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Assessment of the Technical Potential for Micro-Cogeneration in Small Commercial Buildings across the United States

Preprint

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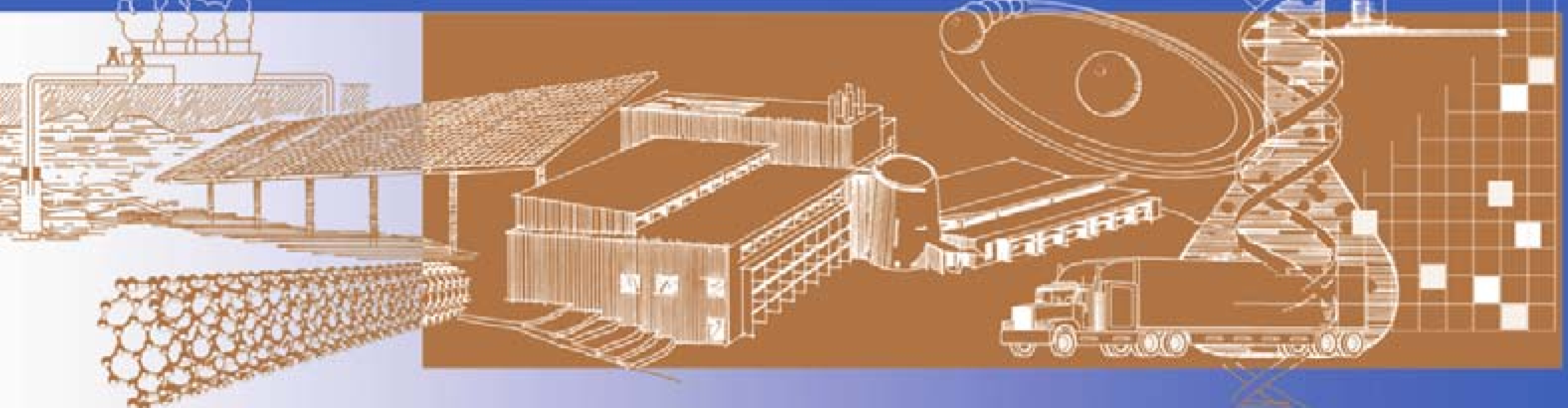

ASSESSMENT OF THE TECHNICAL POTENTIAL FOR MICRO-COGENERATION IN SMALL COMMERCIAL BUILDINGS ACROSS THE UNITED STATES

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ABSTRACT

This paper presents an assessment of the technical potential for micro-cogeneration in small commercial buildings throughout the United States. The cogeneration devices are simulated with the computer program EnergyPlus using models developed by Annex 42, a working group of the International Energy Agency's Energy Efficiency in Buildings and Community Systems (IEA/ECBCS). Although the Annex 42 models were developed for residential applications, this study applies them to small commercial buildings, assumed to have a total floor area of 500 m^2 or less. The potential for micro-cogeneration is examined for the entire existing stock of small U.S. commercial buildings using a bottom-up method based on 1,236 EnergyPlus models. The set of buildings used in the study represents all types of buildings in a range of U.S. weather locations and are based on samples used for the 2003 Commercial Building Energy Consumption Survey (CBECS) conducted by the U.S. Energy Information Agency (EIA). The cogeneration device is modeled in the context of whole-building, integrated systems, dynamic building simulation using annual runs with 15-minute time steps. Technical potential for micro-cogeneration is characterized by adding micro-cogeneration to individual baseline building models and quantifying the changes in a variety of whole-building, area-normalized, performance metrics including site energy, source energy, and energy cost. National implications for the United States are assessed by aggregating results using weighting factors from 2003 CBECS.

INTRODUCTION

Micro-cogeneration devices, developed primarily for residential applications, may find applications in small commercial buildings. Assuming "small" to be those buildings smaller than 500 m^2 total floor area, U.S. survey data [EIA 2006] indicate that the existing stock of small commercial buildings constitutes a significant market segment with some 2.6 million buildings (56% of U.S. commercial buildings) or 656 million m^2 of floor area (11% of U.S. commercial floor area). This segment of the commercial sector includes a wide variety of businesses such restaurants, service, office, education, and retail stores. Each year, this subsector consumes 4.2×10^{17} J of electricity and 2.7×10^{17} J of natural gas.

