

*Final Report*

# Demonstration of Micro-Combined Heat and Power for Light Commercial Applications



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**September 30, 2019**

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Energy and Transportation Science Division

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# **1. INTRODUCTION**

## **1.1 Project Overview**

In 2014 the United States Department of Energy (DOE) Building Technologies Office (BTO) funded a technology assessment of micro Combined Heat and Power ( $\mu$ CHP) systems for light commercial applications. The technology assessment was part of the BTO High Impact Technology (HIT) Catalyst program. The HIT Catalyst program supports research and development into technologies that will yield cost-effective, efficient buildings. It is estimated  $\mu$ CHP in US has the potential to save 10.5 GW of primary energy in the commercial building sector.

Oak Ridge National Laboratory was selected to conduct the assessment in collaboration with the  $\mu$ CHP system manufacturer AO Smith Corporation. A total of six demonstration sites were selected based on site visits and interviews with the building owners and operators. Out of six selected sites, three sites were retrofitted with  $\mu$ CHP systems and performance data collected. Three sites went through the initial screening and selection process, but the site owner opted to not continue as part of the research project. This report provides a detailed description of baseline and  $\mu$ CHP system performance, energy savings analysis and lessons learned from the design, installation, and operation of the  $\mu$ CHP systems.

## **1.2 Project Goals**

The objectives of this technology assessment were to explore market barriers including perceived lack of value proposition, complexity of system, complex end market interface, and lack of state' regulatory consistency.

The expected outcomes are to provide stakeholders (manufacturers, building owners/national account companies and installers) the information they need in order to make informed decisions regarding deployment of this technology.

Specific goals included:

- 1) Verifying the value proposition of <3 year installed cost payback (independently assess performance to help inform payback evaluation)
- 2) Identifying and simplifying design, installation and maintenance/service issues
- 3) Identifying training needs for design, installation and service personnel.
- 4) Identifying Regulatory Issues – permitting, net metering and tariffs

## **1.3 Technology Assessment Process**

The HIT Catalyst assessments follow a similar process that includes:

1. Site Criteria Development
2. Site Recruitment
3. Site Selection
4. General M&V Plan Development

5. Site-Specific M&V Plan Development
6. Install and Commission Data Acquisition
7. Preliminary Data Analysis
8. Develop Technical Report

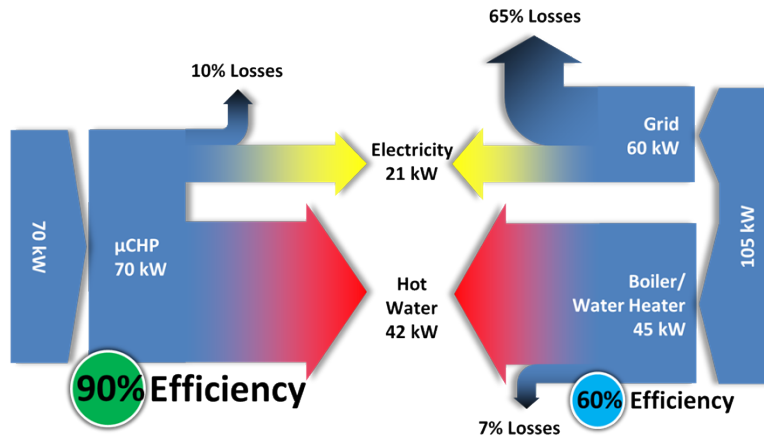
ORNL prepared a site screening form in collaboration with AO Smith, for AO Smith's potential sites to identify building and operation characteristics. AO Smith then conducted site recruitment, including hosting webinars to present the technology and opportunity to prospective sites. Interested sites were asked to complete a site screening form, after which AO Smith evaluated the information to help select sites that met the occupancy and regional criteria. AO Smith then had a field representative conduct site visits to review the existing installations and further evaluate whether the candidate sites were a good match for a technology retrofit. AO Smith then entered into agreements with the sites selected and arranged for a contractor to retrofit the new  $\mu$ CHP system in parallel with the existing hot water systems.

ORNL developed a general technology measurement and verification (M&V) plan and then customized that for each of the respective sites. ORNL procured the M&V equipment and worked with AO Smith to get necessary items to the contractor for installation such as gas and water meters. ORNL then commissioned the data acquisition system, collected the baseline and retrofit data, analyzed the data and developed the final report.

#### **1.4 Technology Description**

The prime mover for the  $\mu$ CHP system is a natural gas-driven Internal Combustion (IC) engine. The engine drives an alternator to generate electricity while waste heat is recovered to deliver hot water for service (domestic) hot water or building (hydronic) heating. The  $\mu$ CHP system can be an alternative to large gas-fired water heaters traditionally installed in facilities with high demand for hot water either for domestic service or for building heating. The system is a thermally led  $\mu$ CHP system, meaning system operation is based on the need for thermal energy (e.g. hot water). When the facility needs hot water the  $\mu$ CHP unit will operate and in turn generate electricity in addition to providing hot water.

Micro combined heat and power systems are generally characterized as those having an electrical output of 50 kW or less. The  $\mu$ CHP system overall has an efficiency of approximately 90% in converting the supplied natural gas to hot water and electricity. In comparison, for a conventional building installation the overall efficiency would be approximately 60% due to significant losses in the generation/transmission/distribution process from generation site to the final end-use building. See Figure 1 for system efficiency comparison.



**Figure 1: μCHP Efficiency vs Conventional System Efficiency, by AO Smith Corporation**

### 1.5 Assessment Target Markets and Geographic Regions

The target market for the technology includes light commercial occupancies that have high (e.g. greater than 3000 gallons) daily usage of hot water. Types of occupancies with high domestic hot water usage include full-service restaurants, lodging (under 200 rooms), multi-family housing (75 units and larger), inpatient healthcare, fitness facilities, car washes and laundromats. In addition, light commercial buildings that have hydronic heating are also a target market. A September 2013 analysis by BRG Building Solutions identified a potential μCHP market of more than 370,000 buildings in North American as of 2012 with the market growing at approximately 1% annually.

Three geographic regions were identified as being of most interest for the assessment process. These included the Northeast, Midwest and California. The drivers for selecting these regions included: favorable spark spread, regional inter-connectivity issues, grid reliability issues and California's more rigorous emissions regulations. The spark spread is the difference between the delivered electricity price and the estimated cost to produce power using the μCHP system. Areas with high electricity tariffs (combined consumption and demand) are typically areas where spark spread is higher (assuming natural gas is available). Site recruitment efforts were focused on candidate sites in the three target geographic areas. Ultimately the three sites with μCHP installations were from the Midwest (two in Wisconsin and one in Michigan).

## 2. Site A: A Resort in Northern Michigan

### 2.1 Site Information and Baseline System

The first demonstration site (Site A) is a resort in Northern Michigan. The building is a mixed-use facility including hotel with 500 rooms and four pools, a casino and five restaurants. The total floor area is around 200,000 sq.ft.

The site was selected due to its consistent hot water use, which is optimal for this  $\mu$ CHP demonstration project. The existing baseline hot water heater was installed in 1997. The total capacity of the water heater is 961,700 BtuH with a 300-gallon storage tank. Figure 2 shows the existing baseline DHW system floorplan and Figure 3 shows the system schematic. (See Figure 2 and Figure 3). The hot water delivery temperature has been set to 160F.

