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Integrated mCHP System for Multifamily Buildings

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Table of Contents

Table of Figures

List of Tables

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Executive Summary

Lochinvar Near CARB-compliant 24 kW XRGI mCHP System.

ccASHP air handler unit (AHU) + Hydronic Coil Integration for Simultaneous Heating.

Thermal and power microgrids are distributed energy resource (DER) systems with innovative controls and hardware strategies that optimally respond to energy demands. Microgrids can serve multiple dwelling units operated with a centralized system and better energy management relative to oversized nanogrid systems. As integrated energy systems, they can provide low-operating costs and reduce the carbon footprint of end-use loads relative to advanced single-fuel technologies in multifamily buildings, which represent nearly 25% of residential buildings.

GTI Energy developed and built a microgrid testbed in the laboratory that integrated commercially available cold-climate air-source heat pumps (ccASHP) and a micro-combined heat and power (mCHP) system and auxiliary hydronic components to simulate multifamily building decentralized space conditioning and water heating loads. This microgrid testbed will provide the infrastructure to evaluate other integrated energy systems (IESs) at micro-scale levels for product development and emerging technology approach/research with built-in Virtual Test Home (VTH) load-based test rigs.

This microgrid demonstrated that ccASHP integration with simultaneous heating from mCHP heat recovery could reduce electric loads by 27%, reduce installation costs by 43%, and reduce greenhouse gas (GHG) emissions by 47% for electrified multifamily HVAC & WH systems with on-site power generation while achieving GHG emission rates of 25% of the U.S. national grid average as of 2023.

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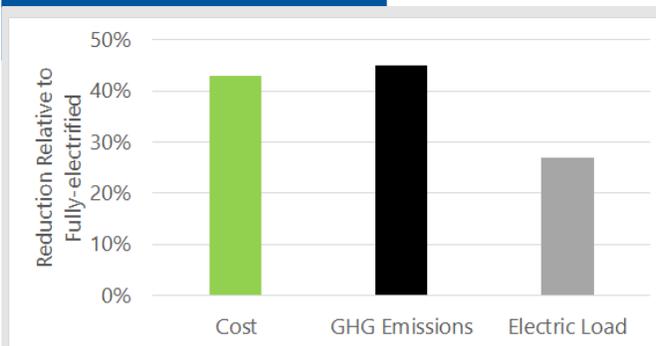
Introduction

With today's energy challenges and targets such as a 50% reduction of end-use carbon footprint, researchers have developed holistic approaches to multi-system integration, including fuel-switching, energy storage, and on-site power generation with renewable energy features. Integrated energy systems (IESs) are an emerging approach to maximize efficiency and resilience for residential and commercial heating, ventilation, air conditioning (HVAC), water heating (WH), and plug loads using off-the-self components with DER and energy storage. IESs include a combination of HVAC, water heating, on-site power generation, and thermal storage equipment that, when properly designed and integrated, can balance energy grid supply and demand while leveraging multiple energy resources. At the nano- and micro-scales, IESs can improve overall operating costs and efficiencies, minimize emission levels, and provide resilient systems at the building level.

IES research has resulted from many UTD research projects to help inform stakeholders of the as-installed performance of many appliances evaluated under GTI Energy's VTH. In these many research projects, performance curves of off-the-shelf appliances were developed and used in the building energy model to identify design optimization and product development opportunities. Two closely related projects were:

High-Efficiency / Self-Powered Combi System Integrating Renewables

UTD project 1.20.G – *High-Efficiency Combi System Integrating Photovoltaics (PV) and Self-Power Phase 1* demonstrated a IES at the nano-scale, with nanogrid annual HVAC & WH efficiencies greater than 110% in cold-climates under VTH evaluations. This research provides insight into the benefits of combining simultaneous mCHP and air-source heat pump (ASHP) heating and integrating battery energy storage systems (BESS). Key benefits for this low-cost, low-GHG emissions method for single-family HVAC & WH are: (1) integration of readily available technologies achieving over 110% efficiency and producing GHG emissions under 50% of the U.S. average; (2) applicability in retrofitting situations where electrification is not cost effective, especially in large, pre-1980 constructed single-family homes; (3) self-powering capabilities for HVAC & WH, primed for renewable energy integration via DER. While nanogrid research demonstrated its benefits, its applicability in multifamily buildings remains unexplored until this report.

Multifamily Infrastructure Challenges for Natural Gas

The multifamily building energy landscape developed under UTD 1.14.J – *Multifamily Infrastructure Challenges for Natural Gas* indicated the following trends:

- Natural gas utilization is declining relative to electricity.

- Natural gas utilization in the Northeast and Midwest continues to be above 60% relative to other energy sources for HVAC & WH.

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- Decentralized HVAC & WH appliances are dominant with over 80% of the landscape.
- Although HVAC loads could be electrified, WH loads remain challenging to convert to electric-driven technology due to cost and operating temperatures.

Project Objectives

This project aimed to evaluate a microgrid design resulting from integrating the Lochinvar XRGI mCHP system with ccASHPs in a simulated multifamily building application at GTI Energy's microgrid testbed. The tangible goals for this project were to:

- Develop integration solutions for the ccASHPs with XRGI mCHP system for space heating and cooling applications.
- Characterize the microgrid space conditioning and water heating performance.
- Develop microgrid design guidelines applicable to cold climates.
- These goals will feed UTD's strategic priorities to:
- Save energy by achieving an annual overall system efficiency over 100%.
- Reduce GHG emissions by at least 30% relative to traditional separate electric and gas equipment.
- Achieve energy resilience with self-powered HVAC and water heating on- or off-grid.
- Save consumers money by reducing operating costs.
- Provide a pathway for integrating with renewable energy sources.

Key Performance Indicators

The key performance indicators (KPIs) for this project included:

- Demonstrate proper integration strategy to provide space heating and cooling using cold-climate heat pumps while managing hot water production for WH loads in multifamily homes.
- Demonstrate annual gas efficiencies greater than 100% for all mild and cold climates at low GHG emissions and operating costs compared to all gas and all-electric baselines.
- Results will be communicated to industry stakeholders, including building professionals (through ASHRAE) and hybrid residential HVAC solution manufacturers.

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- Identify the preferred characteristics or description of the types of Multifamily buildings that would be sought for a field installation validation in a subsequent potential Phase 2 or non-UTD-funded effort.

Technical Approach

GTI Energy developed a thermal and power microgrid by integrating XRGI heating and power generation with ccASHPs to achieve annual efficiencies greater than 100% to meet space conditioning and water heating loads in multifamily building applications. System components specifications, mechanical diagrams, and instrumentation can be found in Appendix – A: Test Plan.

System Component Integration

Figure 1 shows the microgrid testbed design diagram (top) and final physical installation (bottom). Details of the microgrid system components can be found in Appendix – A: Test Plan. This microgrid consisted of one XRGI mCHP system, four ccASHPs, four indirect storage tanks (ISTs) water heaters, four chilled hot-water coils, and a microgrid controller as follows:

- Lochinvar XRGI mCHP: a 12 to 24 kW | 480Y | 60 Hz internal combustion engine-based grid-parallel mCHP with electrical and total efficiencies of 28% and 85%, respectively, in the high heating values (HHV) basis. Equipped with a thermal management controller, the Q-heat, Q-control, and 119-gal buffer tank, the XRGI provides up to 163 kBtu/h of heating output at 180 °F. The iQ-control enables this mCHP to follow the power load and modulate to it using a third-party power meter. If the power load is lower than its minimum power generation output, the XRGI shutdowns produced 12 kW to maintain its buffer tank to a minimum of its 50% thermal capacity of 59 kBtu.

- Mitsubishi HyperHeat and Fujitsu Extra Low-Temperature ccASHP systems: With a modulation range up to 5:1 turndown ratio, these ccAHP systems can provide 36 kBtu/h of heating at 5 °F outdoor air temperature (OAT). These cases are rated up to 10 heating seasonal performance factor (HSPF) and 18 seasonal energy efficiency ratio (SEER).

- Lochinvar SIT050 IST: Four 50-gal ISTs rated to 105 psi and 194 °F were tied to the mCHP hydronic distribution loop (see Hydronic Distribution Loop Infrastructure section in Appendix – A: Test Plan) kept to 140 °F using AquaStats (see Water Heating Operation section in Appendix – A: Test Plan).

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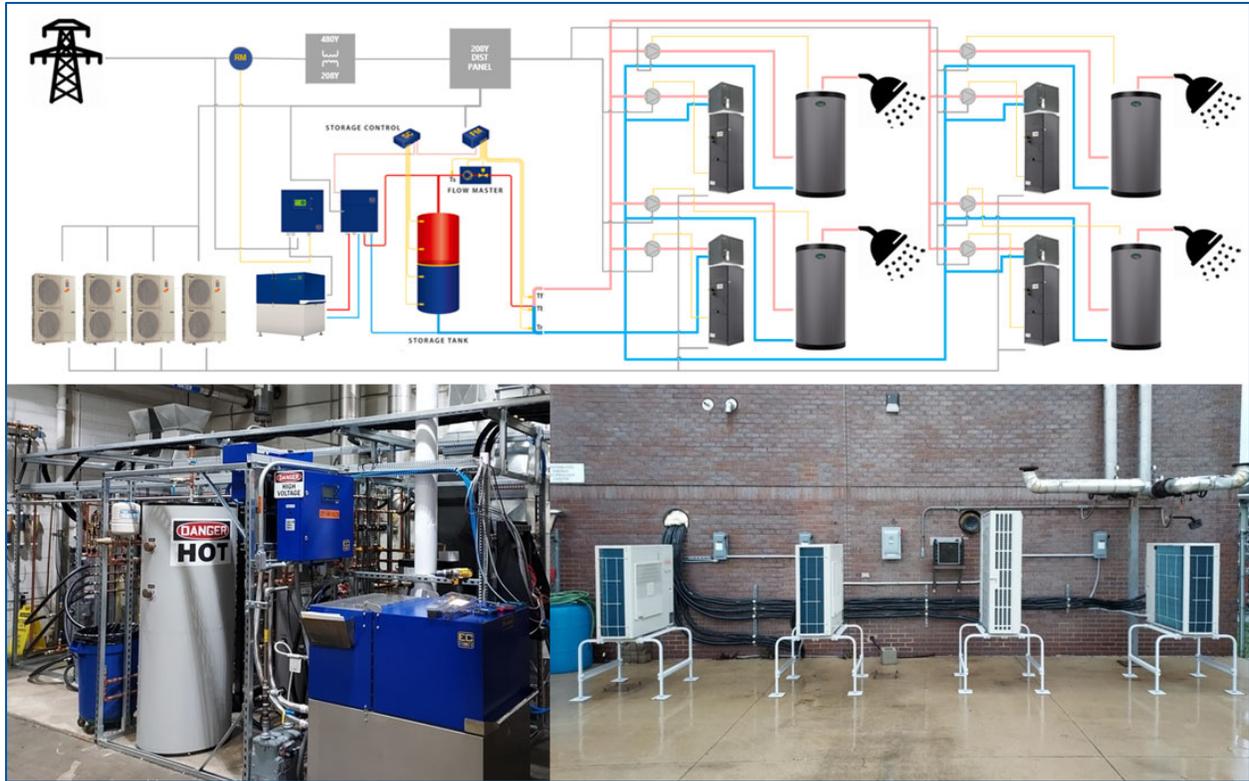
Figure 1: Microgrid testbed diagram (top) and physical installation (bottom)

- SpacePak WPAKI chilled hot-water coils: Four of the chilled hot-water coil rated to 200 °F mCHP hydronic distribution loop (see Hydronic Distribution Loop Infrastructure section in Appendix – A: Test Plan) installed downstream the ccASHP AHUs for space heating (see Space Heating Operation section in Appendix – A: Test Plan).

- In-house microgrid controller: This microgrid controller was designed to operate mCHP and ccASHPs heating output simultaneously during the heating season (see Main Controller section in Appendix – A: Test Plan).

Sequence of Operation

Several factors were considered to properly integrate these microgrid components, including controls and hardware, as follows:

- The XRGI was configured to operate in load-following using a third-party power meter. This power meter was installed on the 480Y Power Monitoring Panel to track the power consumption by the microgrid loads. Thermally, the XRGI was configured to deliver 180 °F, and the *Auxiliary Heating Device* was set to 'off.' This setting found in the XRGI iQ-control Panel allows the XRGI to keep the 119-gal buffer tank at its minimum of 25% capacity. Since the sole source of water heating in the microgrid is the mCHP; the XRGI will produce its lowest power generation output even if the microgrid load is lower than 12 kW while

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exporting power to the simulated grid. See the Power Distribution Infrastructure section in Appendix – A: Test Plan for electrical diagram details.

- The microgrid Main Controller was designed to enable mCHP heating for the chilled hot-water coils when the chips respond to heating calls. This controller actuates solenoid valves and single-speed pumps (see Hydronic Distribution Loop Infrastructure section in Appendix – A: Test Plan) to displace hot water individually to each ccASHP while operating in heating mode. This controller was based on tracking OAT and individual ccASHP current draw.

- AquaStats were set to maintain the ISTs within 120 and 140 °F by actuating single-speed pumps to pull heat from the XRGI buffer tank. For more details, see Hydronic Distribution Loop Infrastructure section in Appendix – A: Test Plan.

Microgrid Evaluation

The microgrid was evaluated in the VTH under simulated use conditions for four multifamily townhouses with 1,600-sqft units with 3-bedroom and 2-bath homes built to the Building America 2010 benchmark reference in International Energy Conservation Code (IECC) zone 5 (cold-climate). The peak heating loads for these units were about 60 kBtu/h at design conditions. For more information on simulated space conditioning and water heating load, see Simulated Use Approach in Appendix – A: Test Plan. Space conditioning and water heating loads were simulated, similar to UTD 1.19.I – *Comparative Assessment of Space and Water Heating Systems in the Virtual Phase 1 and 2* and 1.20.G – *High-Efficiency Combi System Integrating PV and Self-Power.*

Test Results

The following section describes the test results during the VTH assessment and the feasibility assessment for this microgrid to operate off-grid.

