Are high penetrations of commercial cogeneration good for society?

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LETTER

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 2%–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. In the northeast, without policy intervention, a 5% penetration of small commercially owned CHP would increase CO_2 emissions by 2% relative to the bulk power grid. Low emission CHP installations can be encouraged with incentives that promote CHP operation only during times of high heat loads. Time-varying rates, such as time-of-day and seasonal rates, are one option and were shown to reduce customer emissions without reducing profits. 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.

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[3] [1]. Low natural gas prices may encourage more commercial CHP in commercial and institutional settings. Schools, hospitals, nursing homes, laundromats (i.e. a self-service laundry), prisons, swimming pools 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 MWe [4] (supplementary material, figure S8) and US market forecasts predict annual growth rates of between 2% and 9% or about 15–70 GWe over the next five years [5–7]. 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 [8–10], but this work often focuses on universities and hospitals rather than on small commercial buildings such as strip malls. 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. Variable 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 [11–13].

To mitigate the problem of wasted heat, Smith *et al* [12] recommend oversizing water tanks (where space permits) to allow more heat storage and consequent

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[3] We note that CHP systems in the electrical power sector are often located near industrial facilities that purchase heat; an example is the Deer Park Energy Center in Texas.

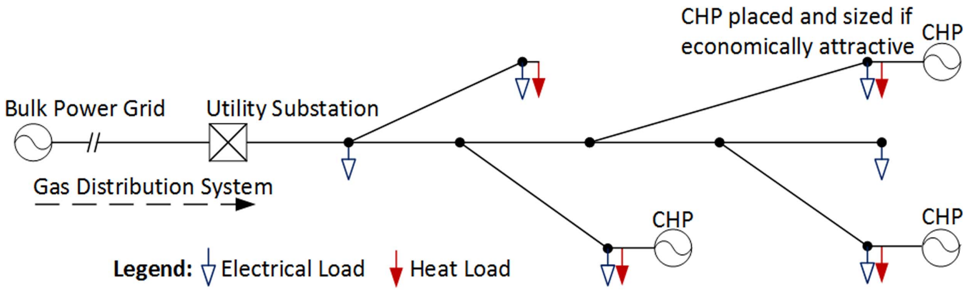

Figure 1. A simplified version of the integrated planning and operations model is shown. Economically attractive CHP are placed on a distribution feeder with time varying electrical and heating loads. The CHP are operated by a customer, subject to a flat tariff, and by a utility subject to time varying 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.

emission reductions. Mago *et al* [13] 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. Lane Clark & Peakcock [14], for example, have shown that industrial cogeneration may produce higher emissions than the bulk grid in Great Britain by 2030. 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. Finally, time varying rates, such as time-of-day and season rates, are demonstrated as one option for reducing emissions.

2. CHP 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 [15] while the New York Reforming Energy Vision process currently prohibits utility ownership of DER [16].

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 [17] and the US Department of Energy commercial reference building model [18, 19], 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 customer owners are subject to retail tariffs and a demand charge. The utility is modeled as an investor owned deregulated utility that buys power on the wholesale market at time-varying locational marginal prices (LMPs), but the model could also be generalized to vertically integrated utilities. 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).

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

		Commercial Buildings							
Owner		Large office	Supermarket	Primary school	Secondary school	Strip mall	Warehouse	Quick service rest.	Stand-alone retail
Customer	Total (kWe)	513	76	62	600	69	85	0	94
Utility	Total (kWe)	10	25	0	20	0	45	0	0

		Commercial Buildings									
Owner		Small office	Hospital	Medium office	Full service rest.	Small hotel	Midrise apt	Outpatient	Large hotel	Penetration	Total (kWe)
Customer	Total (kWe)	7	425	2	0	30	15	50	250	13.4%	2278
Utility	Total (kWe)	0	135	0	0	20	0	85	250	3.4%	590

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 PPA. 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 CO_2 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.