One of the challenges in modeling cogeneration devices is accounting for how thermal energy is used at the building site. Because thermal energy from cogeneration is intended for space heat and service water heating, it is important to include these systems in an integrated analysis when assessing cogeneration. IEA/ECBCS Annex 42 has developed new models for small, residential cogeneration that allow assessing micro-cogeneration devices within the context of detailed, annual building energy simulation programs [Kelly et al. 2008, Beausoleil-Morrison and Kelly 2007]. The author implemented the Annex 42 models in EnergyPlus, a whole-building modeling program developed and maintained by the U.S. Department of Energy [DOE 2007]. This paper provides a summary of a study that used EnergyPlus with the Annex 42 models to conduct a preliminary assessment of the technical potential for micro-cogeneration in small, U.S. commercial buildings.

METHODOLOGY

What might be achieved if all small commercial buildings throughout the United States were retrofitted with micro-cogeneration devices and hydronic heating systems? This study developed quantitative answers to this question using a methodology based on a large set of detailed energy performance simulations of individual buildings. Alternate scenarios are evaluated by comparing simulation results across the entire set of models where each is changed to reflect the addition of micro-cogeneration devices or a change in control strategy.

The set of 1,236 building models used in this study was drawn from a separate study [Griffith et al. 2007; Griffith et al. 2008] that developed models for the entire U.S. commercial sector. The models were derived from 2003 CBECS public use data [EIA 2006] and represent a statistically robust, random sample of U.S. commercial buildings. Each sample is an individual building of a specific type in a specific location and includes a weighting factor to represent how many such buildings exist in the United States. Additional details that are needed to generate complete EnergyPlus models, but are not available from 2003 CBECS data sets, were generated synthetically using a mixture of literature data, iteration, and random number generation. The subset of 1,236 models was derived from the full set of 4,820 models by filtering out only those buildings with floor area smaller than 500 m^2. The details of model generation are provided in Griffith et al. [2008].

The current study involves running the 1,236 EnergyPlus models under six different scenarios. Table 1 summarizes the scenarios by the name used in this paper, the type of heating, ventilation, and air-conditioning (HVAC) system for space conditioning, the type of plant, and how the micro-cogeneration devices are controlled. The scenarios include:

- **EXISTING STOCK** is a scenario that models the stock of small U.S. commercial buildings as of 2003. The set of models is a recent update of those from Griffith et al. [2008]. These are a mix of vintages and have all different kinds of HVAC systems. Some of these buildings lack heating and/or cooling.

- **Boiler PTAC** is a scenario where the entire stock of buildings is retrofit with new HVAC systems that use hot water heating. This is considered the baseline scenario for evaluating micro-cogeneration. Although only 44% of the subsector appears to have natural gas, this scenario assumes that all buildings could use natural gas. The hydronic HVAC systems selected are packaged terminal air conditioners (PTACs) with hot water heating coils. These are through-the-wall direct expansion cooling and ventilating devices with individual zone control. The hot water system is heated by a central boiler with 80% efficiency (with respect to higher heating value) but otherwise uses the same plant topology used to model the micro-cogenerator scenarios (see Figure 1). All of the models are fully heated and cooled and thereby provide a higher level of service in terms of comfort and ventilation than what is in the Existing Stock.

- **CHP Therm PTAC** is a scenario where a micro-cogenerator (CHP) is used and controlled to turn on when there is a thermal load. A net metering arrangement is assumed so if the building's electrical demand is less than the electric generation, then excess electricity is fed back into the grid.

- **CHP Therm Elect Limit PTAC** is a scenario where a micro-cogenerator is operated to turn on when there is a thermal load, however overall production is also limited by the current electrical demand of the building. No excess electricity is allowed to be exported back into the grid.

