Multipurpose Hydronic CO_2 Heat Pump for Commercial Buildings

Final Report

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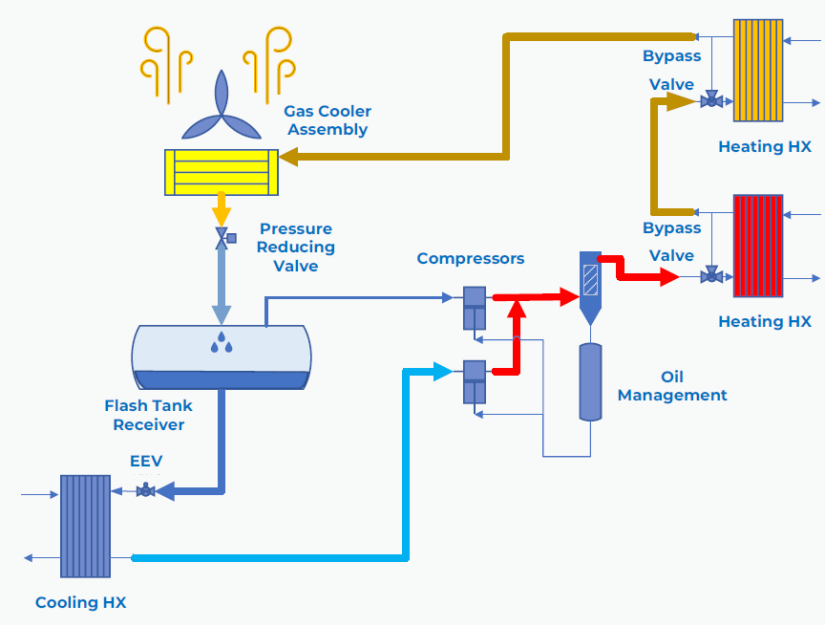

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Disclaimer

Executive Summary

Space cooling, space heating, and domestic hot water (DHW) heating are three of the largest energy end-uses in California and will remain central to efficiency, electrification, and demand management efforts. A new packaged multipurpose hydronic CO_2 heat pump has promising potential for the energy efficient, cost-effective electrification of entire central plants with resultant decarbonization benefits across the commercial building market.

This report examines the design and feasibility of this technology at two buildings in California: an office building and a low-income multifamily building. It includes an initial market potential assessment, technology description, retrofit design, site impacts assessment, cost proposals, and recommendations. The findings highlight the potential benefits of electrifying and decarbonizing heating, cooling, and DHW systems in commercial buildings using a packaged, multipurpose CO_2 heat pump as an all-in-one plug-and-play solution ranging from 30 to 120-tons in size.

Key findings include:

- Energy efficiency: Modeled electricity usage increased at both sites due to replacing natural gas boilers with 120-ton heat pumps. Peak electricity demand also increased due to fuel switching. However, both sites would see overall energy savings compared to their gas-fired baseline systems by eliminating natural gas use and improving system efficiency.
- Greenhouse gas (GHG) emissions reduction: Site 1 was estimated to reduce approximately 22 metric tons of carbon dioxide equivalent (CO_2e) annually, while site 2 achieved an estimated reduction of 79 metric tons of CO_2e. These whole-building central plant GHG reductions were 73 and 60 percent, respectively.
- Cost-effectiveness: Energy savings alone did not offset total full measure capital costs within the system's lifetime. Future evaluation and programs should consider incremental cost, the cost difference between the emerging technology and a comparable code-compliant baseline system. The system demonstrated non-energy benefits and positive annual total system benefits (TSB): $1,428 for Site 1 and $2,259 for Site 2.
- System performance: Modeling indicated high heat pump COPs and significant performance improvements over baseline systems. COPs were highest during simultaneous heating and cooling compared to periods of only heating or cooling. Simultaneous operation is expected year-round for Site 1 in California Climate Zone 6 (CZ6), but less so for the Site 2 multifamily building in CZ4. Site 1 achieved simultaneous COP values of 2.7 to 3.4 and overall average annual COP of 1.9 versus a baseline COP of 1.7. Site 2 achieved simultaneous COP values of 2.6 to 2.8 and overall average annual COP of 1.5 versus a baseline COP of 1.2.

The project team recommends follow up study, including validating manufacturer performance curves with lab or field data, conducting field demonstrations to assess real-world performance, and evaluate energy and cost impacts for a real-world installation in comparison to a code-compliant system and incremental costs. This follow up work can help support early adopters and incentive programs, provide validation and confidence in the promising technology's capabilities, showcase its features, and establish a new starting point for iterative improvements in product design, the specification processes, and best practices for building owners and their service providers.