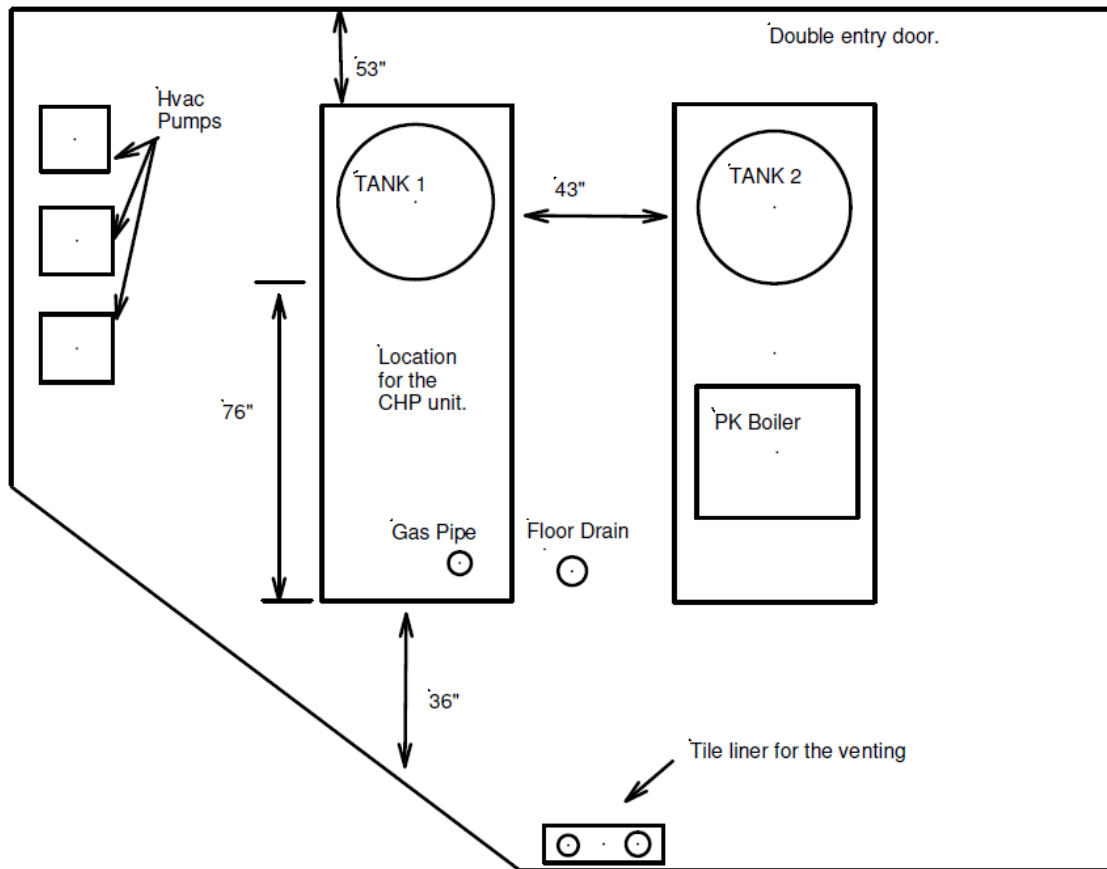
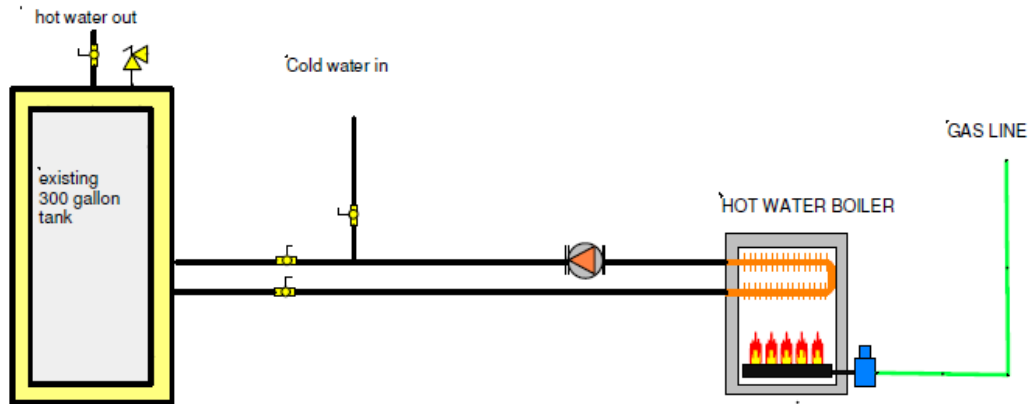


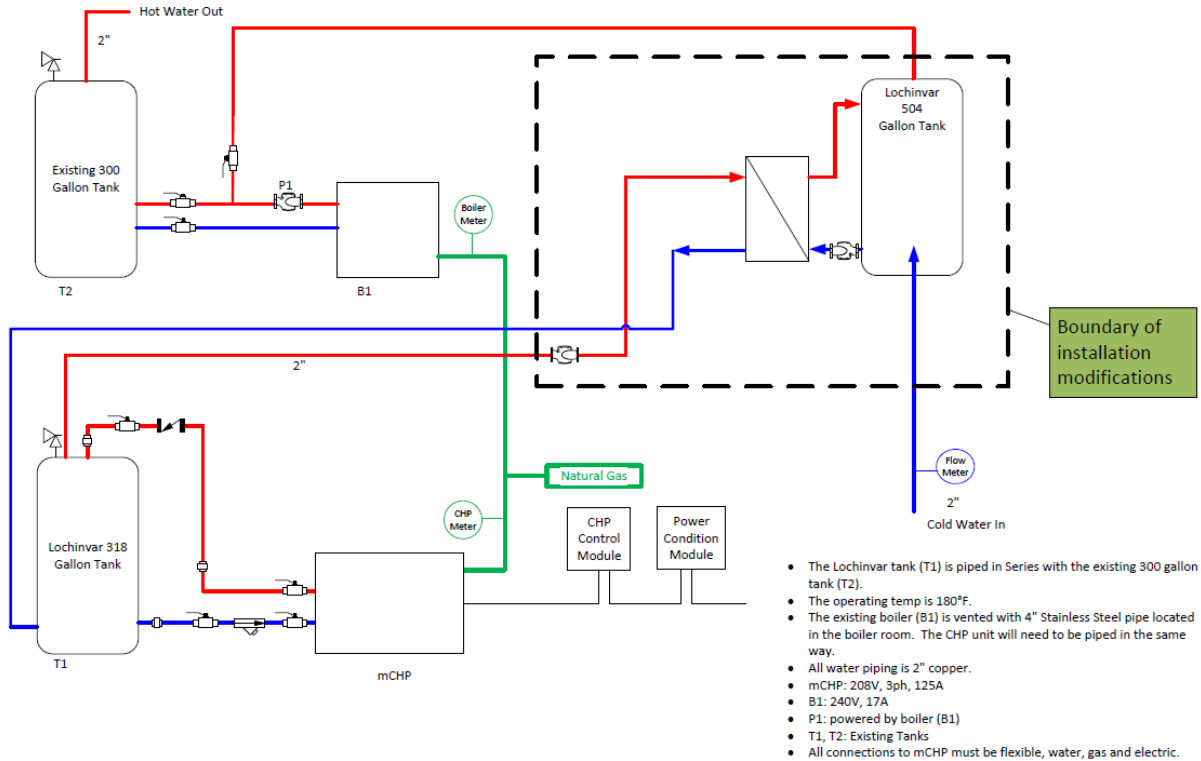
Figure 2: Site A Baseline Water Heater



**Figure 3: Site A Existing Water Heater Schematic**

## **2.2 Description of $\mu$ CHP system**

Figure 4 shows the installed  $\mu$ CHP system at the site. The system is a natural gas fired internal combustion engine and control by engine supplier B, and the total capacity of this system is about  $25\text{kW}_{\text{elec}}$ , and  $54.9\text{ kW}_{\text{thermal}}$ . The  $\mu$ CHP engine and heat exchanger (HX) were added to the existing baseline system, so that the baseline system can also provide auxiliary hot water when the  $\mu$ CHP cannot provide enough HW to the building. The system includes two new storage tanks connected to the  $\mu$ CHP engine and HX, in addition to the existing 300-gallon storage. The  $\mu$ CHP is controlled to meet HW demand.



**Figure 4: Site A μCHP As Installed**

## 2.3 M&V Plan

The measurement and verification plan was developed based on the Option B, Retrofit Isolation with All Parameter Measurement & Option C, Whole Facility Option (IPMVP Volume I EVO 10000 – 1:2012). In this option, the parameters to measure are 1) natural gas and electricity consumption of existing baseline water heater(s) and new μCHP unit, 2) electricity generation from new μCHP unit, 3) heat output of existing water heater and new μCHP unit. The heat output was estimated base on the inlet and outlet water temperature and total flow measured at water outlet from existing water heater and new μCHP unit. Table 1 shows the measurement points.