- **CHP Elect PTAC** is a scenario where a micro-cogenerator is operated to follow the building's electrical demand. No excess electricity is fed back into the grid.

- **CHP Baseload PTAC** is a scenario where a micro-cogenerator is operated to run continuously in a baseline mode.

This study modeled one type of micro-cogeneration device using the Annex 42 model for combustion devices with input data from laboratory measurements [Beausoleil-Morrison and Ferguson 2007]. The Senertech unit, a production internal combustion micro-cogenerator, was chosen for this study because of the availability of robust laboratory test data from Annex 42 and because it was one of the better performing units that was measured. The device is a natural gas-powered, internal combustion cogenerator with nominal electrical capacity of 5,500 W. The electrical efficiency was measured at 27% and the thermal efficiency at 66%, (with respect to lower heating value). In this simulation study, the control and modulation capabilities were extended to model "What If" scenarios; not all the operating schemes modeled were necessarily available in the actual production unit.

The micro-generators are modeled using the hot water plant topology diagrammed in Figure 1. A hot water storage tank serves hot water coils in PTAC units located in each thermal zone. Service water heating uses are also connected to the same tank. The tank is modeled as a stratified tank with ten nodes in the vertical direction. For the boiler and thermal load following scenarios, the hot water storage tank requests indirect heating when its lower control point drops below the tank's set point. If the upper setpoint is not met, then the tank uses backup heat. For the electrical load following scenarios, the recovery loop runs whenever the generator runs and the water heater vents any excess heat.

The EnergyPlus models are all complete building models. Each model includes a full complement of energy-related characteristics including: internal gains, infiltration, occupancy, schedules and HVAC systems. They are annual runs with 15-minute time steps. The models are located across 170 different weather file locations. The geometries are relatively simple with rectangular floor plans and five thermal zones per floor. A pre-release compile of EnergyPlus version 2.2 was used for the study.

Table 1. Summary of scenarios examined in study

No.	Scenario Name	HVAC	Plant	Cogeneration control mode
1	EXISTING STOCK	Various	Various	none
2	BOILER PTAC	Packaged Terminal Air Conditioners with hot water coils	Boiler indirectly heating HW tank, backup in stratified tank	none
3	CHP THERM PTAC	Packaged Terminal Air Conditioners with hot water coil	MicroCHP indirectly heating HW tank, backup in stratified tank	Thermal Load Following (with Net Metering)
4	CHP THERM ELECT LIMIT PTAC	Packaged Terminal Air Conditioners with hot water coil	MicroCHP indirectly heating HW tank, backup in stratified tank	Thermal Load Following but limited by building electric demand (no export)
5	CHP ELECT PTAC	Packaged Terminal Air Conditioners with hot water coil	MicroCHP indirectly heating HW tank, backup in stratified tank	Electric load Following (no export)
6	CHP BASELOAD PTAC	Packaged Terminal Air Conditioners with hot water coil	MicroCHP indirectly heating HW tank, backup in stratified tank	Baseload (continuous rated capacity)