Abbreviations and Acronyms

Acronym	Meaning
AHU	Air handling unit
ASHP	Air-source heat pump
BMS	Building management system
CA	California
CASE	Codes and Standards Enhancement
CEUS	Commercial End-Use Survey
CHW	Chilled water
CHWP	Chilled water pump
CO_2	Carbon dioxide
COP	Coefficient of performance
CZ	Climate zone
DDC	Direct digital controls
DHW	Domestic hot water
DX	Direct expansion
FCU	Fan coil unit
GHG	Greenhouse gas
GWh	Gigawatt-hour
GWP	Global warming potential
HFC	Hydrofluorocarbon (refrigerant)
HHW	Heating hot water
hp	Horsepower

Acronym	Meaning
HTR	Hard-to-reach
HVAC	Heating, ventilation, and air conditioning
IOU	Investor-owned utility
kW	Kilowatt
kWh	Kilowatt-hour
MBH	Thousand BTUs per hour
MTherms	Million therms
OAT	Outside air temperature
ODP	Ozone depletion potential
PG&E	Pacific Gas and Electric
SCE	Southern California Edison
TSB	Total system benefit
VAV	Variable air volume
VFD	Variable frequency drive

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Introduction

Space heating and domestic hot water (DHW) are the two largest decarbonization targets in buildings, accounting for approximately 70% of natural gas usage across all commercial sectors and over 90% in multifamily buildings. Developing energy-efficient, cost-effective solutions to decarbonize these natural gas loads requires innovative technologies. However, there are economic, feasibility, and technological challenges associated with expanding the market for emerging technologies, which must be explored and addressed through studies of early adopters and products.

One such solution is a newly developed, high-efficiency multipurpose hydronic carbon dioxide (CO_2) heat pump technology, capable of providing space cooling, space heating, and DHW. This new packaged product uses carbon dioxide as a low-global warming potential (GWP) refrigerant and is commercially available in the U.S. Unlike other CO_2 heat pumps, it can produce high-temperature hot water that can serve both heating hot water (HHW) and domestic hot water (DHW). This multifunctional capability enables the single low-GWP heat pump to replace HHW boilers and DHW boilers in addition to chillers used for space cooling. By doing so, it can avoid costly electrical and utility infrastructure upgrades often required for new construction, as it operates on the same power service as the chilled water (CHW) system. The evaluated product can operate across a wide range of return and ambient temperatures, broadening the applicability of CO_2 heat pumps. While the efficiency decreases under high return and ambient temperature conditions, the technology offers a practical solution for electrifying high-temperature systems which have limited available options, thereby creating opportunities to expand decarbonization efforts.

The project team collaborated with host site building owners, system designers, and the emerging technology equipment manufacturer to study the performance, multifunction load capabilities, retrofit feasibility, and financial impacts of the technology. These findings were used to quantify energy efficiency benefits, market potential, and integration feasibility while informing recommendations for product design, program support, and future study directions.

Background

Commercial and residential buildings in the U.S. account for 74 percent of the nation's electricity usage, 29 percent of natural gas usage, and are responsible for 35 percent of its carbon emissions (DOE 2024). Thus, decarbonizing the existing building stock is a significant priority. Space heating in U.S. commercial buildings has the largest energy footprint, accounting for 32 percent of total energy use; cooling and DHW account for nine percent and five percent, respectively (U.S. EIA 2023). In California, natural gas continues to be the dominant fuel source of water heating for commercial and multifamily buildings. According to the 2022 California Commercial End-Use Survey (CEUS), 58 percent of commercial buildings use gas water heating systems (ADM Associates 2024). For multifamily buildings, the 2019 Residential Appliance Saturation Survey (RASS) found that 69 percent of buildings in the state rely on gas water heaters (DNV GL Energy Insights USA 2021). As electrification efforts continue to expand, building owners and utilities are turning to technologies like heat pumps to meet these heating demands more efficiently and with lower greenhouse gas

(GHG) emissions. However, building owners looking to adopt these technologies face barriers such as high costs, market availability, and integration difficulties, especially in retrofit scenarios.

Existing solutions for CHW, HHW, and DHW systems are typically single-purpose, addressing only one of these three end-uses. However, multipurpose heat pumps that can accommodate all three end-uses are starting to appear in the market. Additionally, there is increasing pressure to develop systems that use safer, low-GWP refrigerants, especially as many synthetic refrigerants are being phased out over concerns over per- and polyfluoroalkyl substances (PFAS) and their high-GWP impacts. These trends support the adoption of natural refrigerants such as CO_2 (i.e. R744), which offer a safer and more environmentally responsible alternative for heat pump technologies. CO_2-based multipurpose hydronic heat pumps present a promising solution for decarbonization by delivering high efficiency performance while replacing fossil fuel-reliant systems and reducing the need for costly, disparate retrofit measures.

Multipurpose Hydronic CO_2 Heat Pump Market Size

Multipurpose hydronic CO_2 heat pumps are marketed for use in various commercial and light industrial building types and provide the most benefit for those that have applications that include more than one of the following systems: chillers, boilers, and DHW equipment. Common buildings with these loads include but are not limited to offices, hospitality, education, hospitals, multifamily and other high-density housing, and mixed-use buildings.