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 $kWe^{-1}\,yr^{-1}$, 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 by 46% and 400% under the utility and customer ownership scenario, respectively. Thus, high penetration commercial CHP scenarios are likely to require capacity investments in natural gas distribution infrastructure. These new capacity investments, however, may not raise customer natural gas distribution rates since the

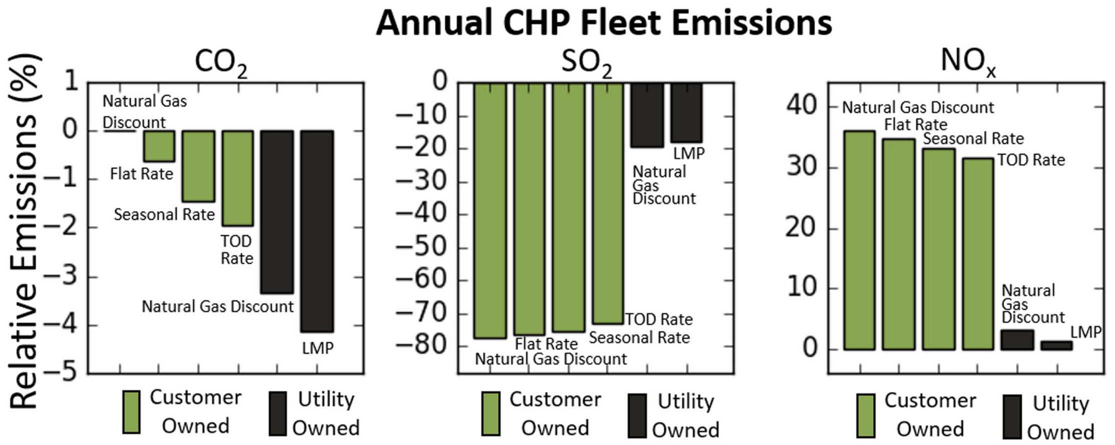

Figure 2. Utility and customer CHP emissions relative to the NPCC bulk power grid. Utility owned CHP reduces CO$_2$ and NO$_x$ emissions more than customer owned CHP despite having less installed CHP capacity. Customer owned CHP emissions are higher than those of utility-owned CHP because the customer's 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 fleets increased natural gas load factors from 11% to 15% and 36% under customer and utility ownership, respectively.

4. Emissions

The relative CO$_2$, SO$_2$ and NO$_x$ emissions of each CHP owner compared to the NPCC bulk power grid are shown in figure 2. CHP decreases CO$_2$ and SO$_2$ emissions, but NO$_x$ emissions increase. We find that utility owned CHP CO$_2$ 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.

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 variable heat loads. We examine this possiblity further in the sensitivity analysis.

A more general way to assess the potential of CHP to reduce emissions is by directly comparing MEFs and CHP emissions (supplementary material figure S11, where MEFs 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 CO$_2$ emissions if heat is not wasted. SO$_2$ 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 variable 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$_x$ emissons.

