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# POTENTIAL FOR DISTRIBUTED COMBINED HEAT AND POWER IN AN URBAN ENVIRONMENT

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## ABSTRACT

Combined heat and power (CHP) has the potential to decrease greenhouse gas emissions by utilizing waste heat that is typically rejected to the environment. CHP systems have been used to satisfy loads on university and corporate campuses but there may be other clusters of mixed used buildings that are viable for a CHP system. In an urban environment, such as New York City, high electricity loads and space heating loads are located in close proximity to each other, whether in a single building or in a neighborhood. This indicates a potential for clusters of buildings demand that could be satisfied by CHP. The analysis presented attempts to determine the potential for CHP systems for the 28,840 blocks of New York City many of which incorporate buildings of mix use. The systems are sized to meet the electrical base load and are considered viable if the CHP efficiency (useful electrical and thermal energy divided by the fuel input) is greater than 60% and the system size is larger than 30kW. The analysis determined that of the 28,840 blocks in New York City, 3,205 could be considered for a CHP system.

## INTRODUCTION

Climate change mitigation has been placed on the agenda for many urban areas. In particular, New York City has created a climate action plan called PlaNYC [1]. Within this plan is a call for an additional 800 MW of distributed generation. Policy makers have realized that distributed generation can help with climate change goals and system reliability. In particular the concept of distributed combined heat and power has the potential for greenhouse gases reductions through efficiently utilizing fuel by capturing the waste heat for local thermal needs.

Recently CHP has been implemented in many individual buildings through out the United States. On a larger scale, district heating and cooling systems supplied by combined heat and power, which distributes thermal energy to multiple buildings, can also achieve benefits by more efficiently utilizing the primary fuel source [2]. These systems, such as the current district steam loop in Manhattan that is partially supplied by CHP systems, typically serve entire neighborhoods and community areas. District heating systems in urban environments have been shown to be economically viable due to the high heating demand and population density [3]. Lying between the building and city scale deployments are university campuses that use CHP systems with a district heating loop. CHP systems are still viable at this scale since there are multiple large buildings of mixed use. This diversity of building types and density of thermal load exists on smaller scales in urban environments such as New York City. In these setting large offices, stores and residential buildings are situated very close together. In New York City, there are multiple different building types incorporated with in a single block.

The analysis presented in this paper seeks to identify areas where opportunities for CHP systems could exist in the current distribution of city blocks in New York City that are able to take advantage of the load profile diversity. The current analysis attempts to determine feasibility of CHP systems for each of the 28,840 blocks of New York City by analyzing estimated load profiles for CHP systems that can maintain suitable energy efficiency.

## METHODOLOGY

To determine the feasibility of the CHP systems the hourly electricity and space heating demand was estimated for each block. The systems were sized to utilize 100% of the electricity produced by the CHP system and the blocks were only considered feasible if the system maintained 60% CHP efficiency over the year. Also the system size was required to be larger than 30kW. The following sections will describe the methodology in more detail.

### Annual and Hourly Building Energy Consumption Estimation

Before CHP system capacities were determined, an estimate of the hourly energy consumption was required. Howard et al [4] estimated annual building energy intensities (energy per building floor area) for 7 different building types; residential 1-4 family (Residential 1-4), residential multi-family (Residential Multi), office, store, education, health and warehouse and 4 end uses; base electric, space heating, space cooling and water heating. In addition to estimating intensities for individual building types, the authors also made estimates based on location. New York City (NYC) is comprised of 5 boroughs: Manhattan, the Bronx, Brooklyn, Queens, and Staten Island. Due to the history of building development, there was a significant difference between the energy intensities of residential multi family and office buildings in Manhattan, residential multi family buildings in the Bronx, and the remainder of the boroughs. Those energy intensities are shown in Figure 1 as Residential Multi MN (Manhattan), Residential Multi BX (the Bronx), Residential Multi BK/QN/SI (Brooklyn, Queens and Staten Island), Office MN (Manhattan), Office NYC-MN (the Bronx, Brooklyn, Queens, and Staten Island). These intensities were applied to the building area of every tax lot in New York City to estimate the annual base electric and space heating energy consumption. The annual building energy intensities are shown in Fig. 1. These building types represent 91% of the building area in New York City meaning that estimates of energy consumption were not provided for 9% of the city. These building types are excluded from the analysis meaning that 9% of the buildings were not considered for CHP systems. This could lead to an under estimation of the CHP potential for the various blocks in NYC since hotels, which have large electricity and space heating loads, are included in the 9%.