The intent of baseline and μCHP performance M&V is to

- To monitor and understand the baseline and Post-Installation operation and energy consumption of the existing water heater and capture any variations due to internal or external factors.
- To measure electricity and natural gas consumption of the baseline water heater(s) and the new μCHP unit
- To measure electricity generations from the new μCHP unit.
- To evaluate the hot water quality (i.e., temperature rise and flow rate) of the baseline water heater(s) and the new μCHP unit.



**Table 1: Measurement Points for Site A**

No.	Type	Data point	Description	Units
1	Temp	THW1	Hot water out to buildings	F
2		TCW1	Return water into boiler	F
3	Water Flow	FCW1	Return water flow to boiler	gpm
4	NG Flow Meter	NG1	Natural gas for existing boilers	Therms
5		NG2	Natural gas for $\mu$ CHP	Therms
6	Power	Aux1	Power for Pump	W
7		Aux2	Aux power for $\mu$ CHP	W
8		$\mu$ CHP_Power	Power generated from $\mu$ CHP	W
9		Aux3	Any aux for boilers	W

**Baseline M&V**

Based on the baseline monitored data, baseline hot water load (MBtu) will be estimated as below:

$$Q1 = K \times FCW1 \times (THW1 - TCW1) / 1000$$

Where:

Q1 = Baseline hot water load (MBtu) for building

FCW1 = Baseline water flow (gpm)

THW1 = baseline boiler supply hot water temperature (F)

TCW1 = baseline boiler feed water temperature (F)

K = 500 (conversion constant)

In addition, the baseline system efficiency is calculated as below

$$BE1 = Q1 / (NG1 / 100)$$

Where:

BE1 = baseline system efficiency (%)

Baseline energy use = NG1 (therm)

Baseline HW load = Q1 (MBtu)

 **$\mu$ CHP M&V**

In a similar fashion, the post retrofit hot water load will be estimated as below.

$$Q2 = K \times FCW2 \times (THW2 - TCW2) / 1000$$

Where:

Q2 = ( $\mu$ CHP + baseline boiler) hot water load (MBtu) for building

K = 500 (conversion constant)

FCW2 = System water flow (gpm)

THW2 = Supply hot water temperature (F)

TCW2 =  $\mu$ CHP feed water temperature (F)

### Savings Calculation

Once baseline and post retrofit hot water load and baseline system efficiency are calculated, the energy and cost savings calculation will be calculated as below.

$$\text{NG Savings} = 100 \times (Q2/BE1) - (NG1_{\mu\text{CHP}} + NG2_{\mu\text{CHP}})$$

Where,

Q2 = ( $\mu$ CHP + baseline boiler) hot water load (MBtu) for building.

BE1 = baseline system efficiency (%)

NG1 $_{\mu\text{CHP}}$  = NG use for  $\mu$ CHP (therm)

NG2 $_{\mu\text{CHP}}$  = NG use for existing boilers as back up during  $\mu$ CHP operation (therm)

$$\text{Elec. Savings} = \text{Aux1}_{\text{baseline}} - \text{Aux1}_{\mu\text{CHP}} - \text{Aux2} + \mu\text{CHP\_Power}$$

Where,

Aux1 $_{\text{Baseline}}$  = Aux elec. use for boiler pump for baseline operation (kWh)

Aux1 $_{\mu\text{CHP}}$  = Aux elec. use for boiler pump for  $\mu$ CHP operation (kWh)

Aux2 = Aux elec. use for  $\mu$ CHP operation (kWh)

$\mu\text{CHP\_Power}$  = Electricity generated by  $\mu$ CHP operation (kWh)

**Total Energy Cost Savings**<sup>1</sup> = Elec. Savings (kWh) x Elec.rate (\$/kWh) + NG. Savings (therms) x NG rate (\$/therm)

## **2.4 Data Analysis**

### **2.4.1 Baseline Analysis**

Baseline data has been monitored since 7/1/2017 through 8/7/2017. The baseline system efficiency was calculated, and the efficiency varied from ~30% to 55% per operational condition (i.e., daily hot water use). Figure 5 shows the relationship between the daily HW load and the boiler efficiency, which shows the logarithmic regression model.

$$Y = 0.0974\ln(x) - 0.2845$$

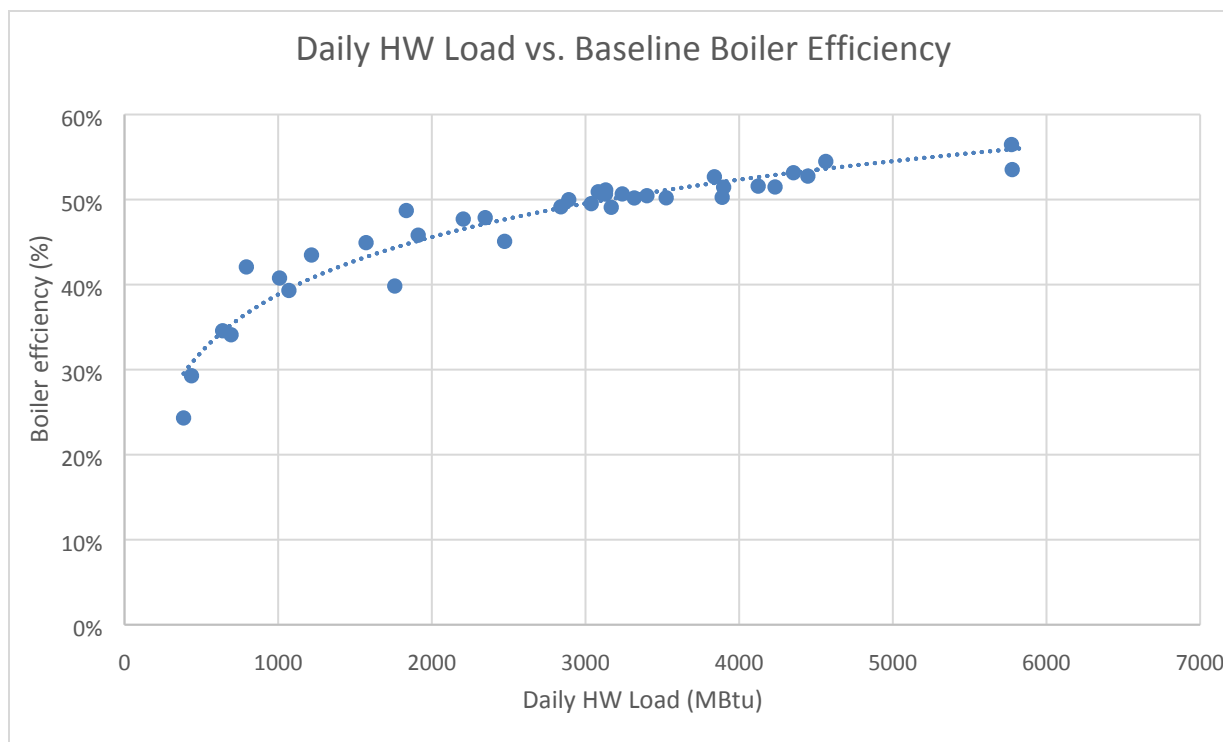
Where,

Y = Boiler efficiency (%)

X = Daily HW use (MBtu)

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<sup>1</sup> Only energy cost savings were calculated, and no  $\mu$ CHP investment cost was considered in this analysis.