Grid Tied Performance

The following evaluation results are limited to the demonstration period in the second quarter of 2023 (Q2 2023) with mild space heating loads only. In this demonstration, the following observations were made:

- Electrical integration was crucial to balance 480Y (three hots and one neutral at 277 VAC hot-to-neutral and 480 VAC hot-to-hot) three-phase (3ph) mCHP power generation utilization with single-phase (1ph) HVAC&WH equipment. On an hourly basis, grid power consumption and export occurred at the individual phases of the 3ph interconnection. Figure 2 shows the hourly power profile for the entire demonstration. Even with abundant mCHP power generation, grid power was still used, resulting in excess power being exported.

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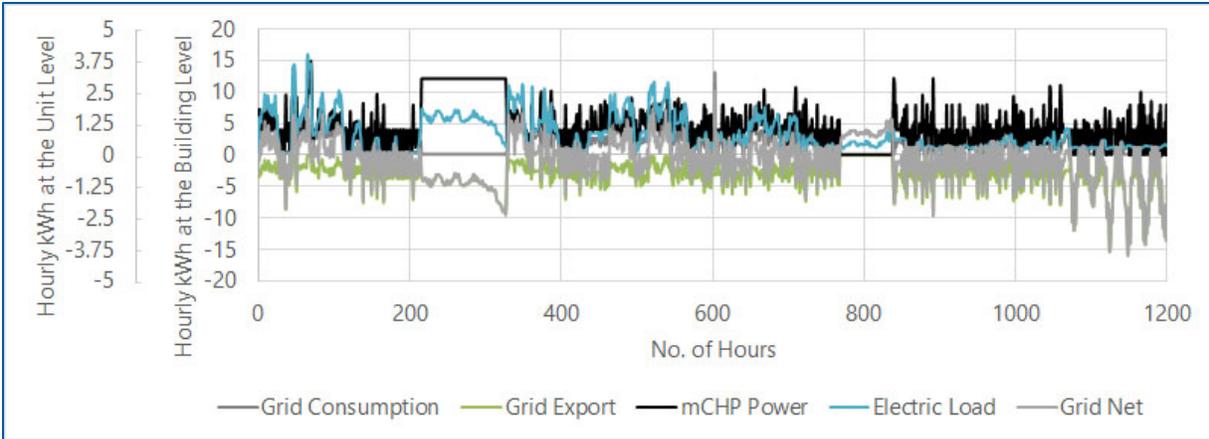
Figure 2: Hourly power profile

- The microgrid experienced occasional inefficiencies in meeting its thermal and power requirements. For example, the buffer tank reached saturation while ccASHPs operated on grid power, which heated ISTs, and resulted in exporting power to the grid in absence of space heating loads. These scenarios were anticipated and recorded, as shown in Figure 3.
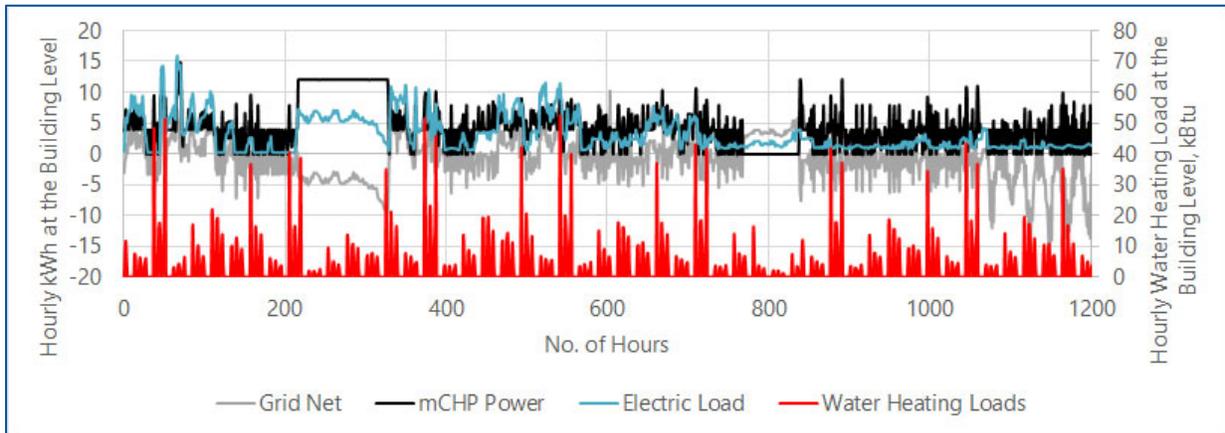
Figure 3: Thermal and power microgrid energy needs

Energy Utilization Assessment

Figure 4 shows the power performance of the microgrid in Q2 2023 in comparison to the simulated commercially available advanced electric system (*Adv Elec* in Figure 4) in the U.S. This simulation was modeled with performance curves and sizing factors described in UTD UTD 1.19.I – *Comparative Assessment of Space and Water Heating Systems in the Virtual Phase 1*. The result leads to the following conclusions:

- The microgrid reduced grid power consumption and exported surplus power from HVAC & WH equipment to supply other building plug loads or exported it to the grid.

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- Integrating mCHP reduced electrified HVAC & WH loads by 27% due to utilizing generated heat for space and water heating.

- Grid power consumption and excess power export were observed hourly in the microgrid.

- mCHP modulation in load-follow mode was demonstrated to reduce excess power production, which could be concerning in certain interconnection agreements.

    o The mCHP power generation resulted in grid power displacement by 42%.

    o Concerns with excess power can be addressed with the implementation of BESS.

- Advanced electric systems consisted of an 11 HSPF ccASHP and 3.5 uniform efficiency factor (UEF) electric heat pump water heater (EHPWH). These equipment were evaluated in UTD 1.19.I – *Comparative Assessment of Space and Water Heating Systems in the Virtual Phase 1.*
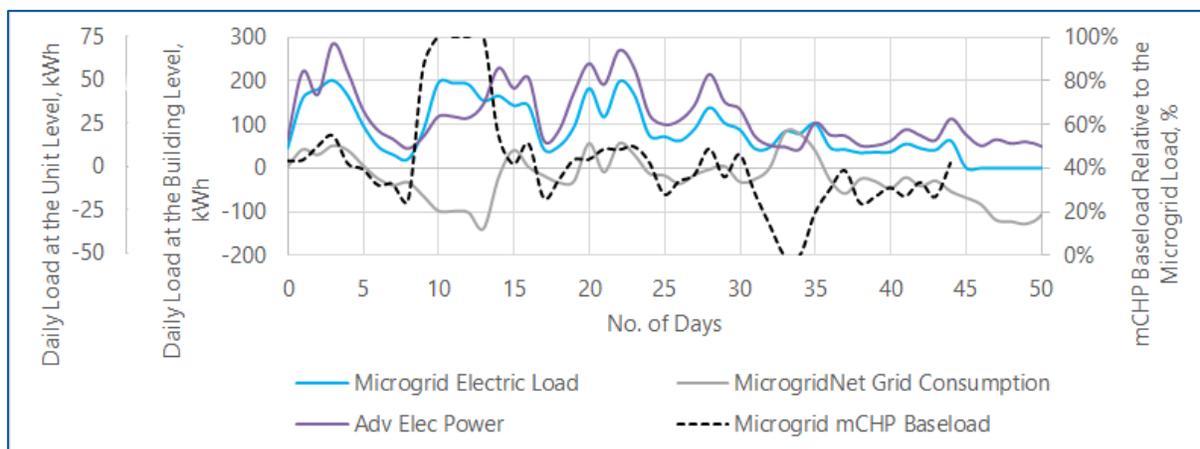
Figure 4: Microgrid and advanced electric systems power assessment

GHG Emission Assessment

The microgrid was demonstrated to generate about 22% lower GHG emissions relative to the advanced electric systems during the shoulder season when the ccASHPs are the most efficient. Figure 5 compares GHG emissions generated by the microgrid during the demonstration period relative to the local regional transmission organization (RTO) PJM and simulated performance of the advanced electric systems. Microgrid GHG emissions, when negative, represent power export outside of the HVAC & WH equipment loads, displacing grid marginal operating emission rates (MOER) at the RTO hourly rate obtained with WattTime.

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Performance Assessment

Figure 6 shows the daily coefficient of performance (COP) and GHG emissions relative to daily HVAC & WH load. The microgrid performance is a function of load and OAT. The microgrid demonstrated an average of 1.5 COP, determined using the equation listed in the Microgrid Efficiency section found in Appendix – A: Test Plan. Figure 6 illustrates a strong correlation between its GHG emissions and HVAC & WH load, revealing average GHG emissions that are 25% lower than the local RTO MOER. These results support similar conclusions drawn under UTD 1.20.G – *High-Efficiency Combi System Integrating PV and Self-Power*, alluding that integrated energy systems are an available solution to reach decarbonization targets for 2050 under the existing administration.[1]
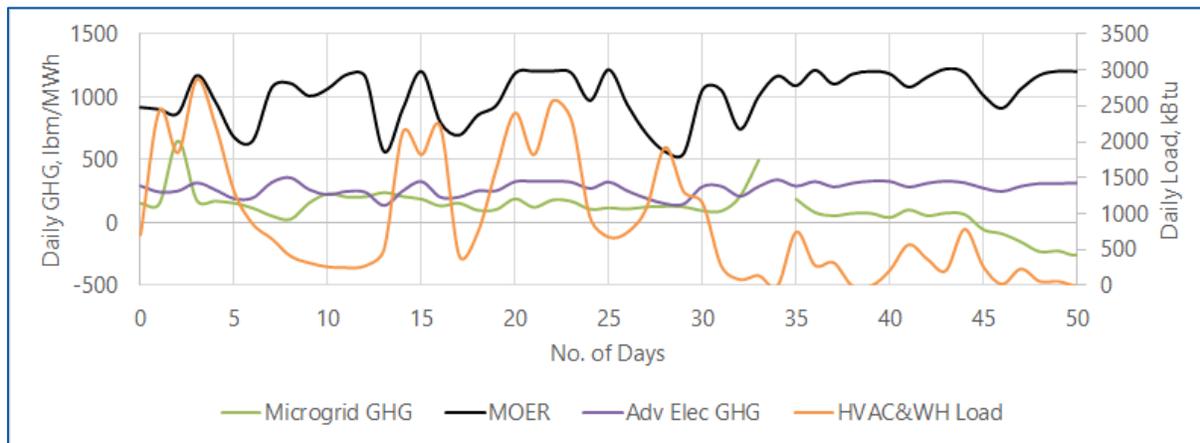
Figure 5: Microgrid and advanced electric systems GHG emission assessment
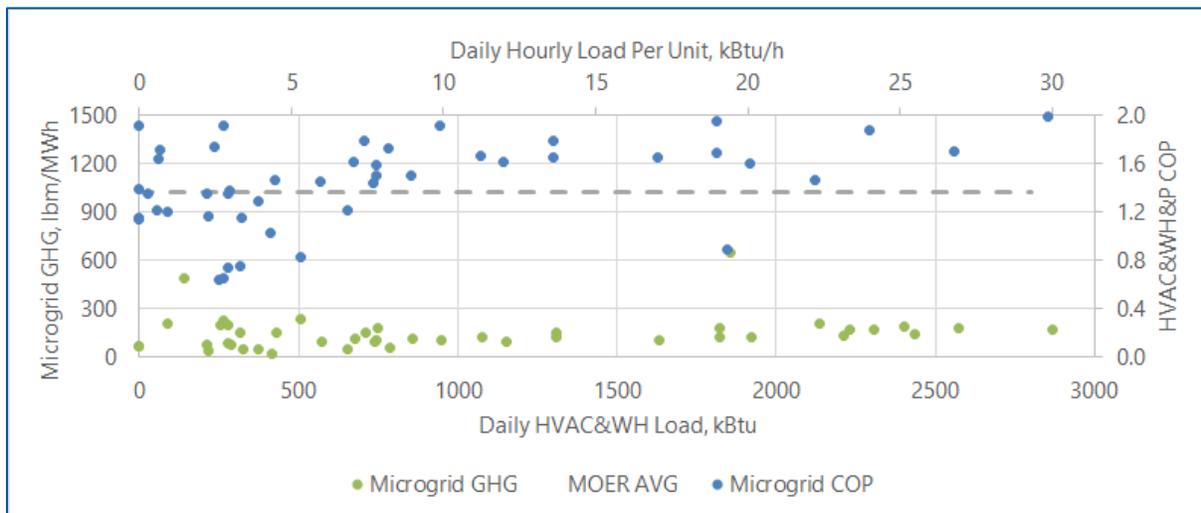
Figure 6: Microgrid daily performance relative to the daily load

1 [FACT SHEET: President Biden Signs Executive Order Catalyzing America's Clean Energy Economy Through Federal Sustainability | The White House](#)

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Off-grid Operation Feasibility Assessment

Off-grid microgrid operation is feasible, especially with black-start mCHP systems like YANMAR mCHP systems. Black-start mCHP systems can start in outages and synchronize with the grid when grid power is available. For non-black-start mCHPs such as the XRGI, BESS is necessary to provide a source of power for the mCHP to synchronize to. BESS are mature technologies commercially available in the U.S., such as products by Schneider Electric and Sol-Ark, which are applicable for multifamily and light commercial buildings. Figure 7 shows the components in BESS and consists of a hybrid inverter able to:

- Synchronize with the grid and combine power generation of multiple sources to A.C. output connection.

- Disconnect from the grid in case of an outage.

- Actuate any backup generator when battery storage is below its threshold.

- Absorb grid power or excess power from A.C. output from on-site power generation sources, such as mCHP or AC-coupled PV (where solar panels are directly connected and synchronized with the grid via inverters).

- Interconnect with DC-coupled PV installations (PV installed with a battery charger feeding a battery) to prioritize battery power from renewable sources.