Hourly energy intensities were extrapolated using the DOE commercial reference building load profiles. These reference buildings, developed using the methodology described in [5], were created to model the behavior of typical commercial buildings. The building energy consumption was estimated for 16 buildings types in 16 different climatic regions. These prototypical buildings were intended not to provide information about a specific building but to provide an estimation of how a building with particular characteristics would behave on average. The building prototypes were created using the energy modeling software EnergyPlus [6] using inputs from various sources.

The current analysis used load profiles from a subset of these buildings to estimate the hourly behavior of the various buildings in New York City based on their building types. The intention of using these hourly profiles was not to accurately estimate the hourly energy consumption for every building in New York City. The intention was to obtain a general picture of the variation of electricity and space heating energy consumption in time. While the annual energy intensities and therefore annual energy consumption are representative of New York City, the hourly breakdown is not.

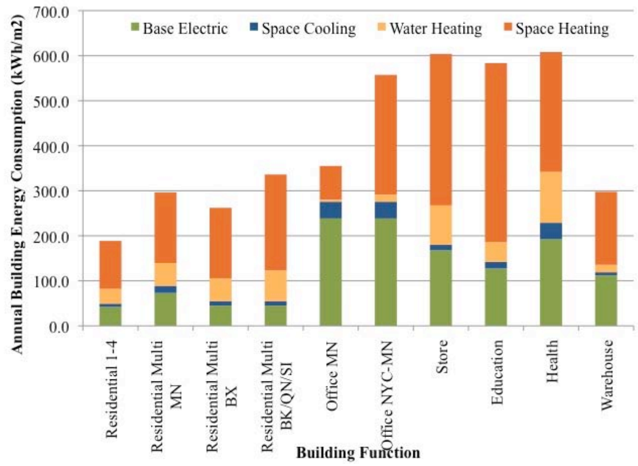


**FIGURE 1.** ANNUAL BUILDING ENERGY INTENSITY ESTIMATES BY BUILDING FUNCTION AND END USE

**TABLE 1.** NYC AND DOE COMMERCIAL REFERENCE BUILDING TYPES

| Annual NYC Building Types | DOE commercial building types |
|---|---|
| Residential 1-4 Family | Mid-rise Apartment |
| Residential Multi Family | Mid-rise Apartment |
| Office | Small Office, Medium Office, Large Office |
| Store | Stand-Alone Retail |
| Education | Primary School |
| Health | Outpatient Health |
| Warehouse | Warehouse |

**TABLE 2.** NYC AND CORRESPONDING DOE COMMERCIAL REFERENCE END USES

| Annual NYC end uses | DOE commercial end uses |
|---|---|
| Base Electric | Electric -cooling |
| Space Heating | Gas + Electric Space Heating |

The DOE commercial reference buildings provide more building types than those defined in [4]. Therefore only the prototypical buildings that corresponded with the building types used to estimate annual intensities were considered. The annual energy intensity building types and the corresponding DOE commercial reference building types are shown in Tab. 1. The climate region used for the DOE commercial reference buildings was 4A, whose representative city was Baltimore, Maryland. The 4A region includes New York City within its boundaries. In addition to specifying more building types, the EnergyPlus model provided estimates of additional end uses.

The estimated NYC annual end uses and the corresponding end uses from the EnergyPlus model are shown in Tab. 2. For the analysis only space heating and base electric loads, which consist of electricity used for lighting, refrigeration, plug loads but not cooling, were considered.

The following equation was used to create NYC specific hourly energy consumption intensities

$$e^{nyc}{}_{h,b,u} = r_{b,e} * e^{doe}{}_{h,b,u} \quad , \tag{1}$$

where $e^{nyc}{}_{h,b,u}$ is the NYC specific energy consumption for hour, h, building type as in the first column of Tab. 1, b, and end use as in the first column of Tab. 2, u, $r_{b,e}$ is the ratio of the annual NYC energy intensity to the annual intensity from the DOE commercial reference building for building type, b, and end use, u, and $e^{doe}{}_{h,b,u}$ is the energy intensity from the DOE commercial reference buildings for hour, h, building type as in the second column of Tab. 1, b, and end use as in Tab. 2, u.