**Figure 5: Daily HW load and the baseline boiler system efficiency**

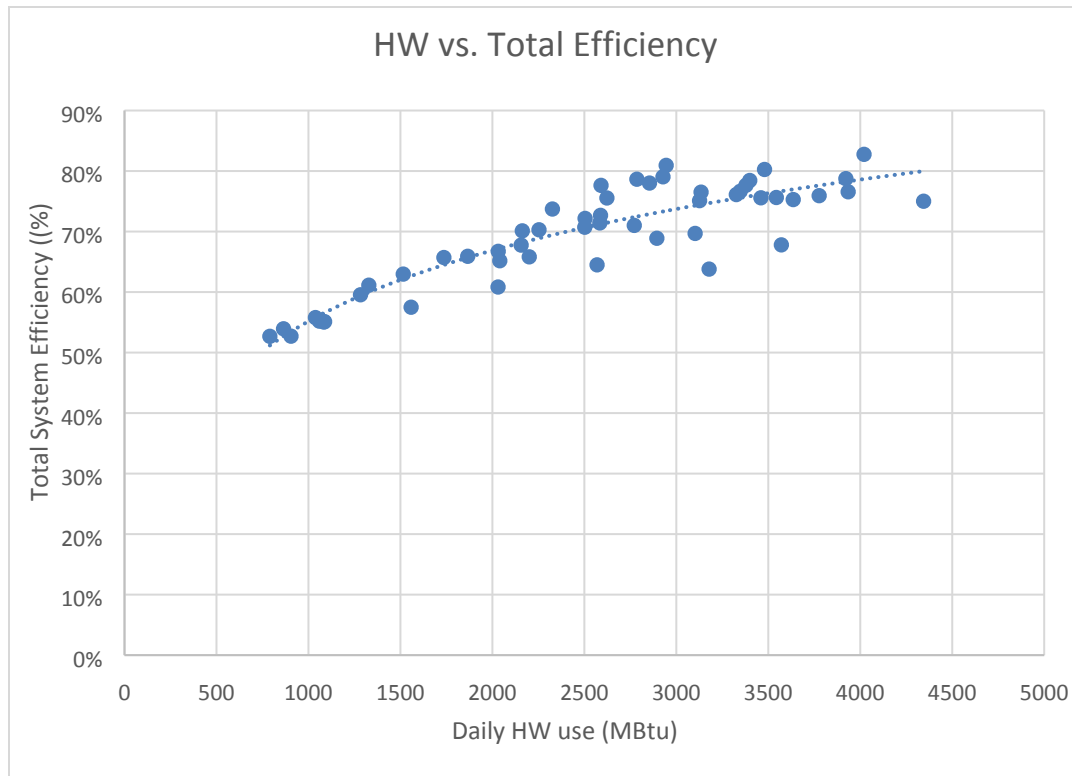
#### 2.4.2 $\mu$ CHP Operation Analysis

$\mu$ CHP system was installed and has been operated since 9/1/2017. Only the days with normal operations without any major issue were selected for the analysis. In order to evaluate how well the  $\mu$ CHP system has been performed, several evaluation metrics were considered including thermal efficiency, effective electric efficiency, and total system efficiency as well as total utility cost savings compare to normalized baseline energy use.

The electric efficiency for this system was calculated, and it varies from 15% to 20%, while the thermal efficiency varies 35% to 67%..

Total system efficiency of this  $\mu$ CHP system varies 53% to 83%. The lower system efficiency was shown when the HW load was relatively lower (Figure 6). While efficiencies vary for  $\mu$ CHP installations based on site-specific parameters, a properly designed  $\mu$ CHP system will typically operate with an overall efficiency of 65–85%<sup>2</sup>, which is consistent with the system efficiency of this site.

<sup>2</sup> ([https://www.energy.gov/sites/prod/files/2017/12/f46/CHP%20Overview-120817\\_compliant\\_0.pdf](https://www.energy.gov/sites/prod/files/2017/12/f46/CHP%20Overview-120817_compliant_0.pdf))



**Figure 6:  $\mu$ CHP system efficiency**

### 2.4.3 Cost Savings Analysis

In order to calculate the energy cost savings, average annual utility rates were assumed. According to EIA, the average elec. and NG rate for Michigan in 2017 were \$0.1128/kWh and \$0.702/ccf (therm), respectively. During the  $\mu$ CHP operations, the  $\mu$ CHP system generated 18,680 kWh of electricity. The total NG use for boiler and  $\mu$ CHP system were 1,073 therm, and 2,486 therm, respectively. Therefore, the total NG use for  $\mu$ CHP system was 3,559 therm.

For the same period, the baseline boiler system would use 3,366 therm of NG, which is slightly lower NG use than the use of  $\mu$ CHP system.

Therefore, the total operational cost savings were \$1,851, which is about \$38 savings per day. The daily savings % varies 47% to 69% per daily HW use.

In addition to the savings calculation, the delivered HW temperature for the  $\mu$ CHP system was evaluated. The HW temperature during  $\mu$ CHP operation was average 161F with minimum and maximum temperatures of 160 and 162. This is similar with the delivered temperature of baseline operation case, which indicate the  $\mu$ CHP system has been working properly.

## **2.5 Lessons Learned**

Some site performance issues were noted initially. These were determined to be associated with a system capacity/circulator pump undersizing for the original hot water system. An additional 504-gallon storage tank with a plate and frame heat exchanger was added to increase stored hot water capacity.

Engine supplier made some adjustments to improve select subcomponent performance during the demonstration. This included a power control box.

Some minor disruptions in  $\mu$ CHP system operation or data collection were noted during the assessment period. For example, 1) site staff inadvertently switched off a circulator pump in March 2017, and 2) twice site staff performing boiler maintenance opened a bypass valve which affected the water circulation path and impacted data collection for the cold-water inlet temperature.

### 3. Site B: A Health Club in Milwaukee, WI

#### 3.1 Site Information and Baseline System

The second site selected for the demonstration is a health club located in Milwaukee, WI. The facility is used for fitness club and gym and would be expected to have high and constant HW use.

The baseline system shown in Figure 7 has two water heaters to provide 133F to 150F HW to the building.