- Disconnect from the grid to prioritize battery power and minimize grid power utilization with time-of-use (TOU) schedules.
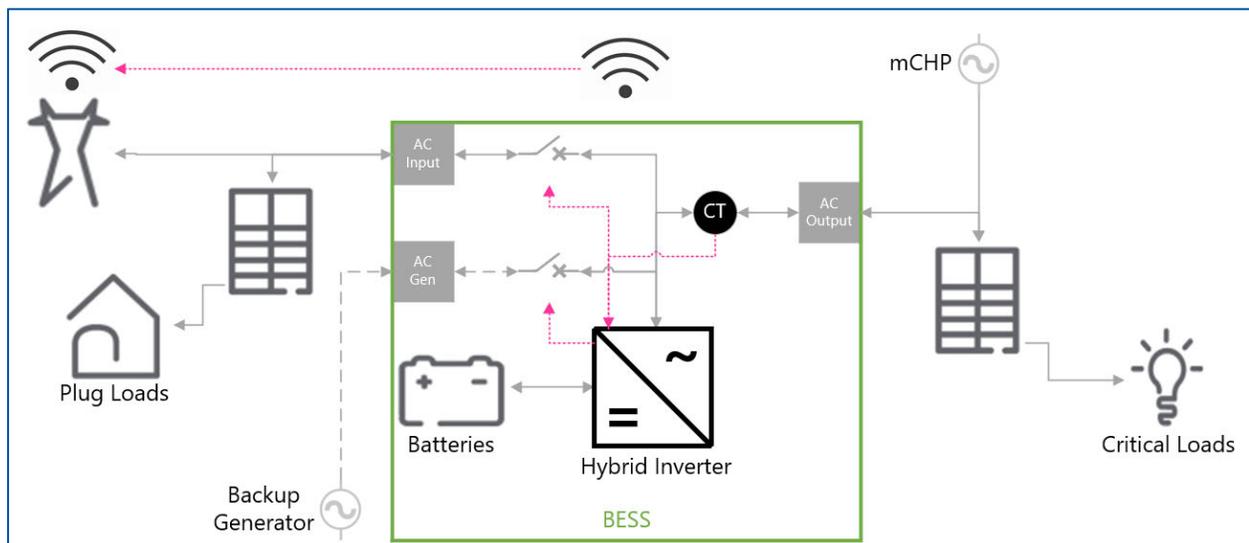
Figure 7: BESS components and integration with electrical components in buildings

Battery Energy Storage System Sizing

One of the most critical paraments in designing off-grid microgrids is sizing regarding critical loads. Figure 8 shows simplified single-line electrical diagrams for microgrids

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depending on whether the CHP can black-start and the microgrid is self-powering the entire building. Heat recovery might be limited and challenging when powering the whole building with mCHP, requiring external radiators or an outdoor mCHP system equipped with built-in radiators. Moreover, the cost per kW of mCHP is substantially higher than backup generators and could be utilized for occasional power outages. For frequent outages, alternate resources like BESS can be leveraged, albeit requiring high-capacity inverters for whole building sizing, coupled with a minimum battery storage size of a 1:1 ratio of continuous kW output and kWh of storage. These BESS systems operate at a minimum cost of $1,000 per continuous kW, excluding installation expenses.

Based on previous research conducted under UTD 2.18.H – *Micro-CHP Characterization and Demonstration*, the optimal design for mCHPs consists of base loading thermal loads in the building. BESS installation for only critical loads can be more cost-effective and provide an environment for PV integration in both A.C.- and DC-coupled ways.
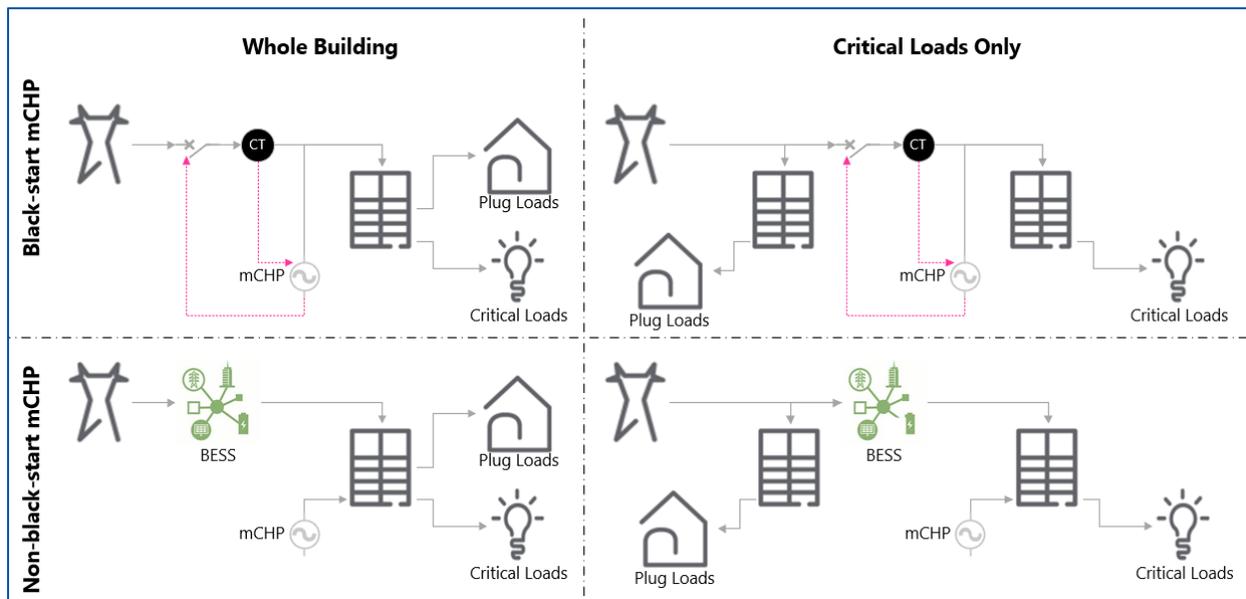
Figure 8: Off-grid mCHP operation strategies. CT stands for current transducers. CTs can be used to monitor power in a circuit.

Microgrid BESS Design

A 50 kW / 500 kWh 3ph BESS could have been integrated into this microgrid to operate during outages, serving as a power source for the XRGI system to synchronize with and ensure uninterrupted operation of HVAC & WH systems. The single-line diagram of this microgrid is shown in Figure 9. The BESS includes a 336 VDC battery bank with lithium-ion batteries and a Sol-Ark 60K-3P-480V-N hybrid inverter. The part cost for this BESS is listed in Table 1.

Table 1: Microgrid BESS part cost

Part Description	Part Number	Manufacturer	Capacity	Cost and Source

Hybrid Inverter	Sol-Ark 60k-3P-480V-N	Sol-Ark	60 kW	$20,446.66
Batteries	RB48V200	RELion	200 Ah	$8,645.76
Total			60 kW / 67 kWh	$81,176.98
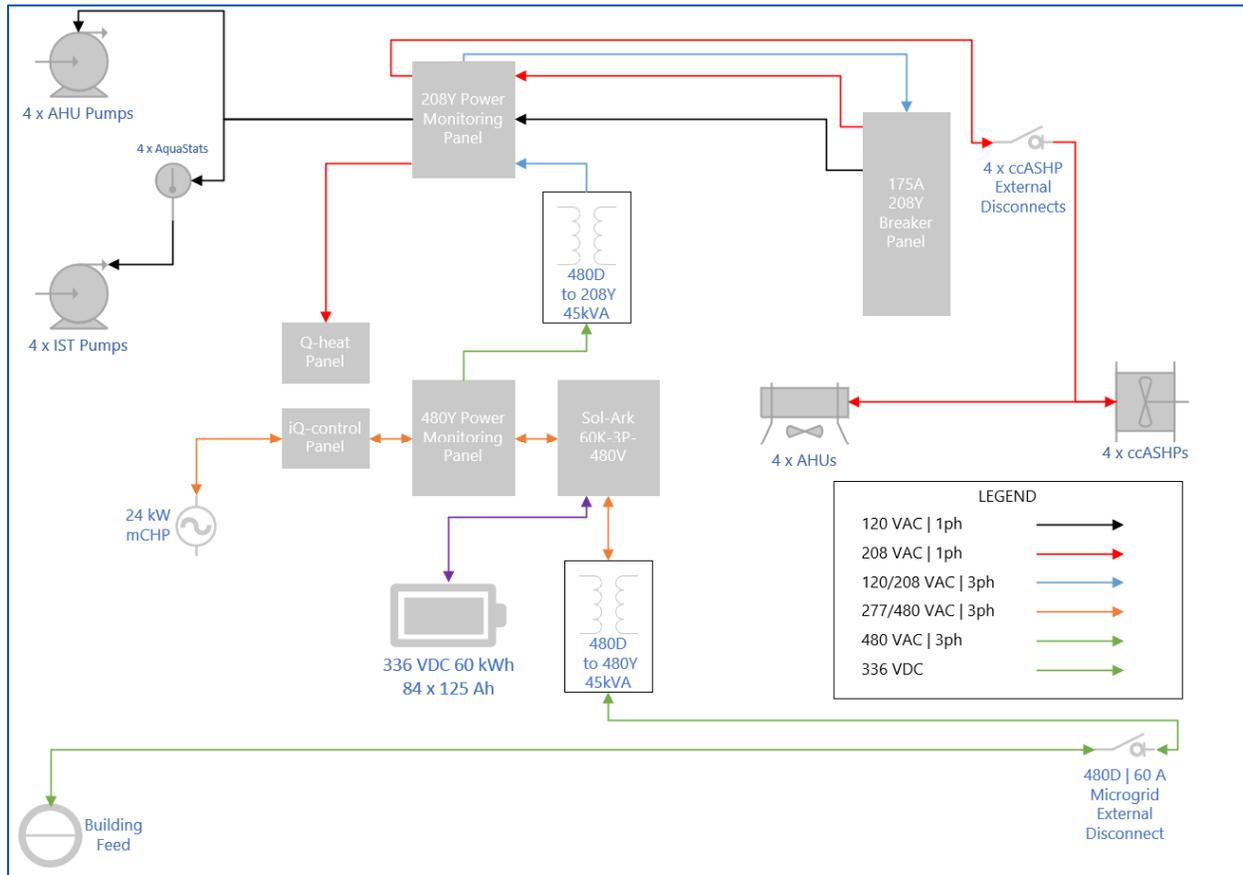
Figure 9: Microgrid single-line diagram with BESS

Commercialization Assessment

This section describes the barriers and benefits of this microgrid implementation.

Installation Costs

Similar to UTD 1.20.G – *High-Efficiency Combi System Integrating PV and Self-Power*, cost and complexity are primary concerns in commercialization. However, the incremental cost percentage is smaller than the nanogrid as it can be implemented as a centralized system. Table 2 displays microgrid costs alongside anticipated costs for fully-electrifying end-use loads in multifamily buildings. The cost estimate for this fully-electrified simulated building is double the microgrid. The fully-electrified scenario requires two ccASHPs to heat each dwelling unit and a BESS to provide on-site power generation and

to reduce grid power consumption by leveraging intermittent renewable power with battery energy storage.

Table 2: Installation cost assessment

Process	Microgrid		Fully-electrified	
	Parts	Cost	Parts	Cost
Space Conditioning	1 x ccASHP per unit	$6,154.30	2 x ccASHPs per unit	$12,309.00
Water Heating	1 IST per unit	$2,031.63	1 x EHPWH	$1,799.00
Power Generation	XRGI + hydronic integration infrastructure	$114,400.00†	24 kW PV and 30 kW / 60 kWh BESS	$201,428.60
Total	N/A	$179,889.04	N/A	$314,292.60
† = $2,000 per kW per mCHP and 100% markup in installation				

Grid Stability and GHG Emissions Reduction

Despite relying on electrically driven technologies for space and water heating in a cold climate, this microgrid showcased a decrease in power consumption for plug loads compared to the fully electrified scenario detailed in the Energy Utilization Assessment section. This microgrid could provide grid stability to the local RTO, which is a valuable resource as residences are fuel-switching HVAC & WH equipment to all electric.

In addition to increasing grid stability, the microgrid demonstrates a 25% GHG emission reduction relative to the fully-electrified scenario, even at conditions favorable to ccASHP operation. If end-use loads are electrified, RTO MOER would likely worsen relative to 2023, where natural gas is mainly used for HVAC & WH in Chicago, IL. Renewable adoption is expected to grow in the U.S. [2]; however, 50% of power production will come from intermittent sources. Continued utilization of steady energy sources like natural gas is anticipated due to their ability to provide resilience[3].

Retrofit and New Construction Implementation

Thermally

The implementation of this microgrid is feasible, especially for retrofit applications. For pre-1980 construction buildings, this microgrid can be implemented with either central or decentralized HVAC & WH terminals. For centralized water heating applications, a bank of ISTs with on-demand recirculation controls could provide water heating to each unit in multifamily buildings. For centralized space conditioning, terminal units for variable refrigerant flow (VRF) from major manufacturers such as Daikin and Mitsubishi can be deployed with hydronic low-temperature forced-air terminals such as SpacePak. A similar approach can be implemented in new construction; however, the microgrid sizing ratio of ccASHPs to mCHP will vary. Regarding hydronic integration requirements for the ccASHPs and hot water coil activation, off-the-shelf components used for floor

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2 Electrification Futures Study: Scenarios of Power System Evolution and Infrastructure Development for the United States (nrel.gov)
3 Annual Energy Outlook 2022 (AEO2022) (eia.gov)

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heating and zoning can be leveraged to actuate single-speed pumps to distribute mCHP heating to the hot-water coils.

Electrically

Microgrid implementation requires a three-phase environment. Typically, main transformers bring 3ph power into 1ph power for residences. These transformers can provide 3ph 120/240 or 120/208 VAC if required. If the other two phases are needed, an electrician and permits will be required for electrical changes in existing multifamily buildings. Examples of multifamily buildings with 3ph 120/208 VAC distribution centers are high-rises with common hallways and facility rooms for centralized load management processes such as HVAC, water heating, and power generation. For new construction, the use of 3ph 120/240 VAC distribution can be implemented as long as this distribution center is within NFPA 70: National Electrical Code.

Regarding interconnection agreements with the electrical utility, the XRGI and its on-demand response to electrical loads allows mitigation of power export to the grid and prevents back feed during an outage. The XRGI is not a black-start mCHP. However, it is recommended to have an external disconnect physically accessible to electric utilities for locking out and tagging out the mCHP during maintenance, providing physical assurance against back feed.

Dissemination of these results is critical to establishing the foundation and support for microgrids and centralized hybrid systems. This project resulted in a conference paper in tandem with Phase 2 of this project (already funded) to be released in February 2024 at the ASHRAE Winter Conference 2024 in Chicago, IL: *Benefits of Integrated Energy Systems for Multifamily End-use Load Including E.V. Charging*. Additionally, the XRGI is applying for California Air Resource District Distribution Generation certification with emissions limits to enable XRGI installation in California.[4].