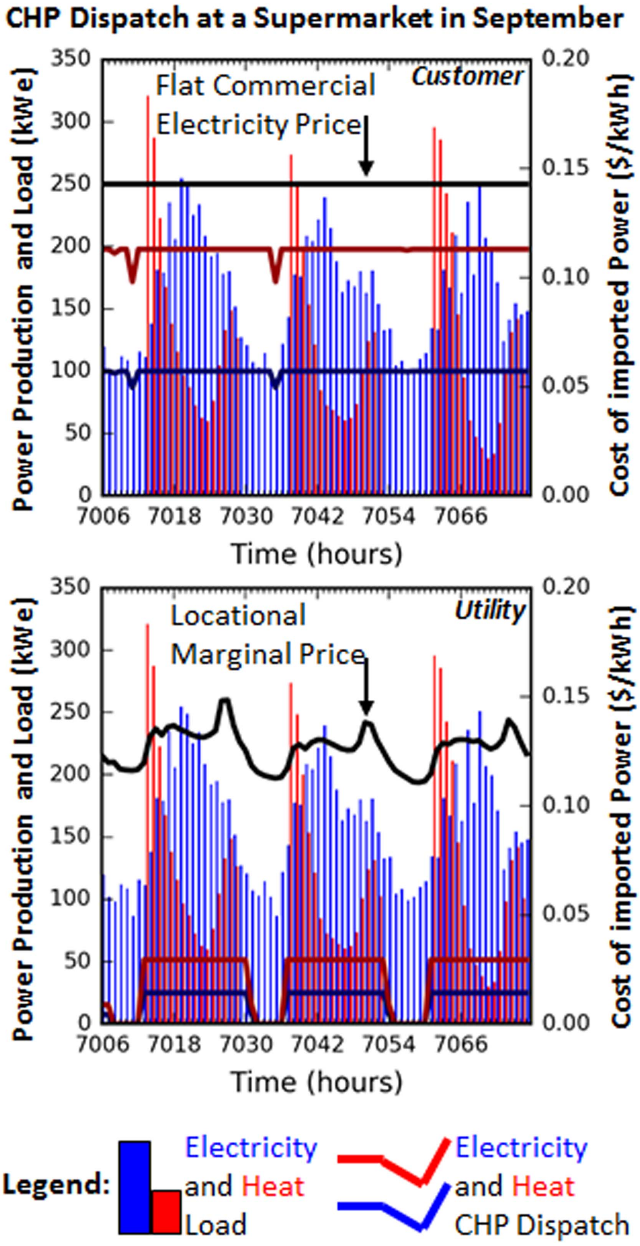

Figure 3. Utility and customer CHP dispatch. A supermarket has large heat loads in the day and very low heat loads during the night. The customer owner will continue to operate the CHP at night, but the utility which sees lower LMPs at night, will turn the CHP off. This results in lower overall emissions 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.

Selective catalytic reduction (SCR) can reduce CHP NO_x emissions by 95% [3] and would ensure NO_x reductions similar to that of SO_2 for commercial CHP. However, SCR would add about \$150–\$700 kWe^{-1} 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% [20], 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^{-1} during the night and \$0.165 during the day and a seasonal summer rate of \$0.128 kWh^{-1} and a winter rate of \$0.158 kWh^{-1} were used. Figures 2 and 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.

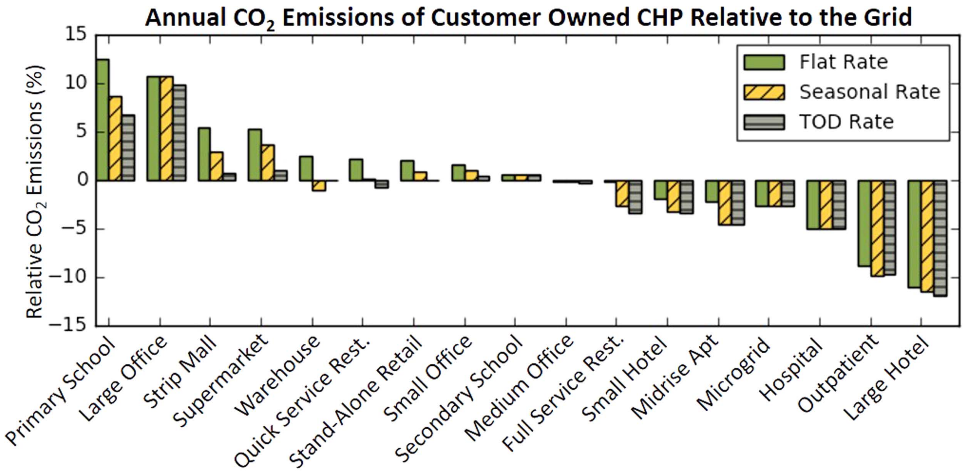

Figure 4. Customer owned CHP CO$_2$ emissions for representative buildings. Seasonal and time-of-day (TOD) rates reduce customer CO$_2$ emissions. CO$_2$, SO$_2$ and NO$_x$ building level emissions are shown for the full fleet in the supplementary material, figure S16. The microgrid is composed of one warehouse and one secondary school.

