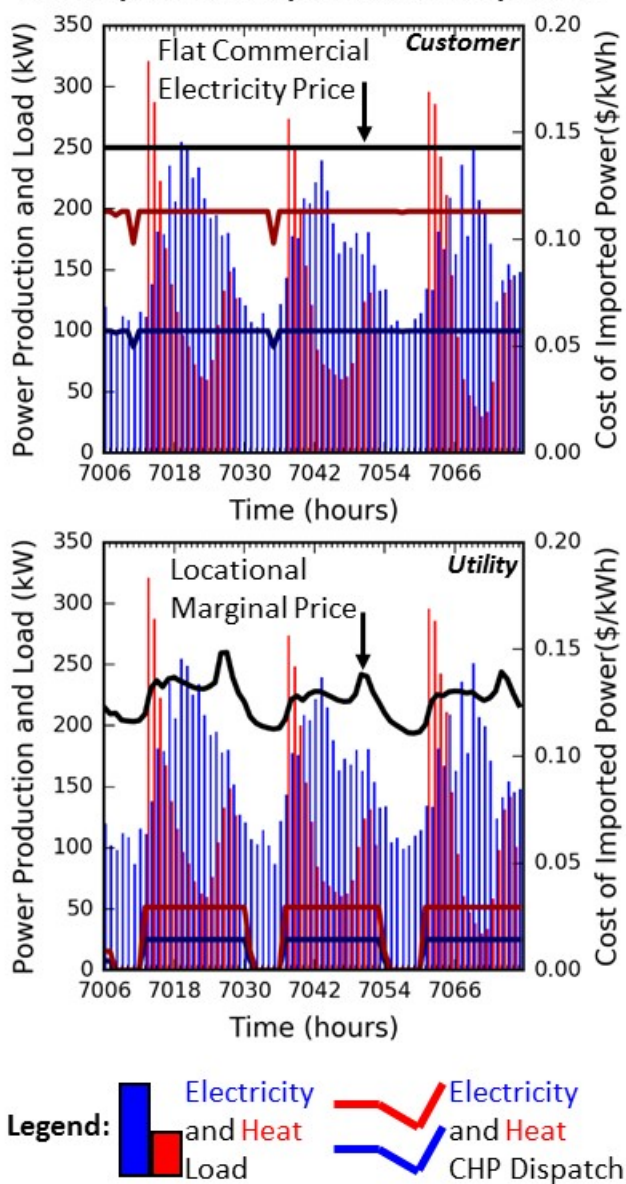


Figure 3. Utility and customer CHP dispatch. A supermarket has large heat loads in the day and very low heat loads during the night. The customer owner will continue to operate the CHP at night, but the utility which sees lower LMPs at night, will turn the CHP off. This results in lower overall emissions from the utility. Generally, dispatch is very sensitive to the heat load and price. Because time-varying rates tend to be small when loads are small, the utility dispatches CHP in a manner that follows the heat load more often.

The second reason that customer CHP ownership produces higher relative emissions is that the customer owned fleet has both larger and more CHP at buildings with higher relative emissions. Large offices with CHP produce more emissions than if powered from the bulk power

grid (Figure 4), and more commercial CHP capacity is profitable at large offices in the customer ownership scenario (Table 1). Taken together, this suggests that higher penetrations of commercial CHP may yield higher relative emissions as CHP is placed at more buildings with inconstant heat loads. We examine this possibility further in the sensitivity analysis.