The hourly base electric and space heating demand intensities for the residential multi family and large office buildings (> 9,290 sq.m.) are shown in Fig. 2 and Fig. 3, respectively. This methodology assumes that the load profiles scale linearly with building size which may create load profiles with more variation for larger buildings or less variation for smaller buildings.

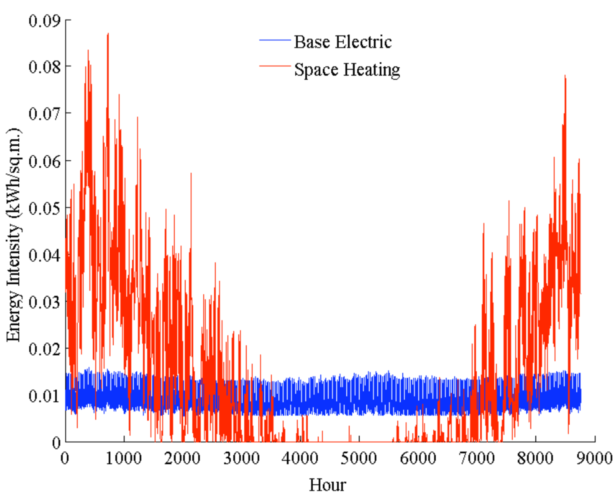


**FIGURE 2.** HOURLY RESIDENTIAL ENERGY INTENSITY ESTIMATES FOR SPACE HEATING AND BASE ELECTRIC DEMANDS

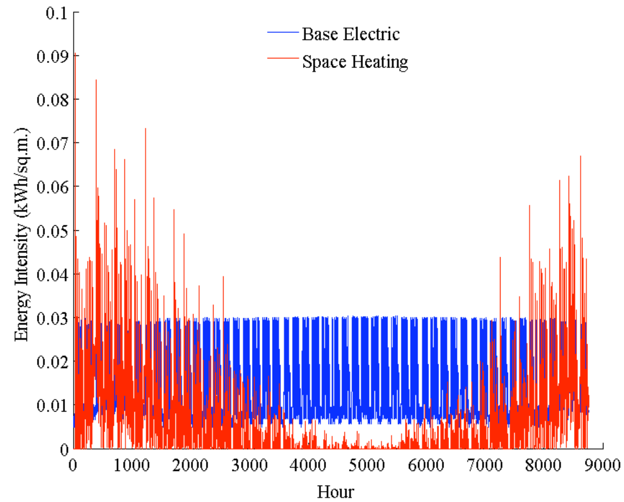


**FIGURE 3.** HOURLY LARGE OFFICE ENERGY INTENSITY ESTIMATES FOR SPACE HEATING AND BASE ELECTRIC DEMANDS

## CHP System Sizing

There are many methods for sizing combined heat and power systems.

One method is to size the CHP system to meet the peak electric demand. The system would supply the electric demand of the facility and would reject heat to the environment if the heat generated were higher than the thermal load. If the heat generated were lower than the thermal demand then auxiliary boilers would supply the remainder.

Another methodology is to size the system to meet the peak thermal demand of the system. Electricity is imported from the grid if the electricity supply from the CHP system is lower than the electricity demand. If the electricity supplied by the CHP system is larger than the demand the excess is sold to the grid.

There are many studies that have determined the optimal operational strategies of CHP systems ensuring demand is met for individual buildings. For example, Vasebi et al [7] used a harmony search algorithm to minimize the cost of employing conventional power, two or three CHP units and boiler while ensuring all heating and electricity demands are satisfied. Beihong and Weiding [8] determined the optimal operational strategy for a CHP or combined cooling heat and power (CCHP) system used to satisfy the energy demands of a hospital by minimizing cost using mixed- integer nonlinear programming. In addition to determining the optimal operations strategies for CHP systems in single buildings, other researchers have considered a spatial component by considering distribution of energy to multiple buildings [9-11]. These methods require solutions to detailed optimization problems, which are beyond the current scope of analysis. Also, many these analyses for determining the operational strategy of the CHP systems are based on cost. When implementing a combined heat and power system within an existing city, there are many costs that are specific to the project. For instance within New York City, there are many buildings that are not connected to the current natural gas infrastructure or would require significant capacity upgrades to deliver the increased amount of natural gas. These costs can make the economic payback unrealistic. There are many such costs when evaluating the feasibility of a combined heat and power system.