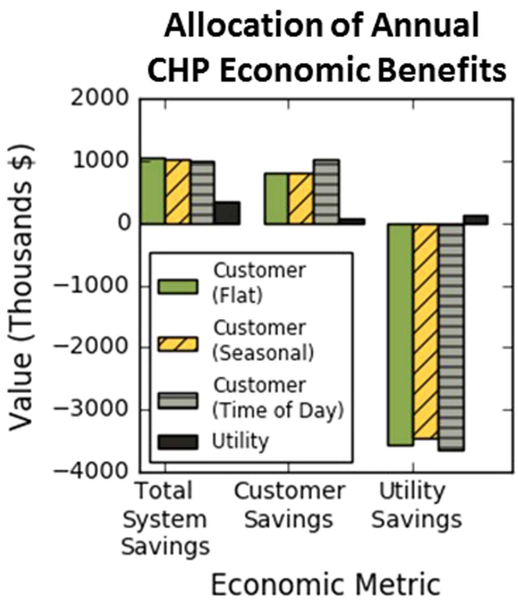

Figure 5. Allocation of CHP savings for the base case and time-varying rates. Total system savings are positive for both owners indicating that the capital costs and energy costs of delivering power with CHP are cheaper than the grid. The high utility losses reflect lost energy sales and sunk distribution 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.

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. Macroeconomic demand supply models have been used on the bulk power grid to quantify the short term price reductions and jobs associated with industrial cogeneration [21]. Work is needed that expands on Baer, Brown and Kim [21] and compares the value of reduced energy costs and reduced long term infrastructure requirements with the short-term cost shifts needed to pay for stranded assets.

Microgrids are sometimes discussed as another option for reducing emissions [22], but we did not observe consistent emission reductions from microgrids. As shown in figures 4 and 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).

Hot water absorption chillers use heat energy to cool buildings and are another option to use waste heat from CHP. We believe more research is needed on absorption chillers, but high capital costs, maintenance challenges, inconstant cooling loads, and low coefficients of performance currently limit their economic feasibility.

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 [23]. We applied a natural gas discount of \$2 MCF^{-1}