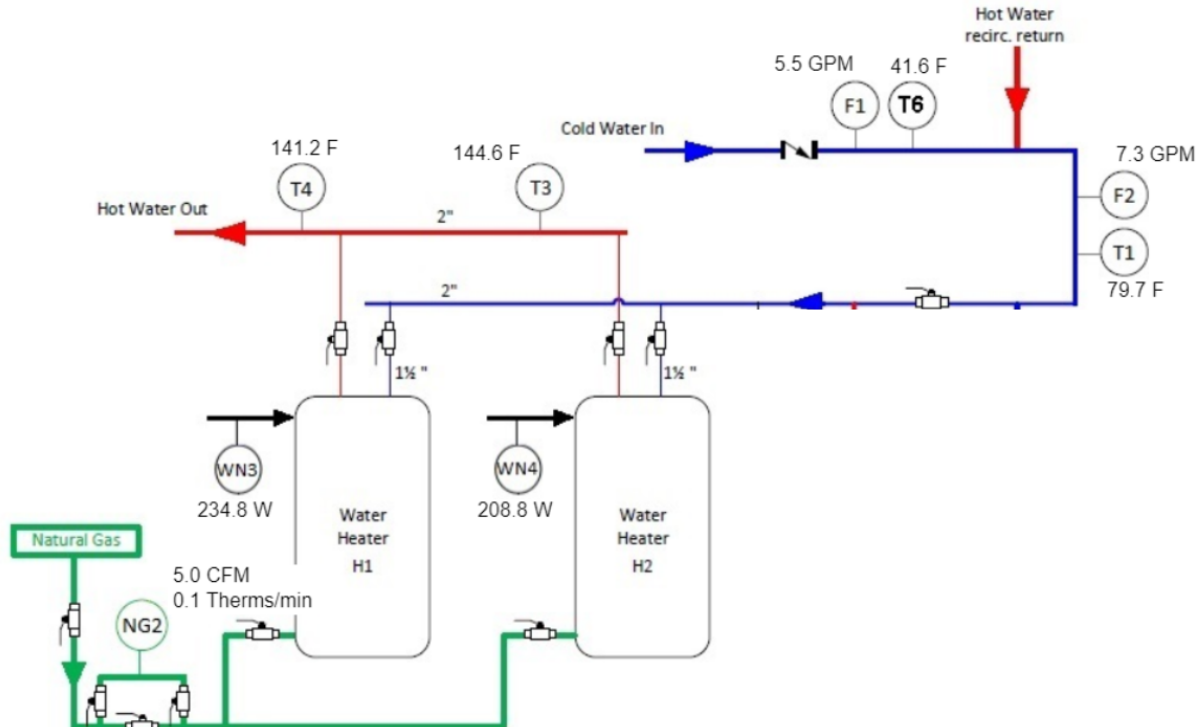
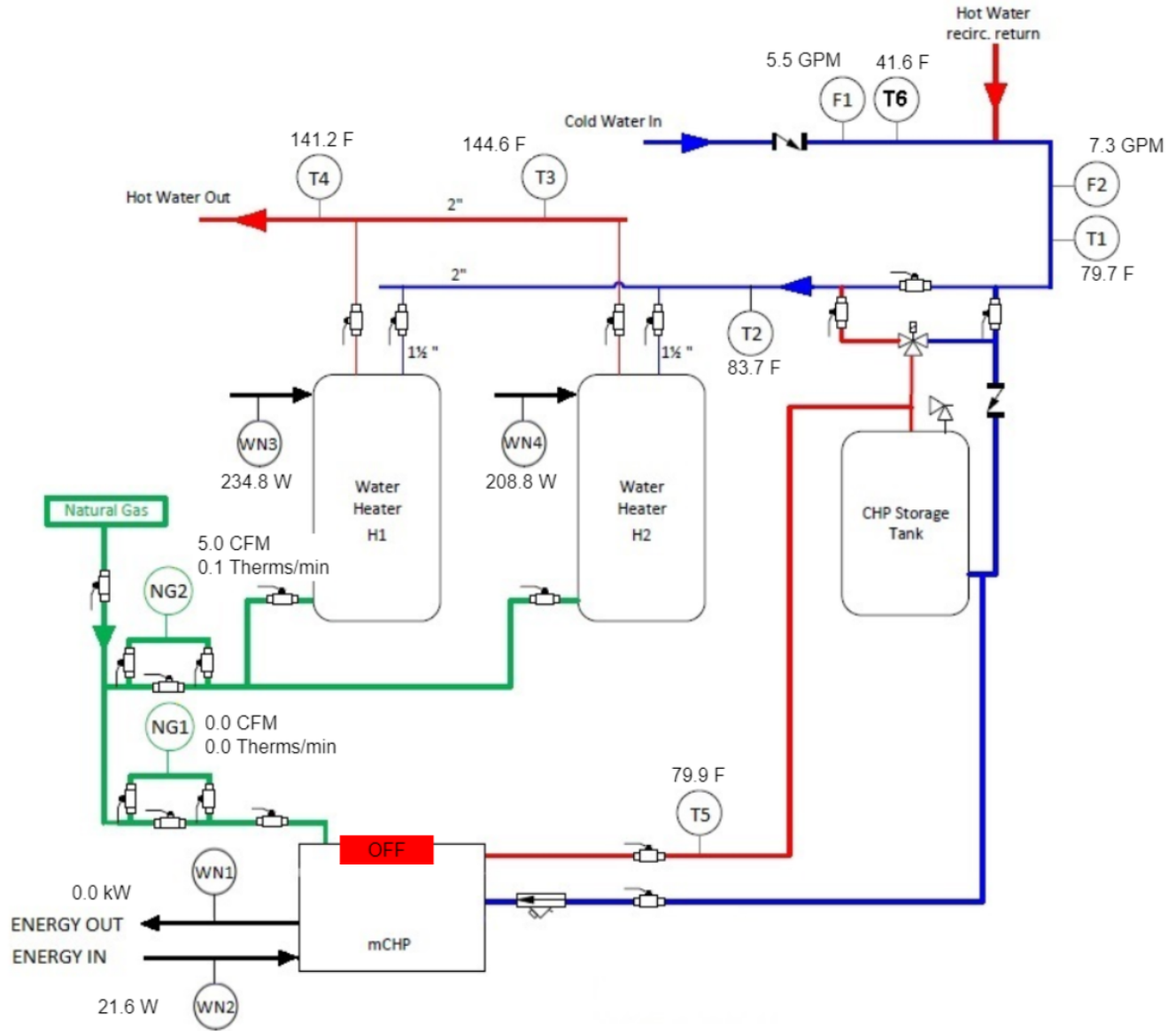


Figure 7: Site B Baseline Water Heater

#### 3.2 Description of $\mu$ CHP System

Figure 8 shows the installed  $\mu$ CHP system at the site. The system is a natural gas fired internal combustion engine and control by engine supplier B, and the total capacity of this system is about  $21\text{kW}_{\text{elec}}$  and  $42\text{kW}_{\text{thermal}}$ . The  $\mu$ CHP engine and  $\mu$ CHP storage tank are added to the existing baseline system, so that the baseline system can also provide auxiliary hot water when the  $\mu$ CHP cannot provide enough HW to the building.



**Figure 8: Site B μCHP As Installed**

### 3.3 M&V Plan

The measurement and verification plan was developed based on the Option B, Retrofit Isolation with All Parameter Measurement & Option C, Whole Facility Option (IPMVP Volume I EVO 10000 – 1:2012). In this option, the parameters to measure are 1) natural gas and electricity consumption of existing baseline water heater(s) and new μCHP unit, 2) electricity generation from new μCHP unit, 3) heat output of existing water heater and new μCHP unit. The heat output was estimated base on the inlet and outlet water temperature and total flow measured at water outlet from existing water heater and new μCHP unit. Table 1 shows the measurement points.

The intent of baseline and  $\mu$ CHP performance M&V is to

- To monitor and understand the baseline and Post-Installation operation and energy consumption of the existing water heater and capture any variations due to internal or external factors.
- To measure electricity and natural gas consumption of the baseline water heater(s) and the new  $\mu$ CHP unit
- To measure electricity generations from the new  $\mu$ CHP unit.
- To evaluate the hot water quality (i.e., temperature rise and flow rate) of the baseline water heater(s) and the new  $\mu$ CHP unit.

**Table 2. Measurement Points for Site B**

No.	Type	Data point	Description	Units
1	Temperature	T1	Feed water Temp to $\mu$ CHP storage tank	F
2		T2	Water temperature after $\mu$ CHP storage tank	F
3		T3	Water temperature after the first water heater	F
4		T4	Water temperature after the second water heater	F
5		T5	Baseline water heater supply hot water temperature	F
6	Water Flow	F1	Water flow for cold water in	gpm
7		F2	Water flow for main hot water line	gpm
8	NG Flow Meter	NG1	Natural gas for $\mu$ CHP	Therms
9		NG2	Natural gas for water heaters	Therms
10	Power	WN1	Power generation from $\mu$ CHP	W
11		WN2	Aux power for $\mu$ CHP	W

#### Baseline M&V

The baseline hot water load (MBtu) will be estimated as below:

$$Q1 = K \times F2 \times (T4 - T1) / 1000$$

Where:

Q1 = Baseline hot water load (MBtu) for building

F2 = Baseline water flow (gpm)

T4 = baseline water heater supply hot water temperature (F)

T1 = baseline feed water temperature (F)

K = 500 (conversion constant)

In addition, the baseline system efficiency is calculated as below

$$BE1 = Q1 / NG2$$

Where:

BE1 = baseline system efficiency (%)



Baseline energy use = NG2 (therm)

Baseline HW load = Q1 (MBtu)

#### μCHP M&V

In a similar fashion, the post retrofit hot water load from μCHP and the baseline boiler will be estimated as below. Unlike Site A, this site has a separate measurement for μCHP hot water load (MBtu) and Water heater hot water load (MBtu) during μCHP Operation, so each hot water load is calculated individually, and combined to have total hot water load.

$$Q2 = K \times F2 \times (T2 - T1)/1000$$

Where:

Q2 = μCHP hot water load (MBtu) for building

K = 500 (conversion constant)

F2 = System water flow (gpm)