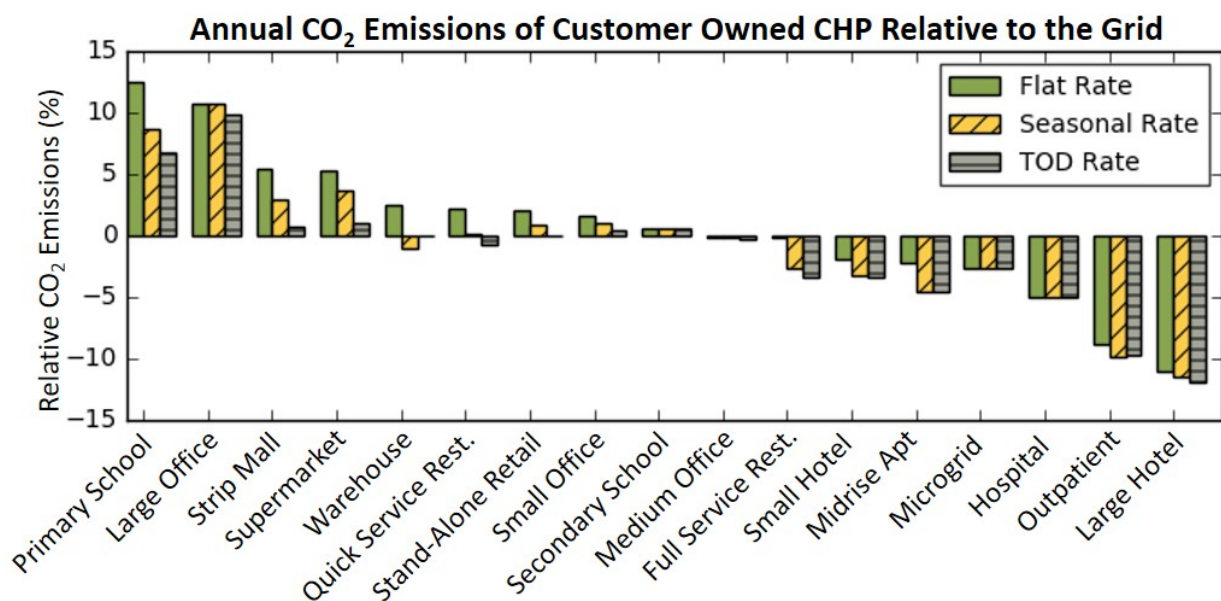


Figure 4. Customer owned CHP CO₂ emissions for representative buildings. Seasonal and Time-of-day (TOD) rates reduce customer CO₂ emissions. CO₂, SO₂ and NO_x building level emissions are shown for the full fleet in the Supplementary Material, Figure S16. The microgrid is composed of one warehouse and one secondary school.

A more general way to assess the potential of CHP to reduce emissions is by directly comparing marginal emission factors and CHP emissions (Supplementary Material Figure S11, where marginal emission factors are shown for the NPCC reliability region in the summer, winter, and shoulder months). CHP emissions are also shown, but have a range that depends on how much boiler heating is avoided. Commercial CHP, for example, can reduce CO₂ emissions if heat is not wasted. SO₂ reductions are certain, because natural gas contains very little sulphur. NO_x

emissions depend greatly on both the CHP and boiler emission technology. In our analysis, we assume a best-case scenario for CHP with low NO_x CHP operation and boilers that do not control NO_x emissions. Despite this assumption, NO_x emissions from uncontrolled boilers are still about ¼ the magnitude of low-NO_x CHP. Because boiler NO_x emissions are relatively low, heat generated from CHP is less effective at reducing NO_x emissions (Figure 2).

Figure S11 of the Supplementary Material can be used to estimate the ability of CHP to reduce emissions in locations other than New York. Regions with high percentages of coal powered generation, such as MRO, will benefit from high penetrations of commercial CHP.

5. Potential emission reduction policies

As previously discussed, CHP is profitable for some commercial buildings with inconstant heat loads; in such installations some emissions can increase. Emission controls placed on commercial CHP and boilers would have a large effect on the relative NO_x emissions. Selective Catalytic Reduction (SCR) can reduce CHP NO_x emissions by 95% [3] and would ensure NO_x reductions similar to that of SO₂ for commercial CHP. However, SCR would add about \$150-\$700/kW to the CHP capital cost (approximately 6-27%, respectively) [3]. On the other hand, improved emission controls can reduce heating system boiler emissions by approximately 70% [18], but would significantly reduce the ability of commercial CHP to avoid NO_x emissions. We find it is unlikely that commercial CHP owners would install these emission controls because yearly emissions do not qualify most buildings for EPA regulation (e.g. as a ‘major source’ of emissions).

We examine the possibility of using time-of-day rates and seasonal rates to reduce CHP emissions. We constructed hypothetical rates centered on the NYSEG commercial customer rate and designed the rates to discourage CHP operation during times of low heat loads. A time-of-day

tariff of \$0.121/kWh during the night and \$0.165 during the day and a seasonal summer rate of \$0.128/kWh and a winter rate of \$0.158/kWh were used. Figure 2 and Figure 4 show that emission reductions are achieved for the CHP fleet and for individual buildings when customers are subject to time-varying rates. The emission reductions are achieved because the time-of-day rate discourages CHP operation and therefore, wasted heat during the night when commercial buildings have low heat loads. Similarly, the seasonal rate avoids wasted heat during the summer.