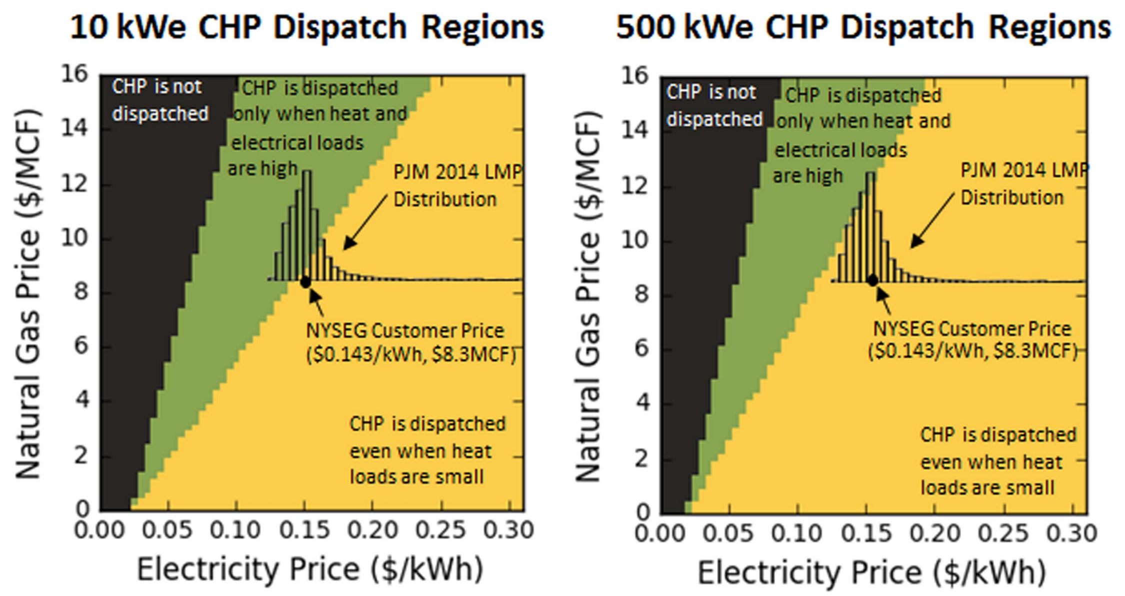

Figure 6. Sensitivity of dispatch of 10 and 500 kWe CHP to natural gas and electricity prices. CHP are not turned on in the black region. In the green region, CHP are turned on only if a heat and electric load is present. In the yellow region, CHP are dispatched at times even when only electric load 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^{-1} and \$8.3 MCF^{-1} (\$7.9 GJ^{-1}) 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.

(\$1.9 GJ^{-1}) 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 CO_2 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 figures 2 and 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. Similarly, a greater reliance on natural gas fired generation could lead to more closely coupled electricity and natural gas prices, and make CHP operations less economical. A simple visual tool is needed to estimate how these future scenarios can affect CHP emissions.

Figure 6 can be used to predict how time-varying rates and varying spark spreads will affect CHP emissions. It shows dispatch regions for a 10 and 500 kWe 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^{-1} [24] and \$8.3 MCF^{-1} (\$7.9 GJ^{-1}) [25], 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 10 kWe have smaller green regions, and will be less sensitive to time-varying rates, as shown in figure 6 for a 500 kWe CHP.

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 kWe) was created by varying the capital cost and discount rate of the CHP investments. As the economic conditions became