Conclusion and Recommendations

Integrated energy system research is a systematic approach that uses off-the-shelf hardware and controls to engineer high-efficiency HVAC & WH systems with DER and energy storage capabilities. This approach demonstrated at the microgrid level in multifamily buildings can reduce the carbon footprint associated with end-use loads while lowering operating costs. This microgrid improves resilience and allows self-powered HVAC & WH when integrated with BESS.

GTI Energy developed integration schemes and microgrids in the Combined Heat and Power and Renewable Energy (CHPRE) Laboratory. This microgrid included the near

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[4] Distributed Generation Certification Evaluation Tool | California Air Resources Board

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CARB-compliant commercially available XRGI mCHP and 11 HSPF ccASHPs. GTI Energy's testbed can evaluate other microgrid components, including gas heat pumps, carbon capture, and fuel cells.

The team evaluated the microgrid under simulated use loads leveraging the VTH in this project. Although limited by the Q2 2023 heating season, evaluation results demonstrated that this microgrid could operate at 25% and under GHG emissions per unit output relative to local RTO MOER and simulated advanced electrical systems with the latest commercially available electric-driven heat pump technology. The microgrid demonstrated that grid power consumption and export can be reduced and mitigated with mCHP following the load meanwhile operating a COP greater than 1. Moreover, this research demonstrated that off-the-shelf technology can achieve GHG emission rates below the predicted grid MOER in 2050.

With expanding electrification efforts, such as ccASHP and electric vehicle adoption, this microgrid can help provide grid stability and resilience. In cold climates, where gas-fired equipment predominates for HVAC & WH, microgrids can aid in introducing high-efficiency electric-driven technology without incurring its cost or causing grid instability. In tandem with end-use electrification, more microgrid manufacturers are coming to the market with plug-and-play products for on-site power generation. mCHPs, not considered in these microgrid products, can be the key to reliable and long-lasting power generation with cogeneration benefits. This research helps to inform these manufacturers of the benefits associated with mCHP integration with BESS.

Appendix – A: Test Plan

Objective

This test plan aims to develop an integrated energy system for multifamily building HVAC&WH loads using the Lochinvar XRGI mCHP system, a combined heat and power microgrid. This microgrid is expected to operate with a gas efficiency greater than 100% for annual space heating, cooling, and water heating loads of a multifamily building located in the International Energy Conservation Code (IECC) zone 5, shown in Figure 10. Sizing and integration guidelines will be developed to minimize HVAC & WH GHG emissions and operating costs for multifamily building applications.
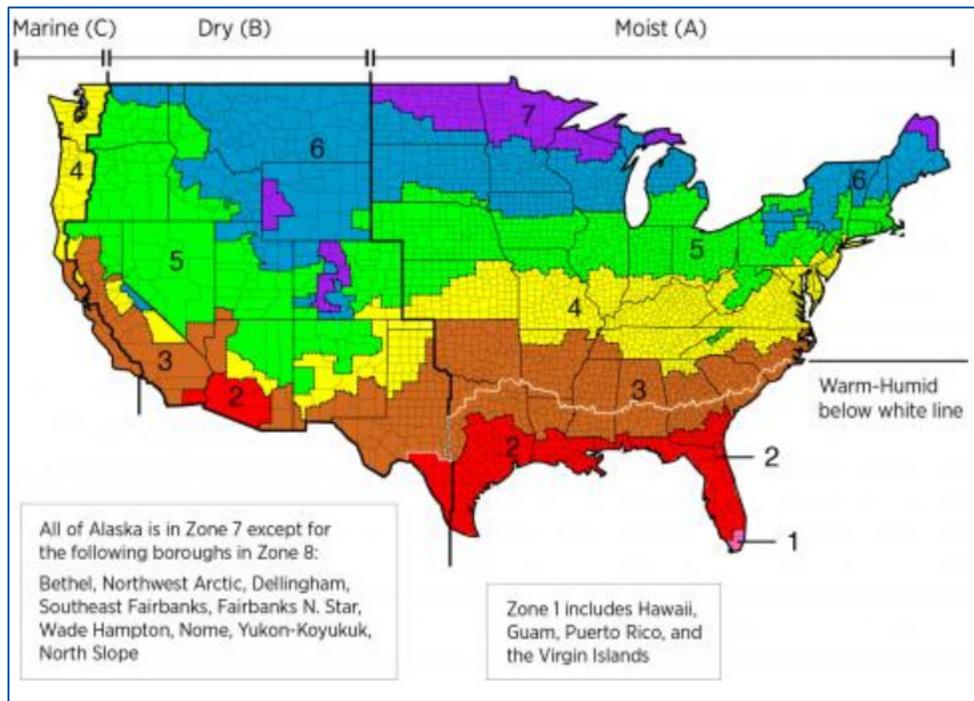
Figure 10: U.S. IECC climate map

Microgrid Components

The following components listed in the section will be used to simulate this microgrid for a 4-unit multifamily building.

mCHP System

The Lochinvar XRGI system will be used in this evaluation, including its iQ-Control Panel, Q-thermal Distribution Panel, Q-control attached to the Flow Master, and 119-gal storage tank.

ccASHP Systems

Four ccASHP systems will be used in this laboratory evaluation. These ccASHP systems can be installed as central and mini-split systems providing heating and cooling to

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multiple zones or units. This evaluation will use two makes and models of ccASHP systems. The specifications of these two systems are shown in Table 3.

Table 3: ccASHP systems specifications

Model Number	Brand		Mitsubishi	Fujitsu
	Indoor Unit		PUZ-A36AA7	ARU18RLF x 2
	Outdoor Unit		PUZ-HA36NHA5	AOU36RLXFZH
Cooling @ 95°F OATdb	Capacity kBtu/h	Max	36.0	39.0
		Rated	33.0	35.2
		Min	18.0	12.0
	Rated Input Power, kW		2.6	2.9
	SEER		17.8	18.0
Heating @ 47°F OATdb	Capacity kBtu/h	Max	40.0	42.0
		Rated	38.0	36.2
		Min	18.0	12.0
	Rated Input Power, kW		3.0	2.7
	HSPF		11.0	9.3
	NEEP Certified		Yes	Yes

Indirect Storage Tank Water Heaters

Four Lochinvar SIT050 ISTs will be used for unit water heaters integrated with the mCHP thermal management infrastructure.

Theory of Operation

The theory of operation is developed based on building type, which determines the heating, cooling, and water heating loads.

Building Type

A multifamily building with 1,600 sq-ft units will be implemented in this evaluation. These units will have 3 bedrooms, 2.5 bathrooms, and 3 occupants. The thermostats in these units will be kept at 70 °F for winter and 75 °F for summer. The building type will be referenced to the 2010 Building America Reference Home standards, incorporating 2009 IECC building code measures.

Target

The microgrid's maximum efficiency will be achieved when the mCHP power is used by the ccASHPs to provide heating for space conditioning and water heating. This test plan will evaluate and optimize the microgrid for multifamily building applications in the IECC zone 5 and humid region. Figure 11 shows the space heating/cooling and water heating load distribution of the 4-unit building hourly and annually. This analysis demonstrates that space heating is the most frequent operation mode.

Figure 12 shows the space and water heating load distribution as a function of OAT. This plot highlights the importance of maximizing the microgrid gas efficiencies within the

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10 to 50 °F OAT range. Table 4 shows the typical operation and maximum efficiencies at multiple OATs.

Sizing

Sizing is critical to optimizing the microgrid performance due to part-load degradation. This part-load degradation is associated with ccASHPs short-cycling and hydronic loop heat losses. The Lochinvar XRGI only modulates from 50% to 100% power generation capacity (12 to 24 kW power output). Therefore, power and heating strategies have been developed to maximize the microgrid heat and power production as a function of loads and OATs. To do so, the microgrid operation has been modeled in the IECC zone 5 climate while varying the space conditioning and water heating loads. This preliminary modeling analysis implemented data from laboratory evaluation of simulated use of the Lochinvar mCHP and Mitsubishi and Fujitsu ccASHP systems from UTD 1.19.I – *Comparative Assessment of Space and Water Heating Systems in the Virtual Test* Home and 2.18H – *Micro-CHP Characterization and Demonstration.*
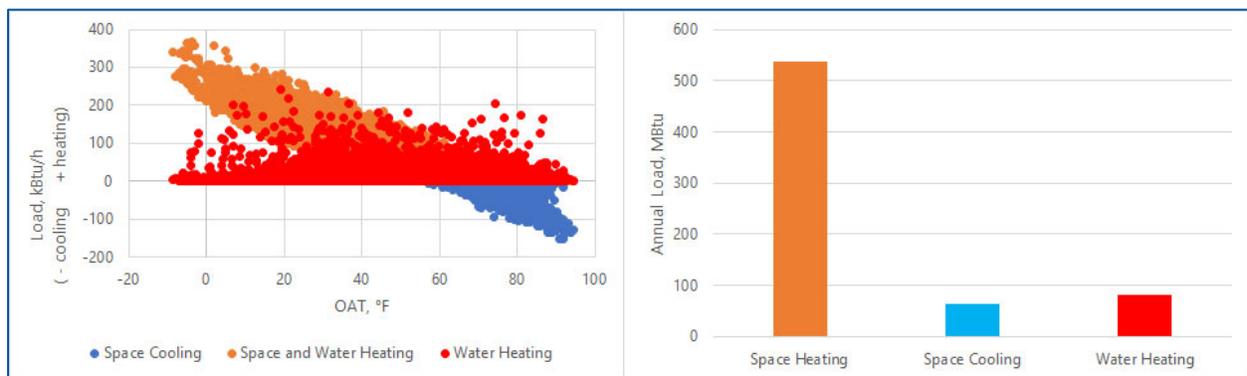
Figure 11: Hourly (left) and annually (right) space conditioning and water heating loads
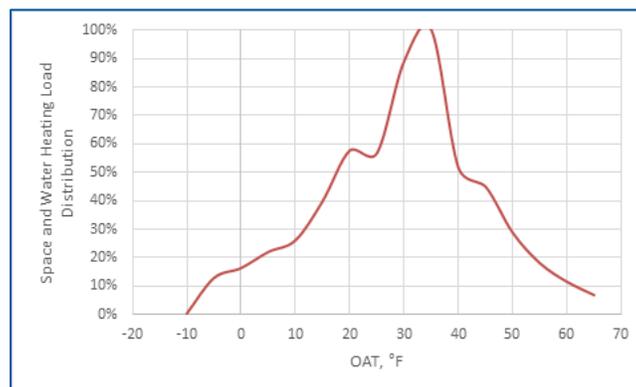
Figure 12: Space and water heating load distribution as a function of OAT

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Table 4: Space heating operation breakdown

Outdoor Air Temperature, °F	mCHP HHV Gas Consumption, kBtu/h	mCHP Power Generation, kW	mCHP Heating Output, kBtu/h	ccASHPs Heating Output, kBtu/h	Microgrid Heating Output, kBtu/h	Microgrid Efficiency, %
47	172	12	101	4 x 40	261	150
20	224	18	126	4 x 40	286	127
5	276	24	163	4 x 36	307	110

Modeling Analysis

The modeling analysis is summarized in Figure 13, showing the mCHP ideal modulation, heating load, and capacity. The following observations were made:

- mCHP and ccASHPs modulation ranges are mismatched.
  - Nevertheless, hydronic thermal storage and innovative hydronic heating can compensate for the mCHP heating and power production range's missing low-end range.
- The combined mCHP and ccASHPs heating should be sized for a balance point between 10 and 20 °F.
  - This balance point minimizes mCHP short cycling operation at warmer OATs. Therefore, the system modulates without using storage heat for extensive water heating.
- For this particular building type and application, each unit requires about 70 kBtu/h of space heating in the IECC zone 5. With a system capacity of 307 kBtu/h at 5 °F OAT, at least four building units are needed to maintain mCHP modulating most of the heating season. Per unit, average daily water heating loads correspond to 27 kBtu.
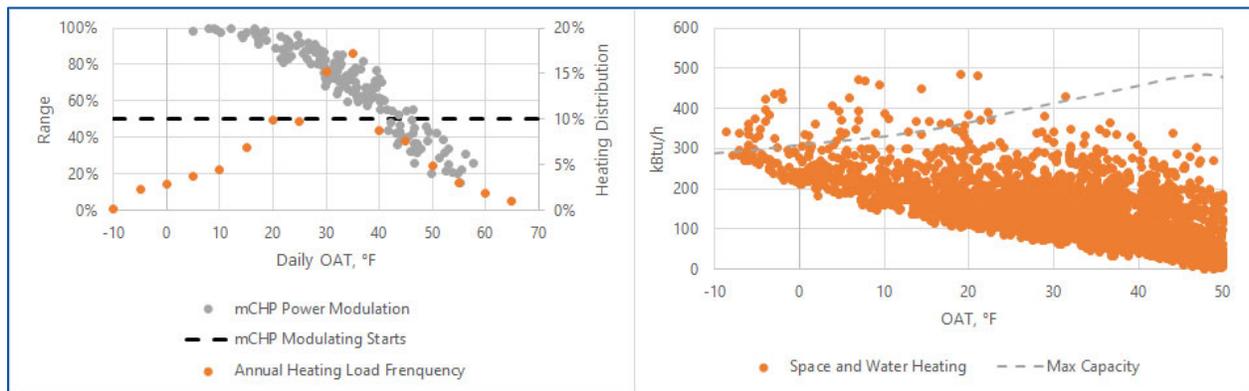
Figure 13: mCHP modulation (left) and load versus capacity (right)

Figure 14 shows the expected space and water heating efficiencies of the microgrid. Two groups of hourly microgrid efficiencies are shown, representing the modulation and

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cycling operation performances. The higher efficiency group is associated with the modulating operation, while the lower efficiency data points represent the challenging operation in cycling mode.

Hydronic Integration

mCHP heating will be used for space and water heating applications. The microgrid will use the hydronic integration solutions designed for the XRGI to respond to loads created by circulators operating by demand response controls, as shown in Figure 15.