The methodology used for the current analysis sizes the CHP systems to meet the minimum electricity demand (base load demand). This results in 100% utilization of the electricity produced and allows the system to run at full load and peak efficiency. In terms of thermal load, for all building types auxiliary boilers would be required to meet the remainder of the demand.

Systems were considered viable if the total system size was greater than 30kW and the CHP efficiency was greater than 60%. The CHP efficiency was defined as the sum of the electrical and thermal efficiencies. The electric efficiency is defined as the net electrical output over the fuel input. The thermal efficiency is defined as the useful thermal energy produced by the system divided by the total fuel input into the system. Part-load efficiencies were not considered. Since the systems are size for the electric base load, a reduction in system efficiency only occurs when a portion of the waste heat produced is not utilized. When the waste heat was not fully utilized the thermal efficiency was reduced by the fraction of heat utilized to the heat available from the prime mover.

In New York State, an entity called the New York State Energy Research and Development Authority (NYSERDA) provides incentives for installing CHP. Many of the existing systems in NYC have been developed using their programs. In order to receive the incentives annual system efficiency must be above 60%, which is the threshold efficiency used for the analysis. The 30kW minimum capacity size was used to limit the systems to microturbines that are commercially viable.

From the NYC specific annual energy intensities and various CHP technologies used, sizing for the base load does not always lead to 60% efficiency of the CHP systems in office buildings and educational facilities. Aggregating these buildings load profiles with those of residential buildings or stores on the same block may allow these buildings to utilize the benefits of the CHP system based on the electric base load sizing methodology. CHP prime movers, such as microturbines and internal combustion engines, have heat to electricity ratios (HE) ranging from approximately 1-2 [12]. The heat to electric ratio for the buildings is defined as the ratio of the space heating demand to the base electric demand. The viability of a CHP requires good alignment between the HE ratio of the load and the HE of the prime mover system.

The technology used for the CHP prime movers was internal combustion engines and microturbines. These technologies were used because they represent the capacities required for these sizes of CHP systems. Each of the systems is assumed to use natural gas as the fuel source. The prime mover type, electrical efficiency and thermal efficiency of the systems chosen are shown in Tab. 3. The systems characteristics were taken from the EPA catalog of CHP technologies and from the GE Jenbacher Technical specifications [12-15]. These efficiencies represent the prime movers performance at full load and standard conditions.

**TABLE 3.** CHP SYSTEM CAPACITIES AND EFFICIENCIES

| **Electrical Capacity** | **Prime Mover** | **Electric Efficiency** | **Thermal Efficiency** |
|---|---|---|---|
| <100 kW | Microturbine [12] | 24.6% | 46.9% |
| 100 – 500 kW | Internal Combustion Engine [13] | 35.9% | 44.8% |
| 500 – 1,000 kW [10] | Internal Combustion Engine [14] | 38.3% | 49.2% |
| >1 MW [11] | Internal Combustion Engine [15] | 45.3% | 41.7% |

## RESULTS AND DISCUSSION

From the criteria stated, 3,205 blocks were identified as potential candidates for CHP systems. Approximately 45% the blocks are located in the borough of Manhattan (MN), 21% in Brooklyn (BK), 17% in the Bronx (BX), 15% in Queens (QN), and 2% in Staten Island (SI). The location and electric system capacity of each system is shown in Fig. 4. Fewer blocks are viable in the southwest areas of Queens, Brooklyn and most of Staten Island. These areas are primary composed of residential 1-4 family buildings which even when aggregated by block did not result in systems above the 30 kW threshold. A histogram of the distribution of system sizes is shown in Fig. 5. Many of the systems (1,258) are smaller than 150 kW with the majority of systems sized below 250 kW. These systems (depicted in the dark and light orange colors in Fig. 4) are primarily located in the higher density residential areas in Brooklyn, Queens and the Bronx as well as the lower density residential neighborhoods of Manhattan such as Inwood, Harlem, the East village and the West Village. The systems between 500 and 1,000 kW are located in the dense residential areas of Manhattan (Upper East and West Sides) and downtown Brooklyn. While these areas have large residential building they also incorporate stores and office buildings. The largest systems (> 1,000 kW and shown in dark blue in Fig. 4) are located in the central business and financial districts of Manhattan, which are primarily composed of large office buildings but still incorporate small amounts of residential and store buildings.