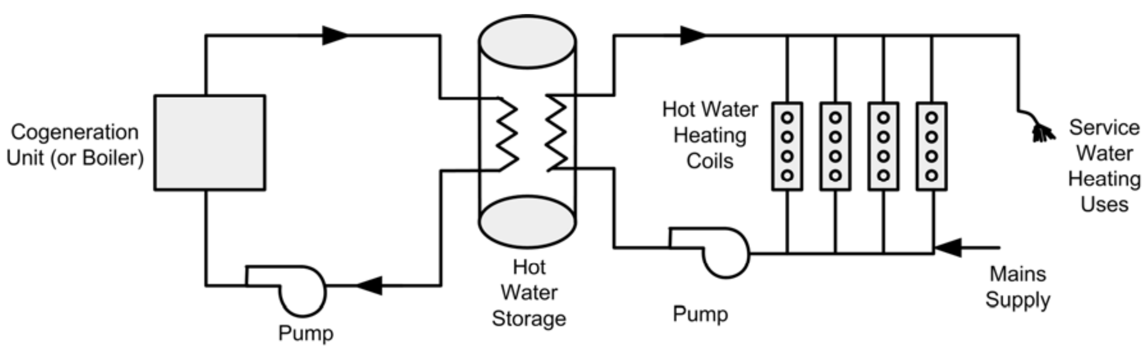

Figure 1. Hot Water Plant Topology in Models

ANALYSIS

The thousands of EnergyPlus results are reduced using weighting factors to combine results across the subsector. Whole-building performance intensity metrics are used to quantify energy use across different buildings. Predicted energy use is normalized by building floor area in the following metrics: total site energy use intensity, net site energy use intensity, net source energy use intensity, total site electricity use intensity, total site gas use intensity, electricity generated intensity, and energy cost intensity. The annual whole building energy use and cost results are based on higher heating value of natural gas. The model input data include site-to-source energy conversion factors from Deru and Torcellini [2007] that are resolved by U.S. states. The model input includes a comprehensive set of utility tariffs, resolved at the state level, for calculating energy costs (assuming availability of net metering). Sector-wide averages are mean values weighted by floor area rather than number of buildings.

The large number of samples also allows examining how energy performance is distributed across the subsector. Analysis of results includes generating probability density functions using a histogram analysis with a bin size of 300 MJ/m^2-yr.

RESULTS

Table 2 provides a summary of the results. Comparing the Boiler PTAC scenario to the Existing Stock scenario shows that the installation of new PTAC-based HVAC systems with hot-water-based heating would improve the thermal conditioning while also improving the average energy performance of the existing stock by 4.7% in terms of site energy and 22% in terms of source energy.

Four scenarios replaced the boiler with a micro-cogenerator using different operating schemes. The thermal load following schemes reduced net source energy. The electric load following scheme did not change source energy use much. The baseload scheme increased source energy use. Energy costs increased in all cases but only the baseload scheme led to dramatic increases in energy costs compared to energy costs for the current existing stock. The cogenerators lead to a substantial shift away from electricity and toward using more natural gas.

Table 2. Summary of Scenario Results for Average Energy Use Intensity Metrics

Whole Building, Whole Sector, Annual Intensities	units	Existing Stock	Boiler PTAC	CHP Therm PTAC	CHP Therm Elect Limit PTAC	CHP Elect PTAC	CHP Baseload PTAC
Total Site EUI	MJ/m^2-yr	1,318	1,256	1,919	1,414	2,060	3,140
Net Site EUI	MJ/m^2-yr	1,318	1,256	1,644	1,258	1,750	2,548
Net Source EUI	MJ/m^2-yr	3,039	2,365	2,314	2,100	2,376	2,746
Electricity Generated	MJ/m^2-yr	0	0	275	156	310	592
Energy Cost Intensity	\$/m^2-yr	$27.88	$22.90	$29.18	$24.47	$30.57	$40.63
Total Electricity EUI	MJ/m^2-yr	934	589	591	591	591	583
Total Natural Gas EUI	MJ/m^2-yr	374	667	1,328	824	1,468	2,557