T2 = HWT after μCHP storage tank/before water heaters (F)

T1 = μCHP storage tank feed water temperature (F)

$$Q3 = K \times F2 \times (T4 - T2)/1000$$

Where:

Q3 = Water heater hot water load (MBtu) during μCHP Operation

K = 500 (conversion constant)

F2 = System water flow (gpm)

T4 = Supply hot water temperature (F)

T2 = HWT after μCHP storage tank/before water heaters (F)

#### Savings Calculation

Once baseline and post retrofit hot water load and baseline system efficiency are calculated, the energy and cost savings calculation will be calculated as below.

$$\text{NG Savings} = 100 \times ((Q2+Q3)/BE1) - (NG1 + NG2)$$

Where,

Q2 = μCHP hot water load (MBtu) for building

Q3 = Water heater hot water load (MBtu) during μCHP Operation

BE1 = baseline water heater efficiency (%)

NG1 = NG use for μCHP (therm)

NG2 = NG use for water heaters

$$\text{Elec. Savings} = WN1 - WN2$$

Where,

WN1 = Power generation from μCHP (kWh)

WN2 = Aux elec. use for μCHP operation (kWh)

**Total Energy Cost Savings** = Elec. Savings (kWh) x Elec.rate (\$/kWh) + NG. Savings (therms) x NG rate (\$/therm)

### 3.4 Data Analysis

#### 3.4.1 Baseline Analysis

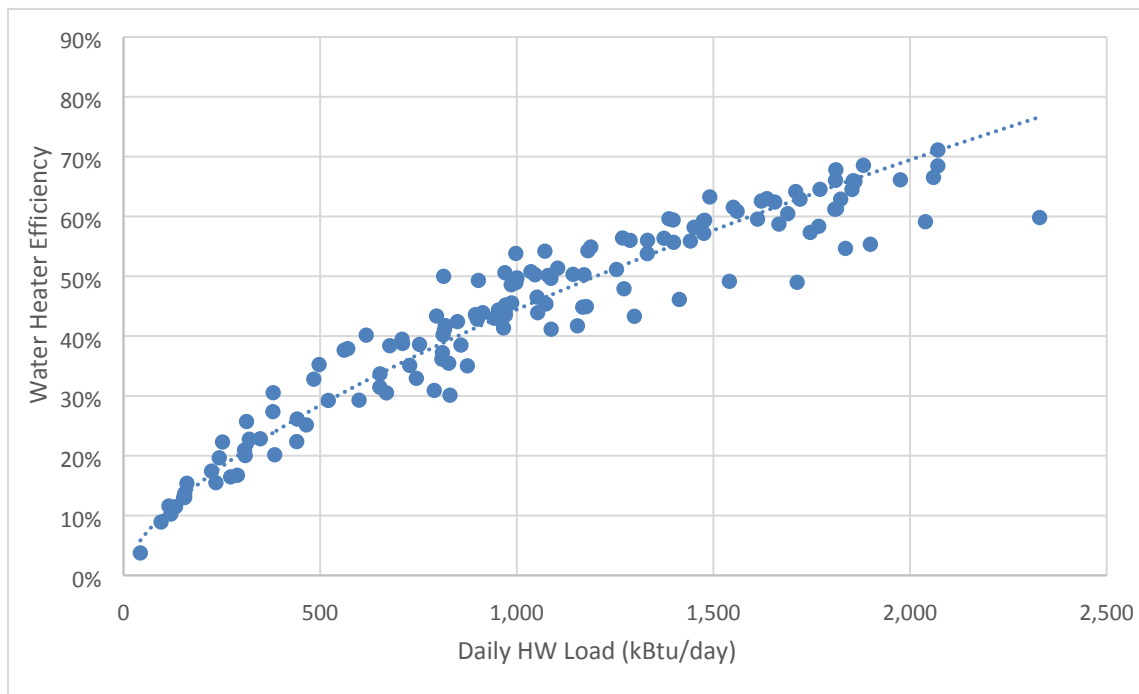
There was no separate baseline operation period, but the water heater efficiency was calculated based on the HW flow and delta temperature before and after water heater storage tanks as described in M&V plan. The monitoring period was from 12/22/2018 through 6/17/2019. Only the days with normal operations without any major issue were selected for the analysis. The final number of chosen days for the analysis is 137 days. The calculated efficiency varied from ~5% to 72% per operational condition (i.e., daily hot water use). Figure 9 shows the relationship between the water heater HW load and the water heater efficiency. The following equation present the water heater efficiency model based on daily HW load.

$$Y = 6E-01X^{0.6443}$$

Where,

Y = Water heater efficiency (%)

X = Daily HW load (kBtu/day)



**Figure 9: Baseline water heater efficiency as a function of HW load**

#### 3.4.2 $\mu$ CHP Operation Analysis

$\mu$ CHP system was installed and has been operated since December 2018. In a similar fashion of Travers site, several evaluation metrics were considered including thermal efficiency, effective electric efficiency, and total system efficiency as well as total utility cost savings compare to normalized baseline energy use.

The electric efficiency for this system was calculated, and it varies from 32% to 35%, while the thermal efficiency varies 31% to 78%. The average total system efficiency was about 90%.

### **3.4.3 Cost Savings Analysis**

In order to calculate the energy cost savings, average annual utility rates were assumed. According to EIA, the average elec. and NG rate for Wisconsin in 2018 were \$0.1076/kWh and \$0.660/ccf, respectively. During the  $\mu$ CHP operations, the  $\mu$ CHP system generated 55,097 kWh of electricity. The total NG use for boiler and  $\mu$ CHP system were 8,505 therm. For the same time period, baseline boiler system would use 5,875 therms of NG. Therefore, total operational cost savings were \$4,388, which is about \$32 savings per day.

### **3.5 Lessons Learned**

The construction permitting (plans review) process was longer than expected. A review official raised concerns about the possibility of cross-contamination of a potable water source if there were a failure in the heat exchanger. Ultimately the official required that the system's ethylene glycol be replaced with propylene glycol before a construction permit would be issued. The engine supplier reevaluated the system performance and replaced a circulating pump on the  $\mu$ CHP unit to account for the different heat transfer characteristics associated with propylene glycol.

During the assessment period, there was a time period when system hot water needs were not being met. Investigation showed that a valve at a commercial extractor (laundry machine) had failed open and created a large, continuous hot water draw that was greater than the design capacity of the system. The valve was repaired, and system hot water flows and temperatures returned to the expected condition.

## 4. Site C: A Manufacturing Facility in Milwaukee, WI

### 4.1 Site Information and Baseline System

The final site selected for the demonstration is a manufacturing facility at Milwaukee, WI. This is a laboratory building, and unlike the other two sites where the  $\mu$ CHP system are used for domestic (service) hot water use, this facility uses the  $\mu$ CHP system to provide HW to the building HVAC reheat. Figure 10 shows the existing baseline system diagram. Currently, there are two of 2.0 MBtu boilers with 85% rated efficiency to provide heating hot water to the reheating loop. The hot water delivery temperature was 140F to 190F during December 2018 through March 2019.