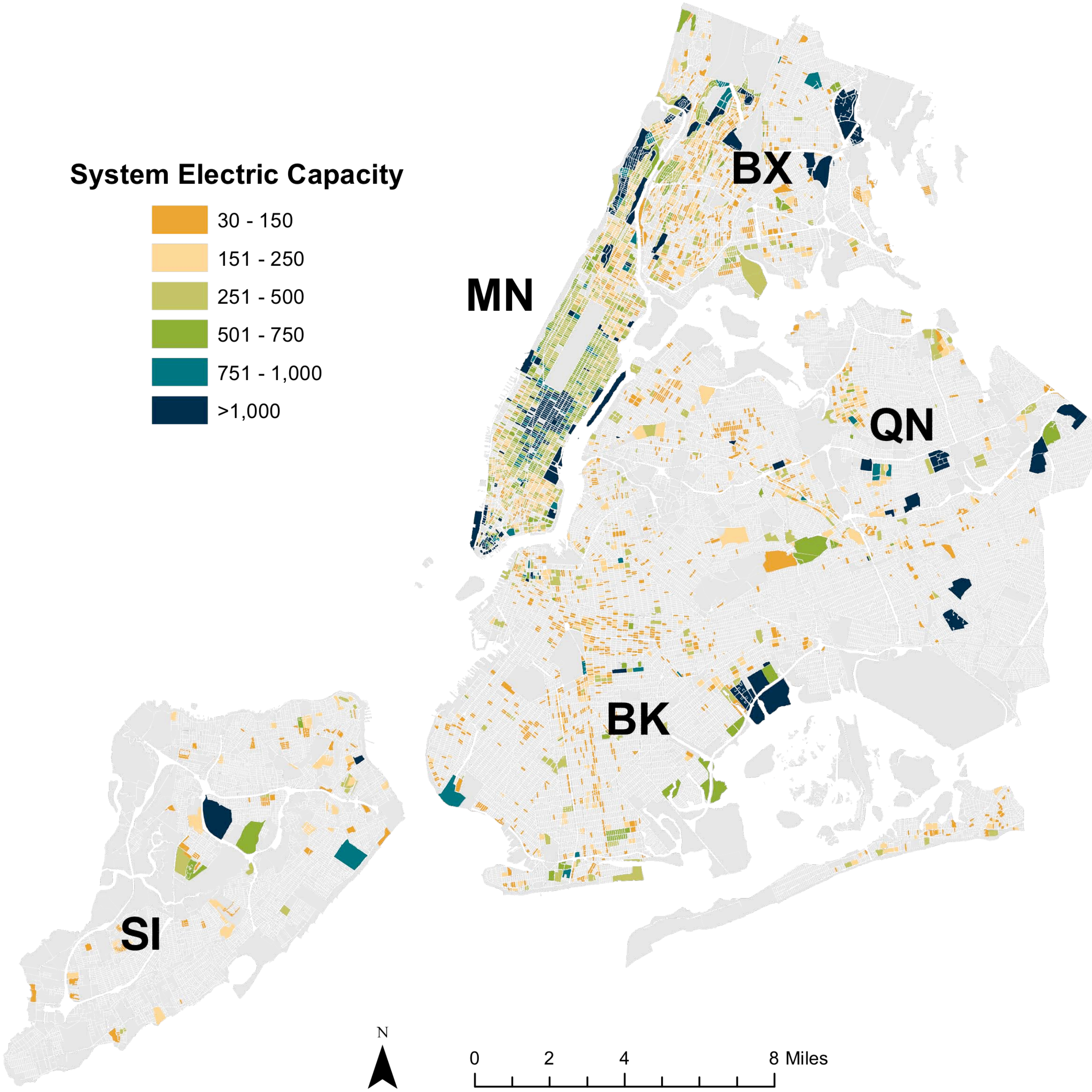


**FIGURE 4.** MAP OF CHP SYSTEM ELECTRIC CAPACITIES FOR VIABLE BLOCKS IN NEW YORK CITY

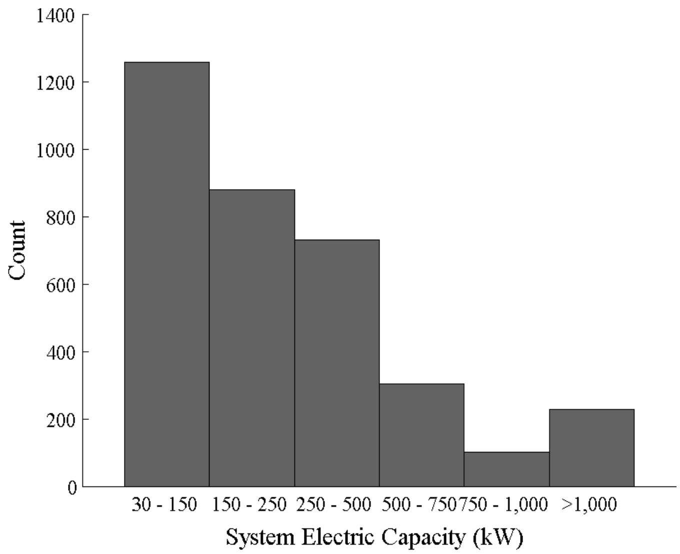


**FIGURE 5.** HISTOGRAM OF CHP SYSTEM ELECTRIC CAPACITY OF VIABLE BLOCKS

The current sizing method of supplying the base load electricity demand is a conservative estimate. Other sizing methodologies may lead to larger systems identified. Also in the current analysis energy consumed to supply domestic hot water was not included as a thermal load. Incorporating this may lead to more viable systems but would require more analysis of the quality of thermal energy produced by the CHP systems.

The 3,205 blocks identified as viable for CHP system sum to a total system capacity of 1,268 MW, which correlates to about 18% of the 2011 New York City generation capacity [16]. The New York City generation capacity doesn't include the systems in other areas of New York State where electricity is generated to serve the energy demands of NYC. The primary fuel for 40% of New York City's generation capacity in 2011 was fuel oil # 2 or 6. Typically these systems are smaller, more expensive and less efficient than the other generation sources like combined cycle gas turbines and steam turbines that use natural gas as a primary fuel. Moving the generation locally and switching the fuel to natural gas would allow for the waste heat to be used for space heating of local buildings as well as potential savings for greenhouse gas emissions.

## FUTURE WORK

The current analysis uses one sizing method, which may underestimate the generation capacity for the CHP system. Future analyses will consider different sizing methodologies similar to those discussed previously. For those methodologies part load efficiencies will need to be considered. Also thermal energy storage mechanisms were not considered in the analysis and utilization of the thermal energy could be increased if storage was incorporated.

The hourly profiles used to estimate the energy consumption were the same for every building function. In future works, additional building load profiles as well as stochastic behavior will be used for the hourly operation.

Using blocks as the basis of grouping buildings could potentially lead to the CHP system supplying a small amount of energy to individual buildings on the block. Future analysis will develop methodologies to cluster buildings to maintain high utilization for each building supplied with energy from CHP systems.

## CONCLUSIONS

The current analysis found that 3,205 blocks in New York City have the potential, from a load profile perspective, to incorporate combined heat and power systems to partially serve their space heating demand and the electricity base load demands. These systems, whose capacity totaled to 1,268 MW, would be able to maintain 60% CHP efficiency over the year. Most of the blocks identified were located in the borough of Manhattan, which is the area of the city with the highest building density and mixed building use. The mostly residential areas in the outer boroughs even when aggregated by block were not viable for CHP systems due to the small size of the base load electricity demand.

The total capacity of the CHP systems is equivalent to 18% of New York City's local generation capacity. These systems are generally less efficient systems that use fuel oils as their primary fuel source. Moving these systems locally to supplement the space heating demands of the buildings they supply electricity to would allow for better fuel utilization and potential greenhouse gas emissions reductions.

## ACKNOWLEDGMENTS

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