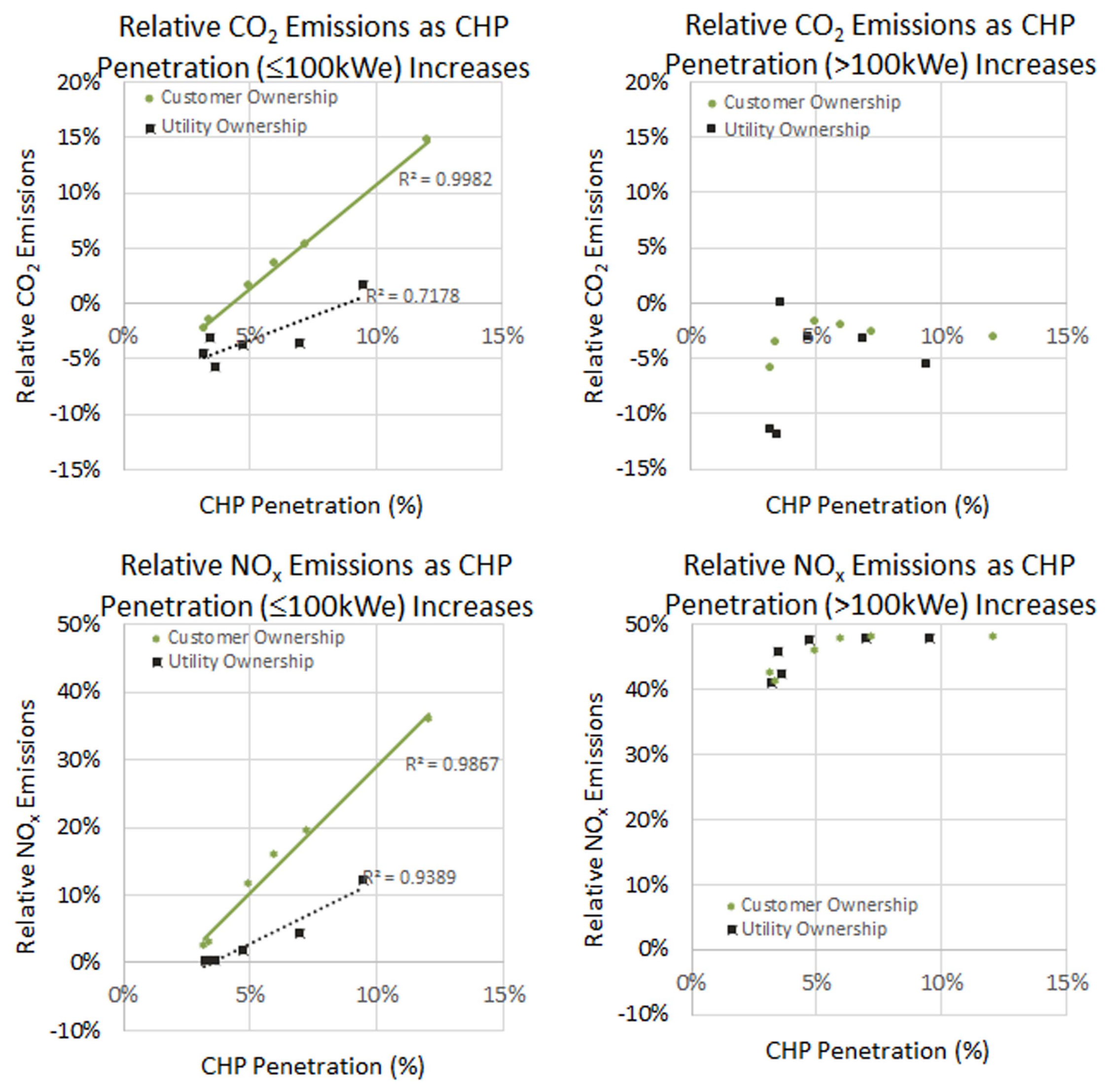

Figure 7. Comparison of utility-owned CHP (subject to locational marginal prices) with customer-owned CHP (non-varying flat rate). Utility locational marginal prices cause lower emissions than customer owned CHP subject to a non-varying retail rate. Emissions increase as the penetration of small CHP (<100 kWe) increase but time-varying locational marginal prices are effective at reducing these emissions for the utility. Emissions do not increase for large CHP (>100 kWe) and time-varying rates are ineffective at reducing emissions.

more favorable to commercial CHP, penetrations increased, but the relative emissions also increased. Time-varying LMPs 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 (>100 kWe) are unaffected by penetration level and time-varying rates (see figure 7, where 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 MEFs would affect the relative emissions or economic benefits of CHP fleets. The

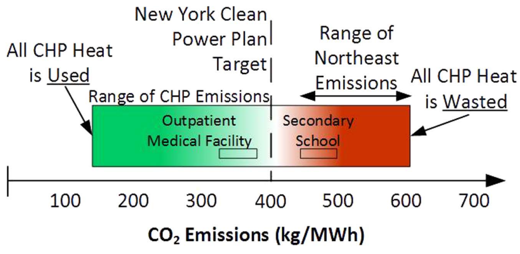

Figure 8. Commercial CHP produce higher emissions because the heat they produce cannot always be used. In some cases, this wasted heat will prevent commercial CHP installations from helping New York meet their clean power plan target. Outpatient medical facilities have more consistent heat loads than secondary schools, and their emissions are lower than current northeast emissions and the clean power plan target. Secondary school emissions are low relative to the current bulk grid but would not help New York meet the clean power plan target. Both commercial buildings produce emissions much higher than their technical potential.

results are shown in figures S17 and 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. Our results agree with previous findings that large CHP will reduce emissions and that policies encouraging large CHP will reduce system wide emissions [26]. Commercial CHP, however, will not always reduce emissions if large amounts of wasted heat are produced, as summarized in figure 8 for the New York Clean Power Plan targets. Both commercial buildings produce emissions much higher than their technical potential, and only the outpatient facility is able to help New York meet its emission target.