We found that time-varying rates can achieve emission reductions without reducing the economic value of customer-owned CHP, but customer-owned CHP can also lead to high utility losses and possible rate increases for ratepayers. Figure 5 shows that the system, customer, and utility savings remain similar if the customer has time-varying rates. However, utility losses are also high under all customer ownership scenarios because the utility loses revenue from reduced demand charges and reduced energy sales that embody the sunk costs of the distribution system infrastructure. In some regions, policies may be necessary to ensure that commercial CHP installations do not both increase customer rates and increase regional emissions.

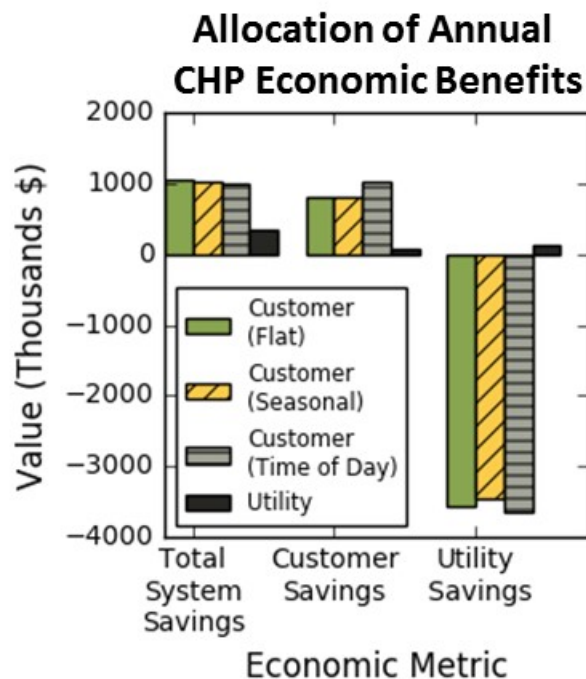


Figure 5. Allocation of CHP Savings for the base case and time-varying rates. Total system savings are positive for both owners indicating that the capital costs and energy costs of delivering power with CHP are cheaper than the grid. The high utility losses reflect lost energy sales and sunk distribution infrastructure costs. Time-varying rates do not have a large effect on customer or utility savings suggesting that time-varying rates can achieve emission reductions without negatively affecting the CHP payback period.

Microgrids are sometimes discussed as another option for reducing emissions [19], but we did not observe consistent emission reductions from microgrids. As shown in Figure 4 and Figure S22 of the Supplementary Material, microgrids composed of a warehouse and secondary school tend to produce lower emissions than if CHP were placed at those loads separately. The opposite is true for microgrids composed of a quick-service restaurant and strip mall. Microgrids may be more effective if emission reductions are included in the CHP sizing objective functions. Also, microgrids composed of many buildings could take advantage of the increasing electrical efficiencies and decreasing heat-to-power ratios of larger sized CHP (Supplementary Material Figure S6). However, despite these improvements, commercial building microgrids will still have

a tendency to produce wasted heat because many commercial buildings have highly correlated heat loads (Supplementary Material Figure S23).

In some states, natural gas discounts are used to encourage CHP. New Jersey Natural Gas, for example, offers natural gas discounts of up to 50% to residential and commercial customers that install CHP [20]. We applied a natural gas discount of \$2/MCF to the CHP fleet in Table 1 and examined the effect of this discount on the CHP fleet emissions, shown in Figure 2. The natural gas discount increases CO₂ and NO_x emissions because it encourages operation of the CHP even during times of low-heat loads. This result is further discussed in the following section.

6. Sensitivity analysis

We examined the robustness of the ability of time-varying rates to reduce emissions. In Figure 2 and Figure 4, we showed that time-varying rates cause utility owned CHP to turn off when heat loads are low, resulting in higher overall fuel utilization efficiencies. An important question is to what extent time-varying rates will be effective at reducing emissions in states that have different electricity and natural gas prices. For example, we also showed in Figure 2 that a natural gas discount would increase both customer and utility CHP fleet emissions, thus reducing the ability of time-varying rates to reduce emissions.