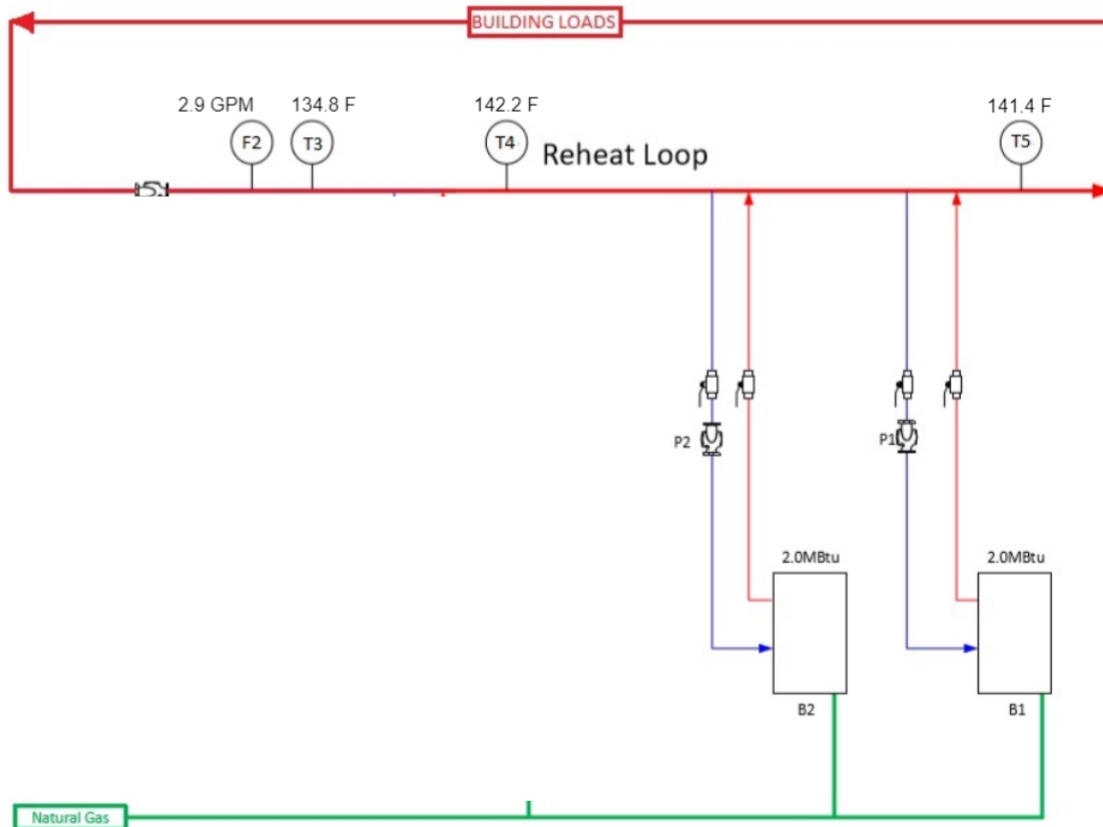
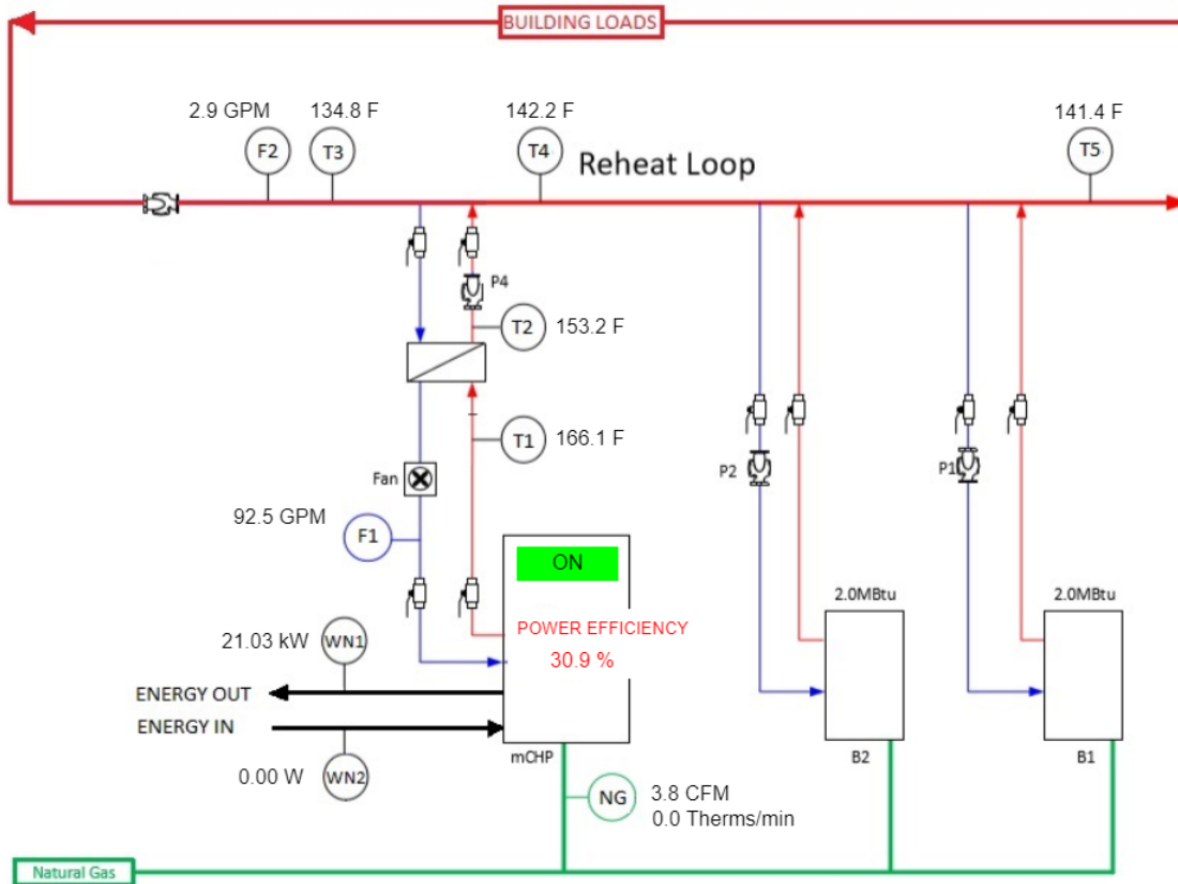


Figure 10: Site C Baseline Water Heater

### 4.2 Description of $\mu$ CHP System

Figure 11 shows the installed  $\mu$ CHP system at the site. The system is a natural gas fired internal combustion engine and control by engine supplier B, and the total capacity of this system is about  $21\text{kW}_{\text{elec}}$  and  $42\text{kW}_{\text{thermal}}$ . The  $\mu$ CHP engine added to the existing baseline system, so that the baseline

system can also provide auxiliary hot water when the  $\mu$ CHP cannot provide enough hot water to the building.



**Figure 11: Site C  $\mu$ CHP As Installed**

### 4.3 M&V Plan

Table 3 shows the measurement points for Site C.

**Table 3: Measurement Points for Site C**

No.	Type	Data point	Description	Units
1	Temperature	T1	$\mu$ CHP: Hot Water Temperature (HWT) from $\mu$ CHP	F
2		T2	$\mu$ CHP: HWT to reheat loop from $\mu$ CHP	F

		T3	Reheat Loop: HWT before $\mu$ CHP	F
		T4	Reheat Loop: HWT after $\mu$ CHP before Boiler	F
		T5	Reheat Loop: HWT after Boiler	F
3	Water Flow	F1	Water flow into $\mu$ CHP	gpm
		F2	Water flow reheat loop	gpm
4	NG Flow Meter	NG	Natural gas for $\mu$ CHP	Therms
6	Power	WN1	Power generation from $\mu$ CHP	W
7		WN2	Aux power for $\mu$ CHP	W

#### Baseline M&V

Baseline system performance can be analysis as followings.

$$Q1 = K \times F2 \times (T5-T3)/1000$$

Where:

Q1 = Baseline hot water load (MBtu) for building

F2 = Baseline water flow (gpm)

T5 = baseline boiler supply hot water temperature (F)

T3 = baseline boiler feed water temperature (F)

K = 500 (conversion constant)

$$NGB = Q1/BE1$$

Where:

BE1 = baseline system efficiency (%) – 85% assumed

Baseline energy use = NGB (therm)

Baseline HW load = Q1 (MBtu)

#### $\mu$ CHP M&V

In a similar fashion, the post retrofit hot water load from  $\mu$ CHP and the baseline boiler will be estimated as below.

$$Q2 = K \times F2 \times (T4 - T3)/1000$$

Where:

Q2 =  $\mu$ CHP hot water load (MBtu) for building

K = 500 (conversion constant)

F2 = System water flow (gpm)

T4 = Reheat Loop: HWT after  $\mu$ CHP before Boiler

T3 =  $\mu$ CHP System feed water temperature (F)

$$Q3 = K \times F2 \times (T5 - T4)/1000$$

Where:

Q3 = Boiler hot water load (MBtu) during  $\mu$ CHP Operation

K = 500 (conversion constant)

F2 = System water flow (gpm)

T5 = Supply hot water temperature (F)

T4 = Reheat Loop: HWT after  $\mu$ CHP before Boiler (F)

### Savings Calculation

Once baseline and post retrofit hot water load and baseline system efficiency are calculated, the energy and cost savings calculation will be calculated as below.

$$\text{NG Savings} = 100 \times ((Q2+Q3)/BE1) - (NG_{\mu\text{CHP}} + 100 \times (Q3/BE1))$$

Where,

Q2 = ( $\mu$ CHP + baseline boiler) hot water load (MBtu) for building.