Space Heating Operation

Space heating will be supplemented with mCHP hydronic heating downstream of the ccASHP AHU. A single-speed pump connected to GTI Energy's Main Controller will actuate the pump when heating calls are observed.

Water Heating Operation

AquaStats L8124A1015 will be implemented to actuate a single-speed pump connected to the mCHP hydronic infrastructure to heat tanks from 120 to 140 °F. The Main Controller will not participate in this operation.

Space Cooling Operation

Space cooling will be operated with the ccASHPs. Solenoid valves will be used to prevent cooling output from the ccASHPs to alter the mCHP hydronic infrastructure. The Main Controller will activate these solenoid valves for OAT greater than 70 °F.

Main Controller

A National Instrument (NI) data acquisition system (DAQ) will be used to control solenoid valves and single-speed pumps connected to the hydronic coils. NI DAQs will receive and send analog and digital signals to instrumentation, solid-state relays, and variable frequency devices. This function will be simulated with the DAQ. However, this can be achieved by third-party components for field implementation purposes.
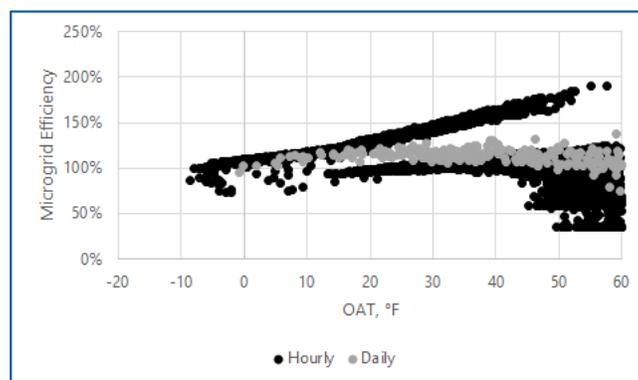
Figure 14: Microgrid hourly and daily space and water heating gas efficiency

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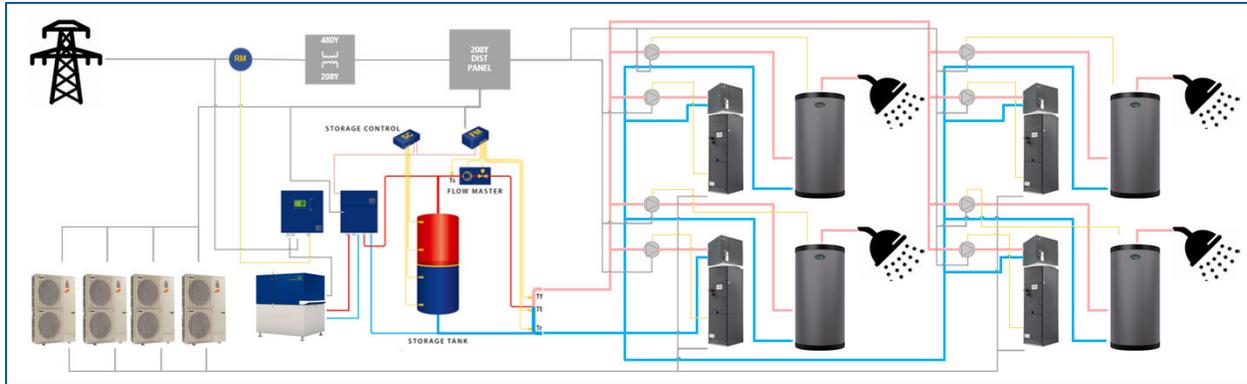
Figure 15: Microgrid schematic.

Product Development Staging Process

The microgrid Main Controller needs to be calibrated with a series of tests. These tests will be performed to:

- Avoid or minimize ccASHP operation while the mCHP is not producing power.

- Deliver the desired amount of hydronic heating to the space.

- Speed up the reaction time between the XRGI's Flow Master Control and the need for heat for space heating only.

mCHP Power Generation

mCHP power generation should be prioritized to avoid powering the ccASHPs with grid power. This challenging scenario will occur when the space and water heating loads are too low. Both mCHP and ccASHP have their proprietary controls. Therefore, GTI Energy will develop a control strategy to make the mCHP provide power when the ccASHPs operate. A series of tests will be developed to learn:

- mCHP shutdown time response to electrical loads less than 12 kW during modulation

- mCHP power generation time response to electrical loads higher than 12 kW during standby mode

- microgrid operation with an electrical load of less than 12 kW.

mCHP Hydronic Heating

mCHP hydronic heating should be prioritized to avoid mCHP storage tank saturation while ccASHPs operation. The following tests will be developed:

- Map hydronic thermal output at the hot-water coils installed downstream of the AHUs

- Determine mCHP time response to dump heat from the mCHP storage tank to the hot-water coils installed downstream of the AHU with the hydronic heating operation.

Simulated Use Approach

The microgrid will be evaluated using simulated use heating, cooling, and water heating loads associated with a multifamily building described in Building Type with four units. The hourly and annual heating, cooling, and water heating loads are shown in Figure 11. Space conditioning and water heating loads will be simulated as described in UTD 1.19.I – *Comparative Assessment of Space and Water Heating Systems in the Virtual Phase 1 and 2*.

Space Heating and Cooling Loads

The space heating and cooling loads will be simulated with CHPRE Laboratory rooms 002 and 004 building heating and cooling loads, shown in Figure 17. These two rooms have 145 kBtu/h heating output gas heaters each. These two rooms' heating and cooling loads will be satisfied with the microgrid heating and cooling capacities. The thermostat heating and cooling set points are 70 °F and 72 °F, respectively. The space heating and cooling loads of the CHPRE Laboratory rooms 002 and 004 should follow a similar trend with outdoor air temperature, as shown in the left of Figure 11. The ccASHPs will be installed as described in the ccASHP Installation section.

Space Heating and Cooling Simulator

Figure 16 shows the infrastructure that will be built to simulate and measure heating and cooling loads. GTI Energy has created many of these simulators for simulated use evaluation in the VTH, as shown in Figure 19. The AHU system pulls room air, and the airflow and mass flow are measured with a thermocouple and low-pressure device PT attached to a pitot-tube array following ISO-3966 *Measurement of Fluid Flow In Closed Conduits- Velocity Area Method Using Pitot Static Tubes* and ISO-5801 *Industrial Fans – Performance Testing Using Standardized Airways* guidance. Two thermocouple arrays are used in the return and supply ductwork to measure air temperature rise following temperature distribution measurements guidance from ANSI/ASHRAE 41.1 – *Standard Methods for Temperature Measurement*. The return and supply air relative humidity are measured by relative humidity transmitters RHTs per ANSI/ASHRAE 41.4 – *Standard Methods for Temperature Measurement*. The AHU thermostat will be installed in the return ductwork to measure room air temperature.

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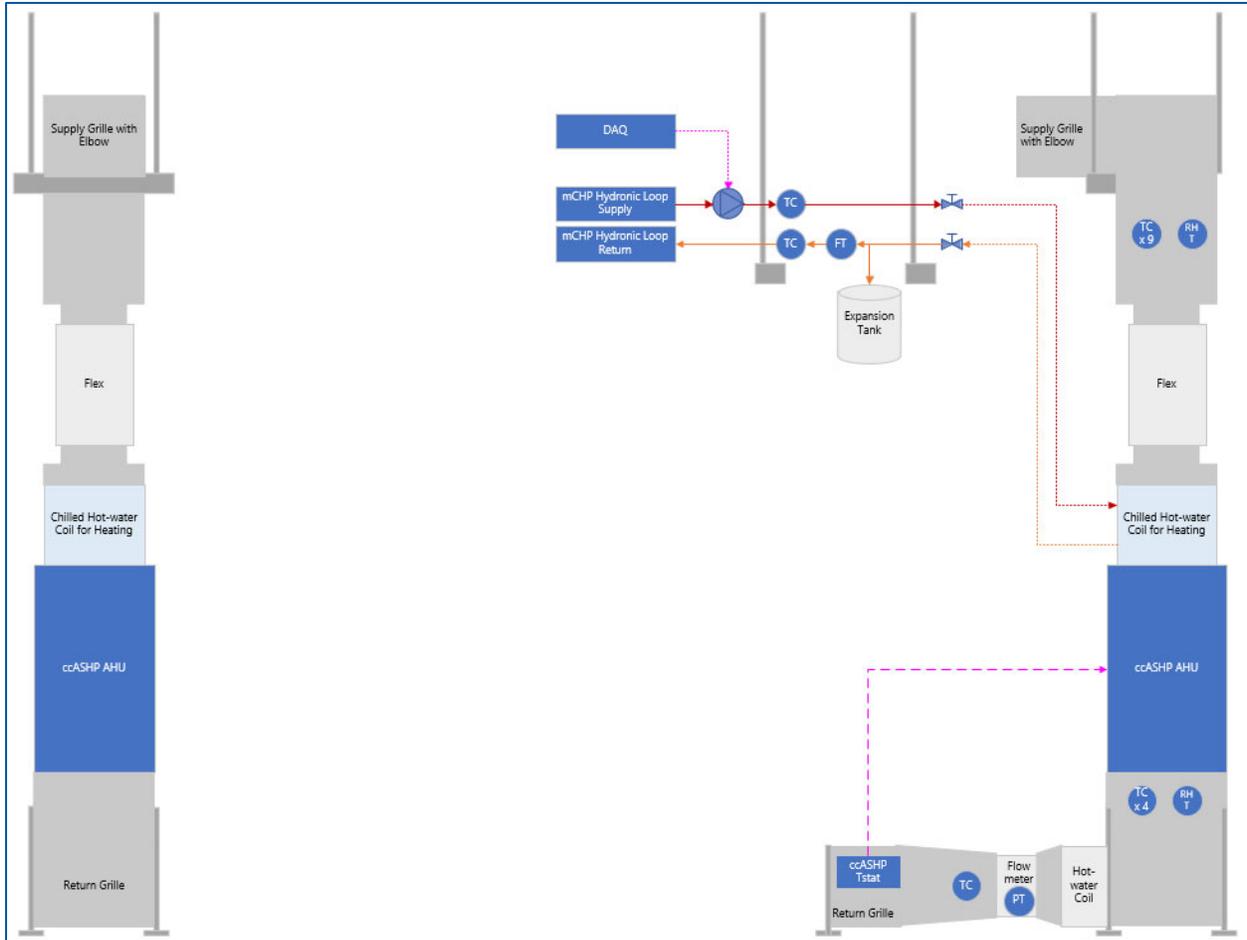
Figure 16: Space conditioning simulator infrastructure

The AHU hot-water coil leaving water flow will be measured with a water flow meter FT. Two thermocouples TCs will be used to measure the AHU hot-water coil leaving and entering water temperatures. A single-speed pump will be used to provide simultaneous heating with the ccASHPs and trim heating for dehumidification. Figure 18 shows the space heating load modulation of the ccASHPs and mCHP as they try to maintain modulation.

Figure 17: CHPRE Laboratory
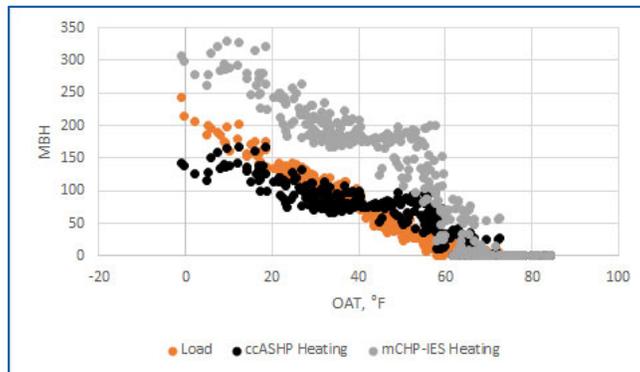
Figure 18: Heating load and 4 x ccASHP and mCHP outputs versus OAT

Figure 19: Space conditioning simulator infrastructure in the HVAC Laboratory.

Water Heating Loads

The water heating loads will be based on National Renewable Energy Laboratory (NREL) Domestic Hot Water Event Schedule Generator. The daily water heating load pattern per unit will be based on a medium-usage draw pattern from Appendix E to Subpart B of Part 43, Title 10, CFR - Uniform Test Method for Measuring the Energy Consumption of Water Heaters developed by the Department of Energy (DOE). The weekly water heating load pattern will be based on the annual water heating load frequency distribution for Chicago, IL, for a 3-bedroom occupancy shown in Figure 20. Figure 21 shows the proposed weekly water heating loads per unit and building. Table 5 and Table 6 show the hourly building unit and whole building water rate and volume.

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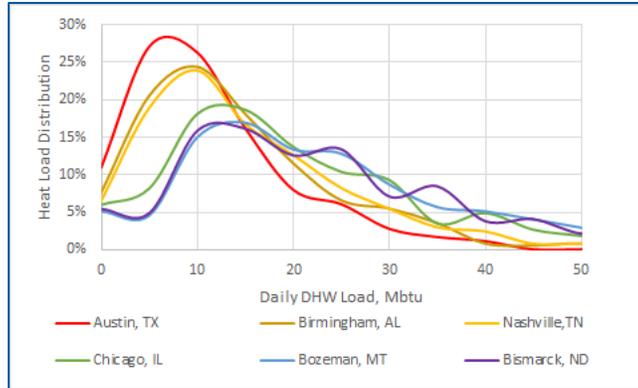
Figure 20: Annual water heating load frequency distribution from NREL modeling tool
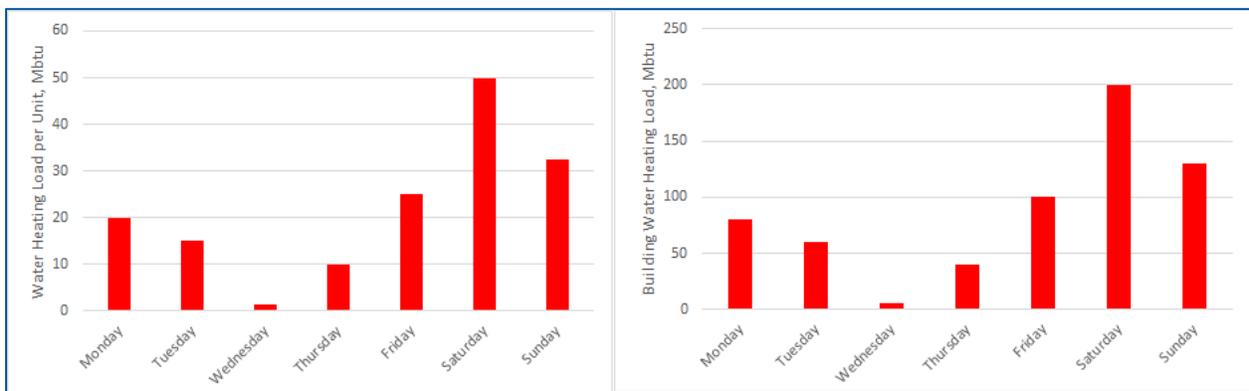
Figure 21: Daily water heating load per unit (left) and building (right)

Decentralized Water Heating System

Figure 24 shows the decentralized water heating system that connects to the hydronic heating loop of the mCHP. Four indirect tanks will be connected in parallel. Water flow meters FTs will measure the water flow to each tank. Thermocouples TCs will be used to measure each tank's leaving and entering water temperatures. Water flow meter FTs will measure the entering city water to each indirect tank. Two thermocouples TCs will be used to measure each tank's entering city water and leaving hot water temperatures. Each tank will have its single-speed pump actuated by the Aquastat to maintain an indirect tank between 120 to 140 °F. The high and low-temperature settings for the AquaStats are shown in Table 7.