Figure 6 can be used to predict how effective time-varying rates will be in achieving emission reduction. It shows dispatch regions for a 10 kW CHP over a range of natural gas and electricity prices. These regions approximate how electricity and gas prices affect CHP dispatch under different loading scenarios. CHP units are not dispatched in the black region. In the green regions, CHP are dispatched only if a heat and electric load are present. In the yellow region, CHP are dispatched even when only the electric load is present. The customer owner's dispatch behavior, presented earlier for New York State with electricity and natural gas at \$0.143/kWh [21]

and \$8.3/MCF [22], falls in the yellow region. The average utility electricity and natural gas prices also fall within the yellow region, but it is subject to a time varying LMP and thus often falls within the green region. Also, low LMPs tend to occur when commercial heat loads are low, so utilities fall within the green region when it is possible to achieve higher efficiencies. In contrast, the customers in the New York State have a flat rate, so they are consistently in the yellow dispatch region, and operate the CHP less efficiently. CHP larger than 10kW have smaller green regions, and will be less sensitive to time-varying rates, as shown in Figure 6 for a 500 kW CHP.

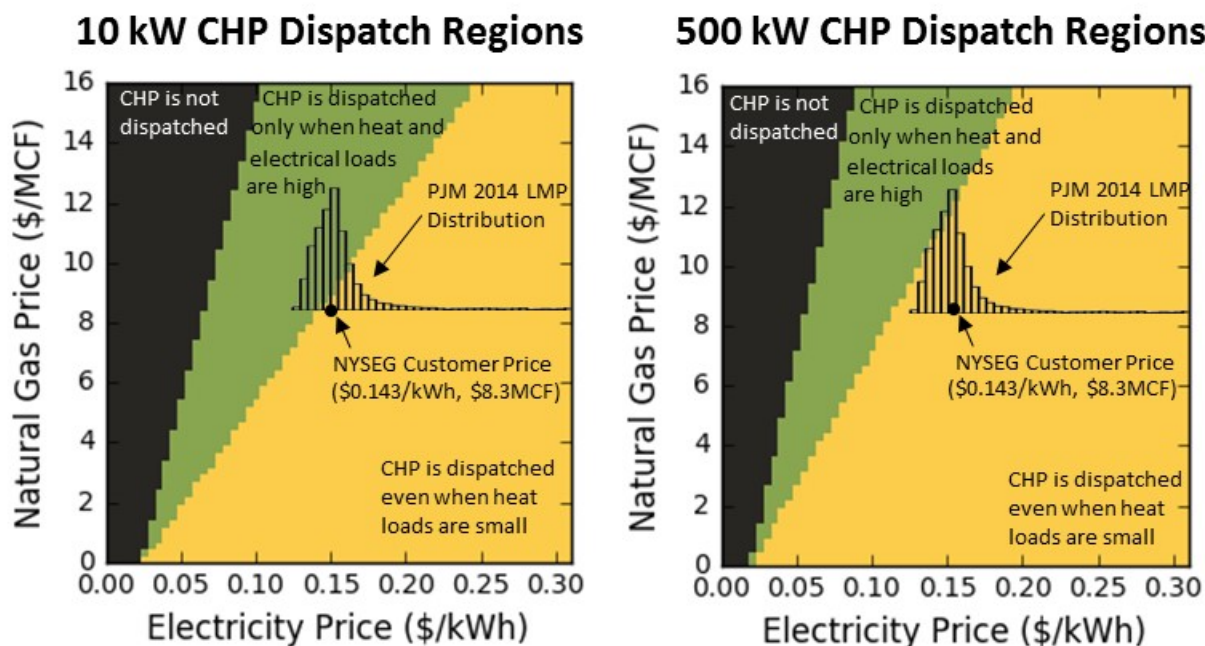


Figure 6. Sensitivity of dispatch of a 10kW and 500kW CHP to natural gas and electricity prices. CHP are not turned on in the black region. In the green region, CHP are only turned on if a heat and electric load is present. In the yellow region, CHP are dispatched at times even when only electric load is present. Dispatch in the green zone is likely to reduce emissions. Dispatch in the yellow zone may not reduce emissions if CHP heat production does not offset building heat load. For small CHP the customer owner's dispatch behavior, presented earlier, with electricity and natural gas at \$0.143/kWh and \$8.3/MCF falls in the yellow region. And, the utility is subject to a time varying LMP and so, it often falls within the green region, leading to lower utility emissions. Larger CHP becomes less sensitive to these effects, so time-varying rates will not be effective at reducing large CHP emissions.