BE1 = baseline system efficiency (%)

$NG_{\mu\text{CHP}}$  = NG use for  $\mu$ CHP (therm)

Q3 = Hot water load for existing boilers as back up during  $\mu$ CHP operation (MBtu)

$$\text{Elec. Savings} = WN1 - WN2$$

Where,

WN1 = Power generation from  $\mu$ CHP (kWh)

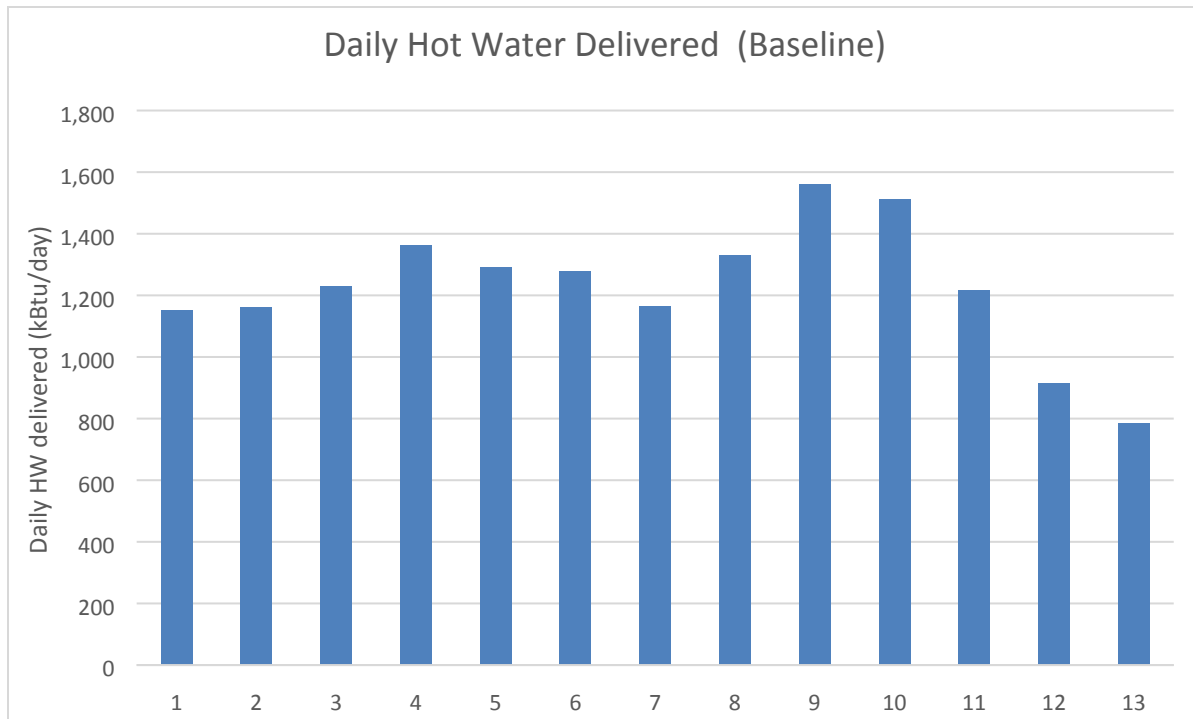
WN2 = Aux elec. use for  $\mu$ CHP operation (kWh)

$$\text{Total Energy Cost Savings} = \text{Elec. Savings (kWh)} \times \text{Elec.rate (\$/kWh)} + \text{NG. Savings (therms)} \times \text{NG rate (\$/therm)}$$

## **4.4 Data Analysis**

### **4.4.1 Baseline Analysis**

As there was no actual NG use measurement for the baseline boilers, boiler system efficiency of 85% was assumed based on the manufacturer's data. Figure 12 shows the baseline HW load for 13 days. During these days, the daily HW loads were fluctuated between 782 kBtu to 1,560 kBtu as the daily HW loads varies per building's reheating load.



**Figure 12: Site C Daily Hot Water Delivered (Baseline)**

#### **4.4.2 $\mu$ CHP Operation Analysis**

For the  $\mu$ CHP operation analysis, 46 days were selected when the  $\mu$ CHP system was operated without any major issue.  $\mu$ CHP system was installed and has been operated since December 2018. In a similar fashion of the other two sites, several evaluation metrics were considered including thermal efficiency, electric efficiency, and total system efficiency as well as total utility cost savings compare to normalized baseline energy use.

The electric efficiency for this system was calculated, and it varies from 24% to 31%, while the thermal efficiency varies 14% to 39%. The thermal efficiency is relatively low due to the low delta T compared to Site A. Delta T for this site is only about 6 to 8 F, while the Site A shows the average Delta T 60F to 120F. This site uses the  $\mu$ CHP system for HVAC reheating (not domestic hot water). With a high hot water return temperature, the operating delta T is relatively low which in turn reduces the thermal efficiency.

As a result, the total system efficiency varies 44% to 70%, which is relatively lower than other sites.

#### **4.4.3 Cost Savings Analysis**

In order to calculate the energy cost savings, average annual utility rate were assumed. According to EIA, the average elec. and NG rate for Wisconsin in 2018 were \$0.1072/kWh and \$0.660/ccf, respectively. During the  $\mu$ CHP operations, the  $\mu$ CHP system generated 19,449 kWh of electricity. The total NG use for boiler and  $\mu$ CHP system were 2,237 therm. For the same period, baseline boiler system would use 512 therm of NG, which is about 23% of NG use for  $\mu$ CHP system. Therefore, the total operational cost savings were \$1,056, which is about \$23 savings per day.



#### **4.5 Lessons Learned**

One service disruption was noted after system startup. Possible root causes included:

- An unspecified electrical issue
- Colder than normal conditions that required the site to increase the HW temperature from the primary boilers. The incoming (HW return) temperature to the  $\mu$ CHP system needed to be under 150F, which could not be achieved once the HW loop system temperature was increased.

## 5. Discussion

The installations ultimately completed for this assessment included two retrofit locations and a laboratory installation. Due to project timing and local codes review issues, a completely new (e.g. greenfield) installation was not available to be evaluated as part of this assessment process. Therefore, it was not possible to directly compare the retrofits versus new installations in terms of effort and issues associated with design, codes review, installation, startup and maintenance.

The three retrofit sites each presented unique site-specific challenges due to existing installation conditions and the codes review process. Some issues initially attributed to the  $\mu$ CHP system were in fact caused by the original heating system – including system storage that was somewhat under capacity and a shortage of hot water that was caused by a valve that had failed open. Staff at the commercial building retrofit locations indicated they were very satisfied with the operation of the  $\mu$ CHP systems and desired to continue their operation after the assessment had concluded. For site staff,  $\mu$ CHP system operation was no more complex than the existing hot water equipment.

Several site installation issues were like those for other forms of Distributed Energy Resources (DER), such as solar photovoltaic (PV) systems, in that electrical system interconnects, safety shutoffs and special electric utility agreements were required. These types of issues are not typical for conventional hot water system equipment installations, therefore installation and training documents that address these issues would be useful for installers.

To better evaluate the impact of the  $\mu$ CHP system on light commercial systems, additional assessments in the remaining target market occupancies (e.g. laundromat, car wash, multi-family housing) would provide additional insight into site-specific installation/operation issues and savings potential.