Domestic Water Heating Simulator

Figure 22 shows the domestic hot water (DHW) simulator piping and instrumentation diagram (P&ID). This simulator has three solenoid valves to allow three different flow rates at the test stand. This simulator enables evaluating water heating systems at different flow rates. This testing infrastructure has been implemented in many simulated use evaluations in the HVAC Laboratory, as shown in Figure 23.

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Table 5: Unit water heating scheduler for the microgrid evaluation

Hour	Water Flow Rate, gpm	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
		Daily Water Heating Load, kBtu						
		20	15	1.5	10	25	50	32.5
		Hourly Water Usage, Gal						
5:00 am	2	5.8	4.3	0.4	2.9	7.2	14.4	9.4
6:00 am	1	3.1	2.3	0.2	1.5	3.8	7.6	5.0
7:00 am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8:00 am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9:00 am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10:00 am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11:00 am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12:00 pm	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1:00 pm	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2:00 pm	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3:00 pm	1	3.1	2.3	0.2	1.5	3.8	7.6	5.0
4:00 pm	1	3.1	2.3	0.2	1.5	3.8	7.6	5.0
5:00 pm	0.5	1.0	0.8	0.1	0.5	1.3	2.5	1.7
6:00 pm	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7:00 pm	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8:00 pm	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9:00 pm	0.5	1.7	1.3	0.1	0.8	2.1	4.2	2.8
10:00 pm	1	2.4	1.8	0.2	1.2	3.0	5.9	3.9
11:00 pm	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12:00 am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1:00 am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2:00 am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3:00 am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4:00 am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
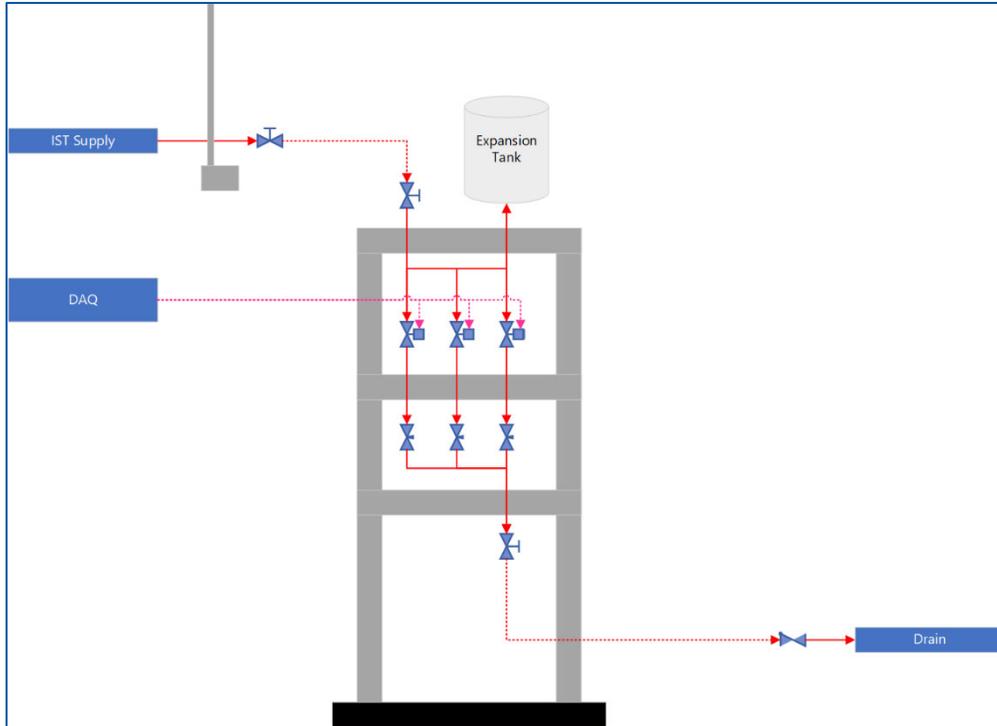
Figure 22: DWH simulator

Figure 23: Water heating simulator infrastructure in the HVAC Laboratory

Table 6: Building water heating scheduler for the microgrid evaluation

Hour	Water Flow Rate, gpm	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
		Daily Water Heating Load, kBtu						
		80	60	6	40	100	200	130
		Hourly Water Usage, Gal						
1	8	41	31	3	21	52	103	67
2	4	22	16	2	11	27	55	36
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0
11	4	22	16	2	11	27	55	36
12	4	22	16	2	11	27	55	36
13	2	7	5	1	4	9	18	12
14	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0
17	2	12	9	1	6	15	30	20
18	4	17	13	1	9	21	43	28
19	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0

For the microgrid evaluation, three flow rates will be selected to represent typical flow rates based on NREL Domestic Hot Water Event Schedule Generator. These hourly water flow rates and volume per weekly day are shown in Table 5.

Table 7: AquaStat high and lower temperature settings

Upper Limit	140°F
Lower Limit	120°F
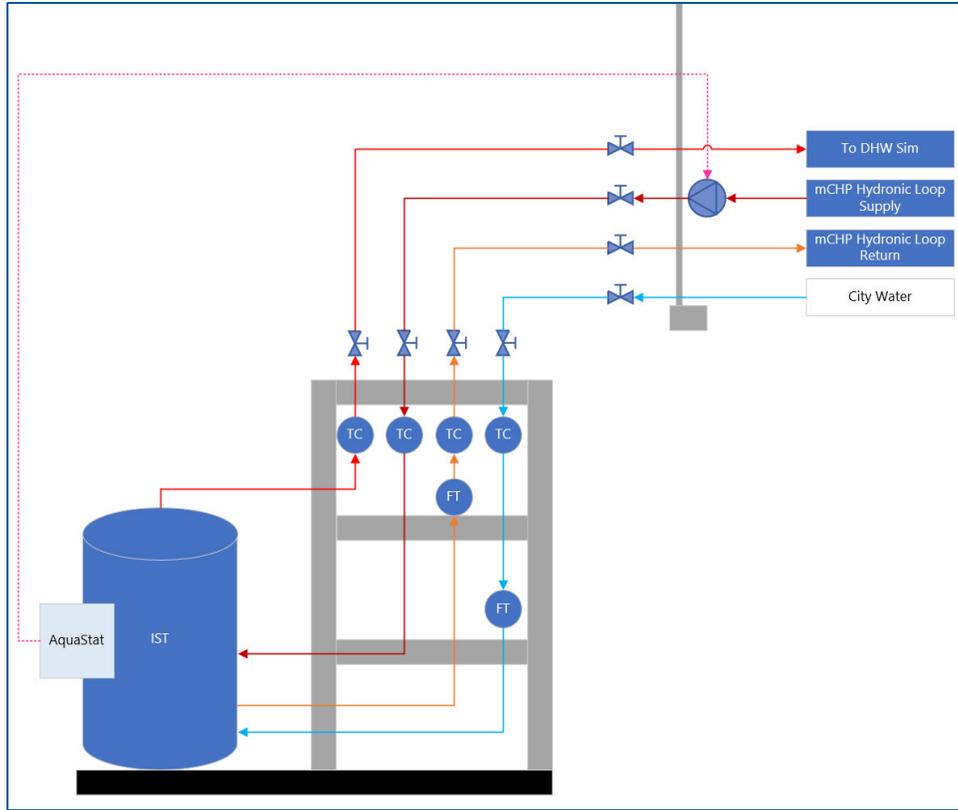
Figure 24: Decentralized water heating system with ISTs

Hydronic Distribution Loop Infrastructure

Figure 25 shows the top view layout for the hydronic distribution loop downstream of the mCHP system installation. Downstream the Flow Master, two heating zones will be installed to differentiate space and water heating operation. Two solenoid valves will separate water flow between these two zones as heating and water heating calls are received. The space heating zone is split into four additional zones to independently control space heating for each AHU. Single-speed pumps will be used for space heating zones and recirculating loops. The Main Controller will manage all these pumps depending on demand operation. The water heating zone pump will be a single-speed pump that the indirect water heaters Aquastats will actuate. Flow meters FTs, and thermocouples TCs will be used to monitor the energy delivered to these zones. The Main Controller can also actuateMain Controller this single-speed pump to recirculate water in this hydronic distribution loop and accelerate the Flow Master Response time as needed.

mCHP Hydronic Infrastructure

Figure 26 shows the hydronic infrastructure for the mCHP system and auxiliary components. Flow meters FTs and thermocouple TCs will be used to measure the

hydronic heating produced by the mCHP system. Thermocouples TCs will be used to monitor the storage tank's entering and leaving water temperatures.
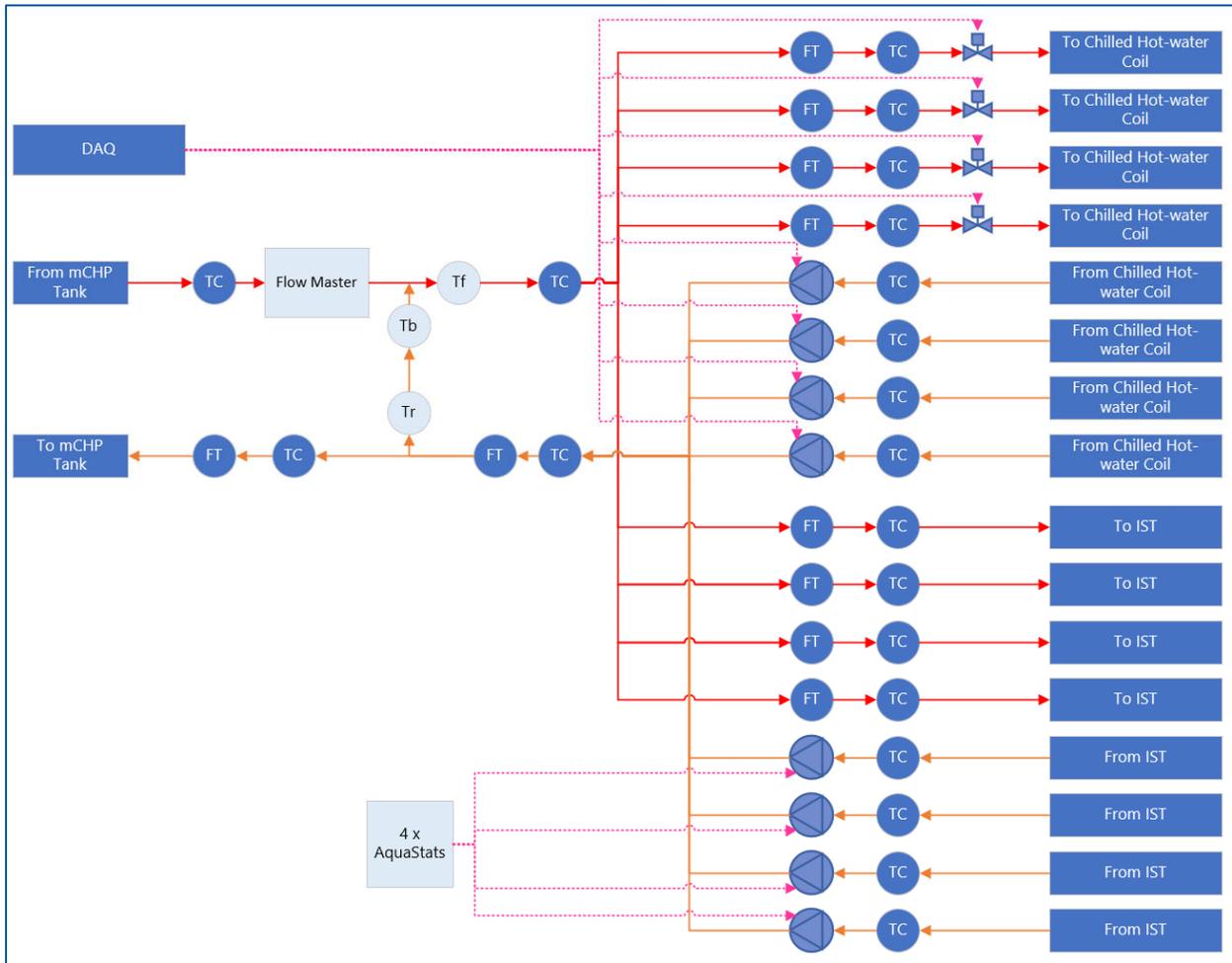
Figure 25: Hydronic distribution infrastructure

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Figure 26: mCHP infrastructure

ccASHP Installation

Figure 27 shows the on-the-wall/suspended ccASHP installation infrastructure. Four-thermocouple array and one relative humidity transmitter RHT will be installed on each ccASHP intake grille. A 100-ft hose for the suction and liquid lines will be used to connect each ccASHP to its corresponding AHU. These ccASHPs will be connected to their corresponding AHU systems with a 208-Delta (two hots) power cable and modulating wiring. A similar infrastructure built in the HVAC Laboratory is shown in Figure 28.