As the penetration of commercial CHP increases, the emission benefits associated with CHP diminish. Figure 2 shows that the smaller utility owned fleet of CHP produces fewer relative emissions than the larger customer owned fleet. The larger customer fleet has more emissions because it has more CHP at buildings with higher relative emissions. This relationship is further examined in Figure 7. A range of CHP penetration scenarios for small CHP (<100 kW) was created by varying the capital cost and discount rate of the CHP investments. As the economic conditions became more favorable to the commercial CHP, penetrations increased, but the relative emissions also increased. Time-varying rates caused the utility owned fleet to produce lower emissions than the customer owned fleet for similar penetration levels. In contrast, the owner emissions of larger CHP (>100kW) are unaffected by penetration level and time-varying rates (see Figure 7).

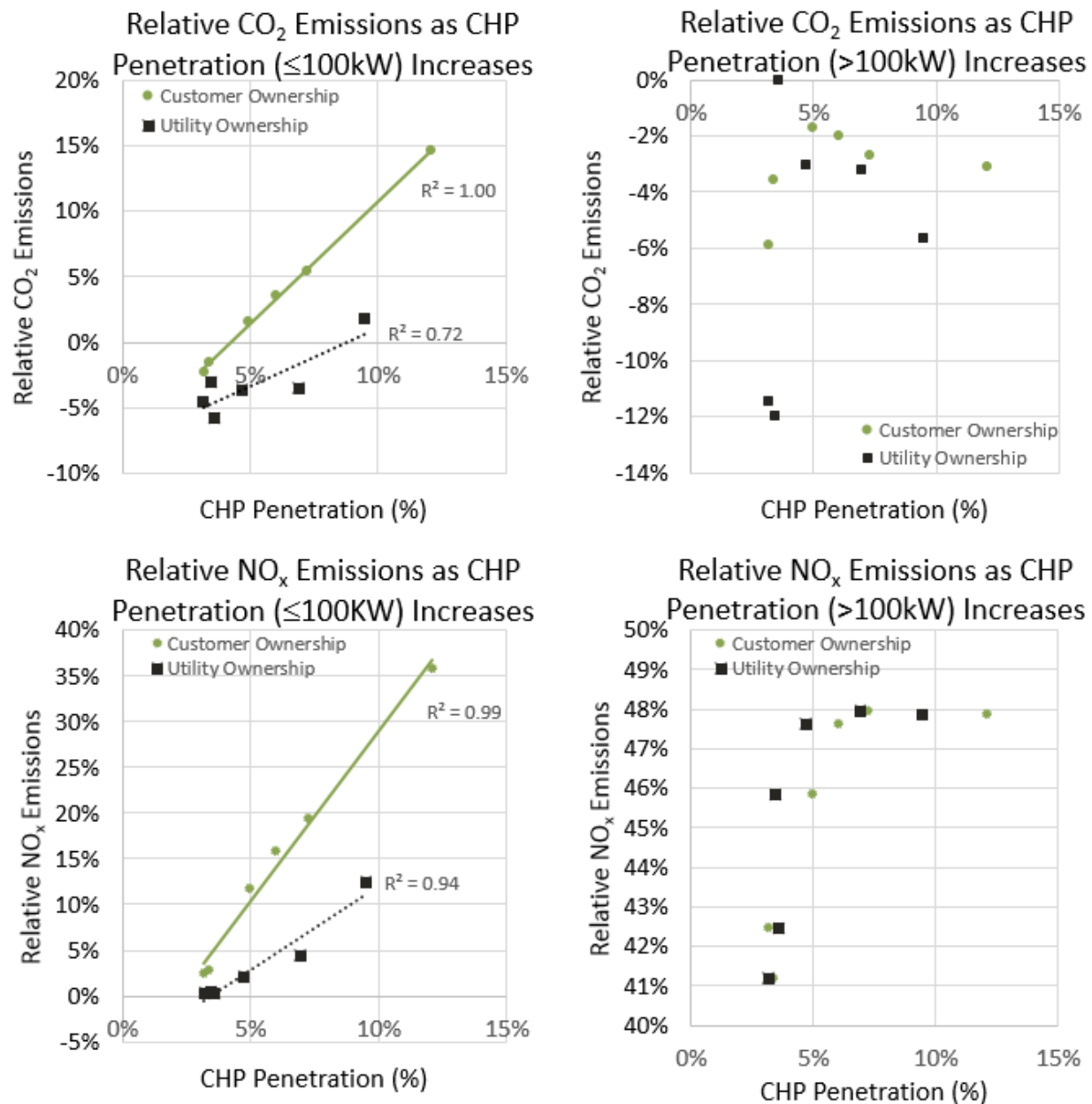


Figure 7. Emissions as the penetration of small CHP (<100 kW) and large CHP (>100kW) increases. Emissions increase as the penetration of small CHP increase but time-varying rates are effective at reducing these emissions. Emissions do not increase for large CHP and time-varying rates are ineffective at reducing emissions. The CHP fleet penetration correspond to the following scenarios moving from left to right: 30% Increase in CHP Capital Costs, 30% Increase in Discount Rate, Base Case, 30% Decrease in Discount Rate, 30% Decrease in CHP Capital Costs, 50% Decrease in Capital Costs and Discount Rate.

The emission and economic benefits of CHP were simulated for the years 2010 through

2014 to determine if the corresponding natural gas prices, electricity prices and marginal emission
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factors would affect the relative emissions or economic benefits of CHP fleets. The results are shown in Figure S17 and Figure S21 of the Supplementary Material, and are consistent with the 2014 results. Customer CHP fleet emissions are generally higher than utility emissions, and the economic benefits are allocated similarly for most years.

7. Conclusion and policy implications

We constructed an integrated planning and operations model that maximizes owner profit through optimal sizing and operation of commercial CHP on a realistic distribution feeder in New York. Using customer and utility ownership models we found that a greater penetration of CHP reduces network congestion and total system costs. Commercial CHP, however, will not always reduce emissions. Based on these results we summarize the following considerations to help policy makers maximize the benefits of CHP in commercial buildings.