Based on our results, we offer the following considerations to help policy makers maximize the benefits of CHP in commercial buildings.

7.1. Commercial CHP will reduce system costs

The capital, O&M, and energy costs of commercial CHP are 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 has higher system savings but causes the utility to lose revenue. This loss of revenue will likely cause higher rates.

7.2. There are advantages of utility owned CHP

In addition to the benefits reported by the ACEEE [15], utility owned CHP avoids customer cost shifts. It may also be easier to regulate utility owned CHP emissions and to encourage operation that does not waste heat. Giving these findings, New York may want to reconsider its policy on utility CHP ownership.

7.3. Commercial CHP will reduce distribution network congestion and losses

On highly congested networks, commercial CHP may be an effective way to defer capacity investments.

7.4. 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. SO_2 emissions decrease when CHP is installed, but CO_2 emission rates depend on the heat load of the building. Local emissions could also violate limits in nonattainment regions, despite regional emission improvements [26]. 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 where marginal emissions range from 600 to 1000 kg MWh^{-1}, high penetrations of commercial CHP may not be effective at reducing emission in the northeast.

7.5. 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 and seasonal rates reduce customer owned CHP emissions and do not reduce customer rates-of-return. A carbon price would also be effective, but the costs of monitoring may be prohibitive for small CHP. Incentives that reduce capital costs such as accelerated depreciation or an investment tax credit, 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. As with industrial cogeneration [14], a production tax credit may cause small commercial CHP to produce higher relative emissions.

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References

[1] United States Energy Information Administration 2012 *Combined Heat and Power Technology Fills an Important Energy Niche* (Washington, DC: United States Energy Information Administration) (http://eia.gov/todayinenergy/detail.cfm?id=8250)

[2] Flin D 2010 *Cogeneration: A User's Guide* (London, UK: The Institution of Engineering and Technology)

[3] United States Environmental Protection Agency 2015 *Catalog of CHP Technologies* (Washington, DC: United States Environmental Protection Agency) (https://epa.gov/sites/production/files/2015-07/documents/catalog_of_chp_technologies.pdf)

[4] United States Department of Energy 2016 *Combined Heat and Power Installations in New York* (Washington, DC: United States Department of Energy) (https://doe.icfwebservices.com/chpdb/state/NY)

[5] Technavio 2015 *Global Combined Heat and Power in Commercial Building Market* (Elmhurst, IL: Technavio) (http://technavio.com/report/global-combined-heat-and-power-in-commercial-building-market-2015-2019?utm_source=T1&utm_medium=BW&utm_campaign=Media)

[6] Navigant 2015 *Combined Heat and Power for Commercial Buildings* (Boulder, CO: Navigant) (http://navigantresearch.com/research/chp-for-commercial-buildings)

[7] United States Energy Information Administration 2016 *Annual Energy Outlook: Electricity Generating Capacity* (Washington, DC: United States Energy Information Administration) (https://eia.gov/forecasts/aeo/data/browser/#/?id=9-AEO2016&region=0-0&cases=ref2016~ref_no_cpp&start=2013&end=2040&f=A&linechart=ref2016-d032416a.4-9-AEO2016~ref_no_cpp-d032316a.4-9-AEO2016~ref2016-d032416a.42-9-AEO2016~~~~~ref_no_cpp-d032316a.62-9-AE)

[8] King D E and Morgan M G 2007 Customer-focused assessment of electric power microgrids *J. Energy Eng.* **133** 150–64

[9] Siler-Evans K, Morgan M G and Azevedo L I 2012 Distributed cogeneration for commercial buildings: Can we make the economics work? *Energy Policy* **42** 580–9