Figure 27: ccASHP Installation

Figure 28: ccASHP outdoor installation at the HVAC Laboratory

Power Distribution Infrastructure

Figure 29 shows the electrical and control diagram for the microgrid. The CHPRE Laboratory will provide grid interconnection at 480D (three hots). A transformer will be used to operate with 480Y from a 480D source. The 480Y power source will be connected to a power metering/distribution panel called 480Y Power Monitoring Panel. Power will be measured and distributed to the mCHP and a 480D-to-208Y 45 kVA transformer. The power output of this transformer will be connected to a secondary power metering/distribution panel 208Y Power Monitoring Panel. This panel will provide and measure power to the mCHP auxiliary devices, ccASHP systems, and hydronic pumps.

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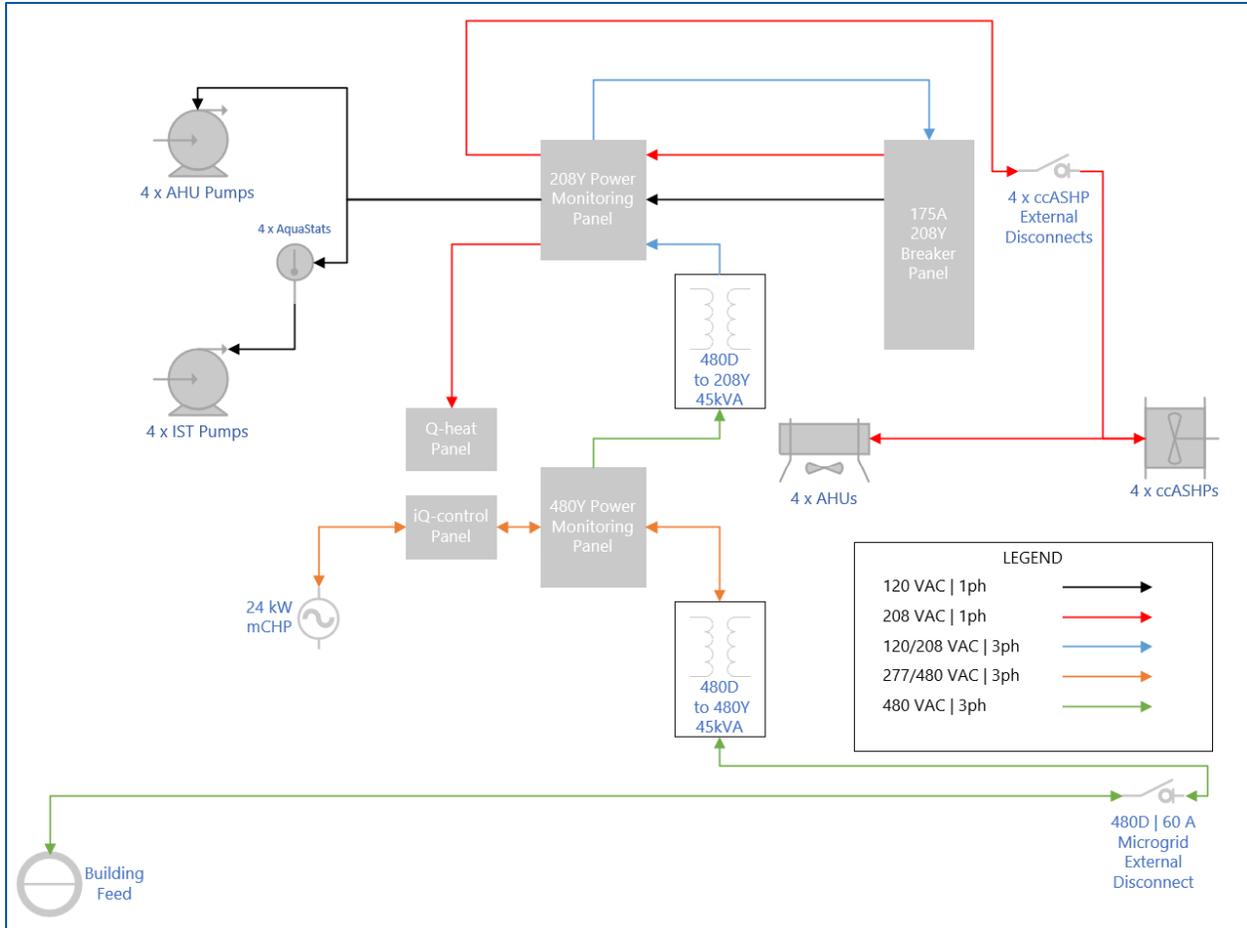
Figure 29: Microgrid electrical and control diagram

480Y Power Monitoring Panel

Figure 30 shows the wiring diagram for 480Y Power Monitoring Panel. Four power meters will be used to measure the power exported and consumed by the microgrid and mCHP power generation. The fourth power meter will be used to actuate the mCHP based on power demand from the ccASHP and other 120/208 VAC devices. A current transmitter CT will be used to monitor the mCHP operation.
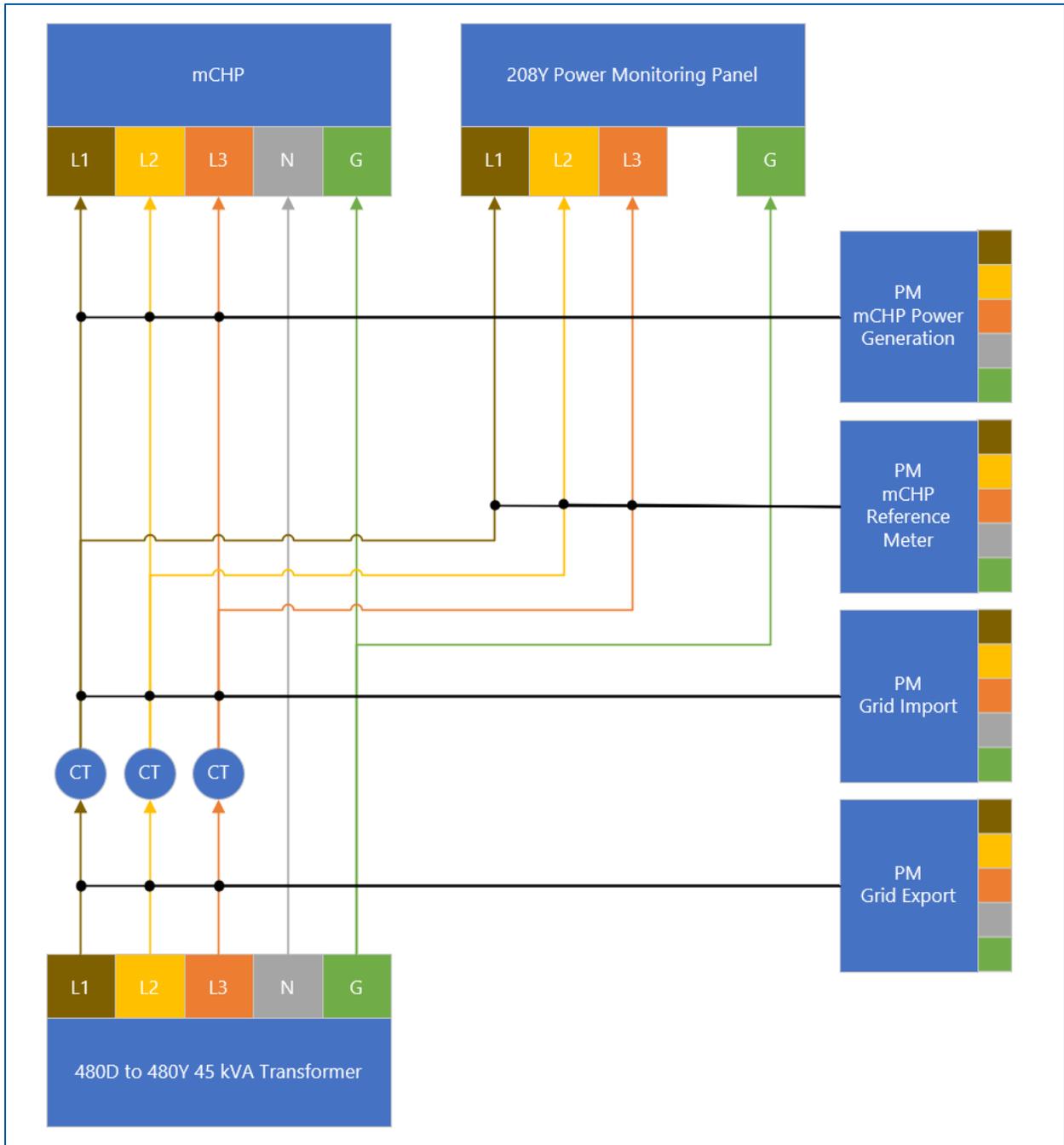
Figure 30: 480Y Power Monitoring Panel diagram

208Y Power Monitoring Panel

Figure 31 shows the wiring diagram of the 208Y Power Monitoring Panel. Four power meters will be used to measure the entering 120/208 VAC power and the power demand of the ccAHPs, mCHP auxiliary devices, indirect water heater resistive elements,

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and hydronic pumps. Four current transmitter CTs will be used to monitor the operation of the four ccASHPs.
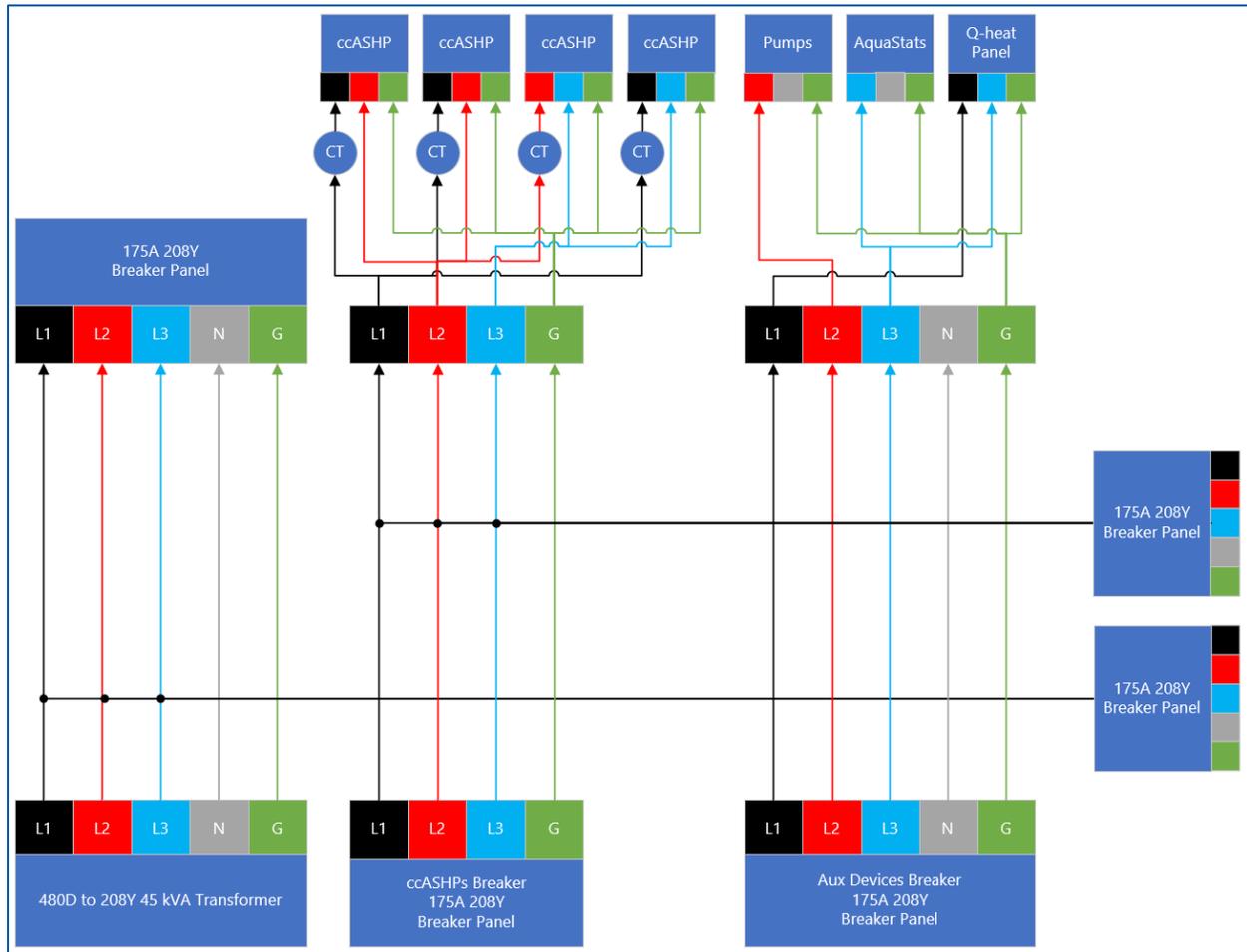
Figure 31: 208Y Power Monitoring Panel diagram

System Boundary

The microgrid system boundary is shown in Figure 32. This boundary is defined by the amount of energy delivered to heating, cooling, and water heating load while providing residue power to the building over the natural gas and power consumption.

Natural Gas Energy Input

The following equation is used to calculate the energy input utilizing the appropriate calculation methods depending on the fuel type and measurement equipment:

$$Q_{fuel} = \sum HHV \cdot \dot{V}_f \cdot \Delta t / \rho_f$$

where:

Q_{fuel} = accumulated HHV fuel energy input, Btu.

HHV = fuel higher heating value, Btu/ft³.

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$\dot{V}_f$ = flow rate of fuel, lbm/h.

Δt = testing period, h.