Commercial CHP will reduce system costs. The capital, O&M, and energy costs of commercial CHP are lower than the lower than the capital, O&M, and energy costs of the grid. Overall, this will produce system savings, but there is likely to be a debate over who should be able to own commercial CHP and benefit from these savings. In particular, customer ownership leads to lost revenue for the utility.

Commercial CHP will reduce distribution network congestion and losses. On highly congested networks, commercial CHP may be an effective way to defer capacity investments.

Commercial CHP will reduce emissions less as penetrations increase. Commercial buildings vary in the quantity and consistency of their heat loads. Favorable economic conditions, such as a natural gas discount or a high electricity price relative to that of natural gas, may result in CHP at these buildings. SO₂ emissions decrease when CHP is installed, but CO₂ emissions rates

depend on the head load of the building. In our New York model, we found large emission reductions for some buildings that have consistent heat loads, such as large hotels. However, the emission of some other building types, such as large offices, are sometimes larger than the bulk power grid emissions in the northeast because their inconsistent heat loads do not take advantage of the potential reductions due to CHP. A consequence of this finding is that high incentives for commercial CHP can have diminishing environmental benefits. In short, while commercial CHP are likely to be effective at reducing emissions in emission intensive regions, such as the Midwest, high penetrations of commercial CHP may not be effective at reducing emission in the northeast.

Policies aimed at reducing emissions should encourage small commercial CHP operation only during times of high heat loads. Time varying rates can be used to encourage CHP dispatch only when heat loads are high. We showed that time-of-day rates reduce customer owned CHP emissions and do not reduce customer rates-of-return. Incentives that reduce capital costs, such as accelerated depreciation, are also an option where regional grid emissions are high. Reduced capital costs will neither encourage nor discourage CHP dispatch during times of high heat loads. In contrast, natural gas rate discounts, a common incentive for industrial CHP in some states, can encourage CHP operation during low heat loads and increase relative emissions. Similarly, a production tax credit will cause most commercial CHP to produce higher relative emissions.

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