[10] Flores R J, Brendan S P and Brouwer J 2014 Economic and sensitivity analysis of dynamic distributed generation dispatch to reduce building energy cost *Energy Build.* **85** 293–204

[11] Barbieri E S, Melino F and Morini M 2012 Influence of the thermal energy storage on the profitability of micro-CHP systems for residential building applications *Appl. Energy* **97** 714–22

[12] Smith A D, Mago P J and Fumo N 2013 Benefits of thermal energy storage option combined with CHP system for different commercial building types *Sustainable Energy Technol. Assess.* **1** 3–12

[13] Mago P J, Chamra L M and Hueffed A 2009 A review on energy, economical, and environmental benefits of the use of CHP systems for small commercial buildings for the North Amercian climate *Int. J. Energy Res.* **33** 1252–65

[14] Lane Clark & Peacock 2014 *Modelling the Impacts of Additional Gas CHP Capacity in the GB Market* (London: Lane Clark & Peacock) (https://gov.uk/government/uploads/system/uploads/attachment_data/file/389070/LCP_Modelling.pdfx)

[15] Chittum A and Farley K 2013 Utilities and the CHP value proposition *ACEEE Report Number* IE134 Washington, DC, (http://aceee.org/research-report/ie134)

[16] Opalka W and Heidorn R *New York PSC Bars Utility Ownership of Distributed Energy Resources* (http://rtoinsider.com/new-york-rev-der-13376/)

[17] Schneider K P, Chen Y, Chassin D, Engel D and Thompson S 2008 *Modern Grid Initiative Distribution Taxonomy Final Report* (Richland, WA: Pacific Northwest National Laboratory) (http://gridlabd.org/models/feeders/taxonomy_of_prototypical_feeders.pdf)

[18] United States Department of Energy 2012 *New Construction-Commercial Reference Buildings* (Washington, DC: United States Department of Energy) (http://energy.gov/eere/buildings/new-construction-commercial-reference-buildings.)

[19] United States Department of Energy, Office of Energy Efficieincy and Renewable Energy 2013 *Commercial and Residential Hourly Load Profiles for all TMY3 Locations in the United States* (Washington, DC: United States Department of Energy, Office of Energy Efficieincy and Renewable Energy) (https://catalog.data.gov/dataset/commercial-and-residential-hourly-load-profiles-for-all-tmy3-locations-in-the-united-state-1d21c)

[20] US Environmental Protection Agency 1998 Natural gas combustion *Compilation of Air Pollutant Emission Factors (AP 42)* vol I 5th edn (Research Triangle Park, NC: US Environmental Protection Agency) ch 1.4 (https://3.epa.gov/ttn/chief/ap42/ch01/final/c01s04.pdf)

[21] Baer P, Marilyn A B and Gyungwon K 2015 The job generation impacts of expanding industrial cogeneration *Ecological Econ.* **110** 141–53

[22] United States Department of Energy Office of Electricity Delivery and Energy Reliability : Smart Grid R&D Program 2012 *Summary Report: 2012 DOE Microgrid Workshop* (Chicago, IL: United States Department of Energy Office of Electricity Delivery and Energy Reliability: Smart Grid R&D Program) (http://energy.gov/sites/prod/files/2012%20Microgrid%20Workshop%20Report%2009102012.pdf)

[23] *Save Energy & Money: Distributed Generation* http://njng.com/save-energy-money/distrGen/index.asp

[24] *US Utility Rate Database* http://en.openei.org/wiki/Utility_Rate_Database

[25] United States Energy Information Agency 2016 *Natural Gas Prices* (Washington, DC: United States Energy Information Agency) (http://eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PCS_DMcf_a.htm)

[26] Brown M A, Cox M and Baer P 2013 Reviving manufacturing with a federal cogeneration policy *Energy Policy* **52** 264–76