ρ_f = fuel density, lbm/ft³

Note: fuel high heating value will be 1050 Btu/cF based on GTI Energy historical measurements found in Appendix B – Historical Natural Gas.
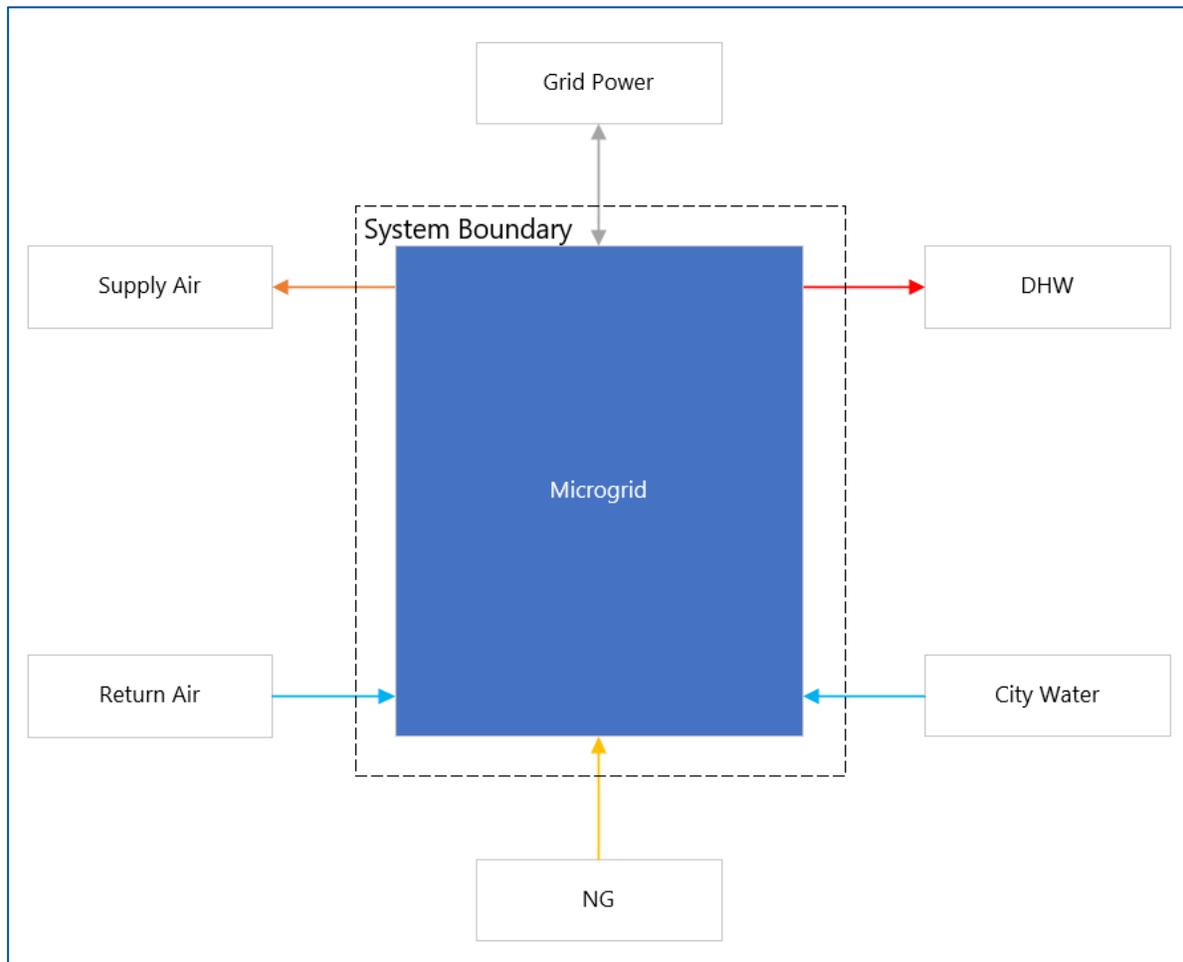
Figure 32: System boundary

Net Power Utilization

Electrical output shall be measured and reported based on the real power indication (electrical output) as measured at the user's interconnection location and shall include parasitic losses, as appropriate. The unit's electrical output is based on the direct measurements taken during testing at the load bank minus the electrical consumption of the unit from the grid. The measurement will take place in the 480Y Power Monitoring Panel. The net power utilization is calculated with the following equation:

$$E_{NET} = E_{out} - E_{in}$$

where:

E_{NET} = net electrical output, Wh.

E_{in} = electricity consumption by the microgrid, Wh.
E_{out} = electricity exported by the microgrid, Wh.

Water Heating Output

The water heating output calculation is based on the direct measurements taken during testing at any stream within the hydronic and decentralized water heating system calculated with the following equation:

$$Q_{WH} = \sum V \cdot \rho \cdot C_p \cdot \Delta T$$

where:
Q_{WH} = energy delivered for water heating loads, Btu.
V = hot water consumption, gal.
ΔT = positive temperature difference between domestic hot water/supply water and city water/return temperatures, ⁰F.
C_p = water-specific heat at the average operating temperature, Btu/lbm-⁰F.
ρ = water density based on the fluid temperature at the flow meter, lbm/gal.

Space Heating Output

AHU heating output is based on the direct measurement taken during testing of heat transferred at the space conditioning simulator infrastructure calculated with the following equation:

$$Q_{heat} = \dot{V} \cdot \rho \cdot c_p \cdot \Delta T \cdot t$$

where:
Q_{heat} = accumulated total thermal output at the AHU, Btu.
$\dot{V}$ = AHU airflow, cfm.
ΔT = positive temperature difference between leaving and entering air temperatures at the AHU, ⁰F.
c_p = air specific heat at the average operating temperature, Btu/lbm-⁰F.
ρ = air density based on the fluid temperature at the airflow meter, lbm/cF.
t = data collection time step, min.

Space Cooling Output

AHU cooling output is based on the direct measurement taken during testing of heat transferred at the space conditioning simulator infrastructure calculated with the following equation:

$$Q_{cool} = \dot{V} \cdot \rho \cdot -\Delta h \cdot t$$

where:
Q_{cool} = accumulated total cooling output at the AHU, Btu.
$\dot{V}$ = AHU airflow, cfm.

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-Δh = negative enthalpy difference between leaving and entering air temperatures at the AHU, ℉.

ρ = air density based on the fluid temperature at the airflow meter, lbm/cF.

t = data collection time step, min.

Enthalpy Calculation

The air enthalpy is calculated with the following series of equations:

$$h = 0.24 \cdot T + x \cdot (0.444 \cdot T + h_{we})$$

where:

h = air enthalpy, Btu/lbm.

T = air temperature, Btu.

h_{we} = evaporation heat of water, 1061 Btu/lbm.

X = mass of water vapor.

$$x = 0.62198 \cdot \frac{p_v}{p - p_v}$$

where:

p = humid air density, Pa.

p_v = dry air density, Pa.

$$p_v = (RH/100) \cdot 6.1078 \times 10^{\frac{[7.5 \cdot (T-32)]}{[(T-32)+237.3 \cdot 1.8]}}$$

where:

RH = air relative humidity, %.

Microgrid Efficiency

The system efficiency will be calculated with the following equation:

$$\eta = \left(\frac{Q_{WH} + Q_{heat} + Q_{cool} + E_{NET}}{Q_{fuel}} \right) \cdot 100\%$$

where:

η = microgrid efficiency, (%)

Instrumentation Plan

The following section lists the instrumentation that will be used for the measurements at the mCHP hydronic, hydronic distribution, space heating, and cooling simulator infrastructure, decentralized water heating, and both power metering and distribution panels.

mCHP Hydronic Infrastructure

Table 8 shows the instrumentation for mCHP hydronic infrastructure.

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Table 8: mCHP hydronic infrastructure instrumentation list

Parameter	Make	Model	Range	Accuracy
NG flow	IMAC	AL-425	0 to 425 cfh	± 1% of reading
NG temperature	Omega	TMQSS-125G-6	–454 to 700 °F	± 1.8 °F or 0.75%
NG line pressure	Setra	2091001PG2M1102	0 to 1 psi	± 0.25% full-scale
Exhaust temperature	Omega	TMQSS-125G-6	–454 to 700 °F	± 1.8 °F or 0.75%
Combustion air temperature	Omega	TMQSS-125G-6	–454 to 700 °F	± 1.8 °F or 0.75%
Q-heat Panel flow	Seametrics	MJHR-075-20P	0 to 18 gpm	± 1% of reading
Q-heat Panel leaving temperature	Omega	TMQSS-125G-6	–454 to 700 °F	± 1.8 °F or 0.75%
Q-heat Panel entering temperature	Omega	TMQSS-125G-6	–454 to 700 °F	± 1.8 °F or 0.75%
Storage tank leaving temperature	Omega	TMQSS-125G-6	–454 to 700 °F	± 1.8 °F or 0.75%
Storage tank entering temperature	Omega	TMQSS-125G-6	–454 to 700 °F	± 1.8 °F or 0.75%

Hydronic Distribution Infrastructure

Table 9 shows the instrumentation for the hydronic distribution infrastructure.

Table 9: Hydronic distribution instrumentation list

Parameter	Make	Model	Range	Accuracy
Hydronic distribution return flow	Seametrics	MJHR-075-20P	0 to 18 gpm	± 1% of reading
Hydronic space heating flow	Seametrics	MJHR-075-20P	0 to 18 gpm	± 1% of reading
Hydronic distribution supply temperature	Omega	TMQSS-125G-6	–454 to 700 °F	± 1.8 °F or 0.75%
Hydronic distribution return temperature	Omega	TMQSS-125G-6	–454 to 700 °F	± 1.8 °F or 0.75%
Hydronic space heating supply temperature	Omega	TMQSS-125G-6	–454 to 700 °F	± 1.8 °F or 0.75%
Hydronic space heating return temperature	Omega	TMQSS-125G-6	–454 to 700 °F	± 1.8 °F or 0.75%

Space Heating and Cooling Simulator Infrastructure

Table 10 shows the instrumentation for the space heating and cooling simulator infrastructure.

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Table 10: Space conditioning simulator instrumentation list

Parameter	Make	Model	Range	Accuracy
Airflow velocity pressure	Setra	2641-R25WD-11-T1-F	0 to 0.25 inWC	± 0.25% full-scale
Airflow cfm	Paragon	FE-1500-1-A-0-16x08-R-0-FX-1	300 to 1800 cfm	± 2% reading ± 0.12% full-scale
Airflow temperature at the flow meter	Omega	5TC-TT-T-24-72	–454 to 700 °F	± 1.8 °F or 0.75%
Return air temperature	Omega	5TC-TT-T-24-72	–454 to 700 °F	± 1.8 °F or 0.75%
Supply air temperature	Omega	5TC-TT-T-24-72	–454 to 700 °F	± 1.8 °F or 0.75%
Hydronic space heating return temperature	Omega	TMQSS-125G-6	–454 to 700 °F	± 1.8 °F or 0.75%
Return air relative humidity	Dwyer	RHP-2D10	0 to 100% @ -40 to 140 °F	± 2.0% of reading
Supply air relative humidity	Dwyer	RHP-2D10	0 to 100% @ -40 to 140 °F	± 2.0% of reading

Decentralized Water Heating Infrastructure

Table 11 shows the instrumentation list for the decentralized water heating system infrastructure.

Table 11: Decentralized water heating system instrumentation list

Parameter	Make	Model	Range	Accuracy
City water flow	Seametrics	MJHR-075-20P	0 – 18 gpm	± 1% of reading
Hydronic heating flow	Seametrics	MJHR-075-20P	0 – 18 gpm	± 1% of reading
City water temperature	Omega	TMQSS-125G-6	–454 to 700 °F	± 1.8 °F or 0.75%
Domestic hot water temperature	Omega	TMQSS-125G-6	–454 to 700 °F	± 1.8 °F or 0.75%
Hydronic heating supply temperature	Omega	TMQSS-125G-6	–454 to 700 °F	± 1.8 °F or 0.75%
Hydronic heating return temperature	Omega	TMQSS-125G-6	–454 to 700 °F	± 1.8 °F or 0.75%

ccASHP System Infrastructure

Table 12 shows the instrumentation list for the ccASHP system infrastructure.

Table 12: ccASHP system infrastructure instrumentation list

Parameter	Make	Model	Range	Accuracy
Entering air temperature	Omega	TMQSS-125G-6	–454 to 700 °F	± 1.8 °F or 0.75%
Domestic hot water temperature	Dwyer	RHP-2O10	0 to 100% @ -40 to 140 °F	± 2.0% of reading

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Power Metring and Distribution Infrastructure

Table 13 and Table 14 show the instrumentation list for the 208Y Power Monitoring Panel and 480Y Power Monitoring Panel.

Table 13: 208Y Power Monitoring Panel instrumentation list

Parameter	Make	Model	Range	Accuracy
Panel entering power	Continental Control System	WNB-3Y-208-P	0 – 200 amps/leg	±0.5% nominal
ccASHP system power	Continental Control System	WNB-3Y-208-P	0 – 150 amps/leg	±0.5% nominal
ccASHP current	AcuAMP	ACT050-10-S	0 – 50 amps/leg	±1% full-scale

Table 14: 480Y Power Monitoring Panel instrumentation list

Parameter	Make	Model	Range	Accuracy
Panel entering power	Continental Control System	WNB-3Y-480-P	0 – 100 amps/leg	±0.5% nominal
mCHP power	Continental Control System	WNB-3Y-480-P	0 – 100 amps/leg	±0.5% nominal
mCHP power reference meter	Continental Control System	WNB-3Y-480-P	0 – 100 amps/leg	±0.5% nominal
Power to 480WYE to 2480WYE transformer	Continental Control System	WNB-3Y-480-P	0 – 100 amps/leg	±0.5% nominal
Grid power current	AcuAMP	ACT050-10-S	0 – 100 amps/leg	±1% full-scale

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Appendix B – Historical Natural Gas
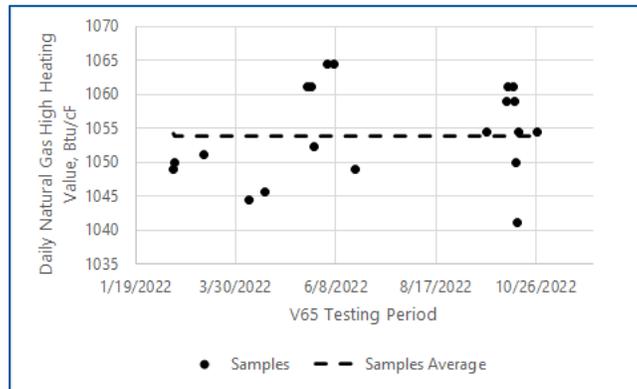
Figure 33 shows the historical natural gas composition at GTI Energy.

Figure 33: GTI Energy's historical composition