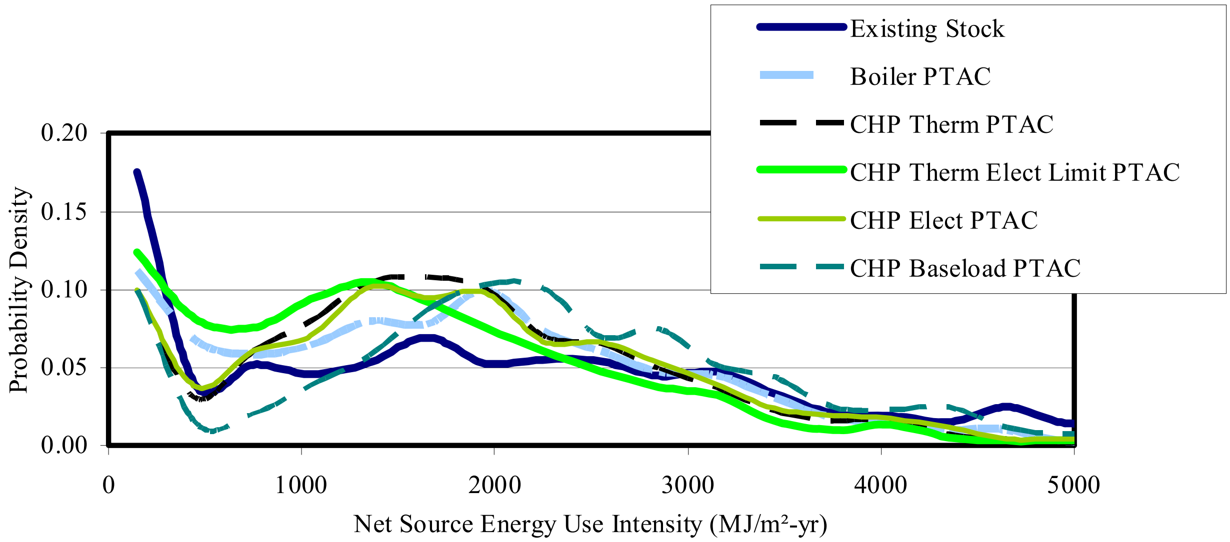

Figure 2 Probability Density Functions for Scenarios

Table 3. Average Results for Energy End Uses

Average Energy End Uses	units	Existing Stock	Boiler PTAC	CHP Therm PTAC	CHP Therm Elect Limit PTAC	CHP Elect PTAC	CHP Baseload PTAC
Cooling Electricity	MJ/m^2-yr	182	161	164	163	157	158
Heating Gas	MJ/m^2-yr	226	491	0	0	0	0
Fans Electricity	MJ/m^2-yr	342	81	74	74	73	64
Pumps Electricity	MJ/m^2-yr	1	6	7	7	15	15
Lighting Electricity	MJ/m^2-yr	160	160	160	160	160	160
Plug/process Electricity	MJ/m^2-yr	88	88	88	88	88	88
Process Gas	MJ/m^2-yr	101	101	101	101	101	101
Refrigeration Electricity	MJ/m^2-yr	98	98	98	98	98	98
Water Heater Gas	MJ/m^2-yr	77	75	64	65	95	24
Generator Gas	MJ/m^2-yr	0	0	1163	658	1272	2432

Figure 2 plots probability density functions that show how source energy performance is distributed across the subsector. Performance in the subsector varies widely. The higher probability of low energy buildings in the Existing Stock is because many of those buildings lack heating and/or cooling systems but in the other scenarios, all the buildings are completely heated and cooled. The density functions show that the CHP Baseload PTAC scenario is the worst and that the CHP Therm Elect Limit PTAC scenario is the best.

Table 3 lists end uses that show the breakdown for where energy used at site is consumed, on average. The hot water storage tank always used a small amount of gas for backup heating. All of the CHP scenarios were effective at replacing the energy used for space heating. The operating scheme that followed thermal loads with electrical demand limit ran the CHP unit the least but was, on average, able to meet the heating loads. This indicates that the other operating schemes are not able to use all the thermal energy being produced.

CONCLUSIONS

This study applied the Annex 42 model for combustion-based micro-cogeneration devices to assess how one such device would affect energy use in the subsector composed of small U.S. commercial buildings. This study leads to the following conclusions:

- EnergyPlus is useful for analyzing the annual energy performance of micro-cogeneration devices in a modeling framework that includes complete hot water systems and the building's thermal loads.
- The production internal combustion micro-cogenerator evaluated has the potential to reduce net source energy use in the subsector by an average of 11%.
- Over the course of a year, the electricity demands of most of the subsector could be met by micro-cogenerators operated continuously with a 5.5-kW electrical output.
- The most favorable operating scheme from a cost and source energy viewpoint is for the micro-cogenerator to be operated to follow thermal loads.
- Micro-cogeneration is effective at shifting from electricity to natural gas, but does not decrease net site energy use or energy costs.
- Some operating schemes will produce excess thermal energy that cannot be used at the site.

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