To assess the applicability of the emerging technology to existing building stock, the project team reviewed available literature on statewide energy consumption by market sector, hydronic system utilization rates, and end-use energy impacts.

Market Size and Energy Consumption

The project team used the 2022 California Commercial End-Use Survey (CEUS) to estimate total annual electricity and natural gas consumption for commercial and multifamily buildings in California (ADM Associates 2024). Additionally, research from the Northwest Energy Efficiency Alliance (NEEA) was referenced to determine the market shares of CHW and HHW systems in commercial buildings (Cadmus Group 2020). Table 1 summarizes the approximate prevalence of CHW and HHW systems by commercial building segment that could benefit from this technology. For this analysis, it is assumed that the emerging technology is applicable for retrofitting all existing electric and natural gas DHW systems, including storage and instantaneous water heaters, representing the maximum potential market share. The buildings with all three systems – CHW, HHW, and DHW – was calculated to estimate the percentage of commercial buildings most suitable for the technology. Buildings with all three systems are considered ideal candidates since the heat pump can serve all three loads.

Table 1: Prevalence of CHW and HHW Systems in Commercial Sector

Segment	HHW	CHW	All three systems present
Assembly	18%	18%	18%
Hospital	84%	83%	82%
Lodging	20%	26%	19%
Mixed Commercial	17%	7%	6%
Office	14%	13%	13%
Residential Care	15%	8%	7%
School	63%	51%	45%
Warehouse	0%	7%	0%

Source: (ADM Associates 2024) (Cadmus Group 2020)

In 2022, commercial buildings across California consumed an estimated 93,532 GWh of electricity and 2,250 million therms (MTherms) of natural gas (ADM Associates 2024). By multiplying the rate at which all three end-uses occur by the end-use energy consumption and an assumed 10 percent design and feasibility factor, the potential statewide energy impact of this emerging technology in California was estimated in Table 2.

Table 2: Annual Energy and Potential Emerging Technology Impact for Commercial Sector in California

	Electricity (GWh)	Natural Gas (MTherms)
Annual Energy Consumption	93,532	2,250
Potential Emerging Technology Impact (percent)	1,546 (1.7%)	48 (2.1%)

Multifamily Sector Market Size and Energy Consumption

To determine the prevalence of central plant in multifamily buildings, the project team referenced the U.S. Energy Information Administration's 2020 Residential Energy Consumption Survey (U.S. EIA 2020). The analysis found approximately 21 percent of multifamily dwellings have central plants serving multiple units. Table 3 summarizes these findings.

Table 3: Prevalence of Central Plant Cooling and Heating Systems in Multifamily Sector

	2-4 Unit Building	5+ Unit Building	Total
Total Number of Units Surveyed	9,340,000	22,840,000	32,180,000
Number of Units with AC	7,570,000	19,560,000	27,130,000
Number of Units with Central Plant (percent)	1,390,000 (15%)	5,460,000 (24%)	6,850,000 (21%)

Source: (U.S. EIA 2020)

Recent Title 24, Part 6 studies by the Statewide Codes and Standards Enhancement (CASE) team summarize the prevalence of various DHW systems by multifamily building type (Pande, et al. 2022) (Goyal, et al. 2022). These reports assessed both new construction and existing multifamily building market size for central DHW systems based on four building categories. The CASE reports also identified the number of existing multifamily dwellings in each category. Combining this data with market share rates indicates that about 2.8 million multifamily dwellings in California are served by central DHW systems. Table 4 presents the prevalence of central DHW systems and the corresponding impacted number of units.

Table 4: Prevalence of DHW Systems in Multifamily Sector

Building Size	Central DHW Percent	Number of Dwellings in Dataset	Percent of Dwellings	Total Central DHW Units
1 - 2 story	37%	4,720	24%	1,016,017
3 story	49%	7,882	39%	1,696,662
4 - 6 story	97%	4,296	21%	924,748
7+ story	100%	3,125	16%	672,681
Total			**64%**	**2,776,977**

Source: (Pande, et al. 2022), (Goyal, et al. 2022)

Given that 21 percent of multifamily buildings have central plants for cooling and heating and 64 percent also have central DHW systems, it is estimated that 14 percent of multifamily buildings have both central HHW and CHW plants and a central DHW system.

The 2019 California Residential Appliance Saturation Study provides a breakdown of household energy end-uses (DNV GL Energy Insights USA 2021). Figure 1 illustrates end-use breakdown for electricity consumption while Figure 2 shows natural gas end-use consumption. The emerging technology has the potential to impact air conditioning, space heating, and DHW end-uses, which together account for approximately 20 percent of the electricity consumption and 91 percent of the natural gas consumption.

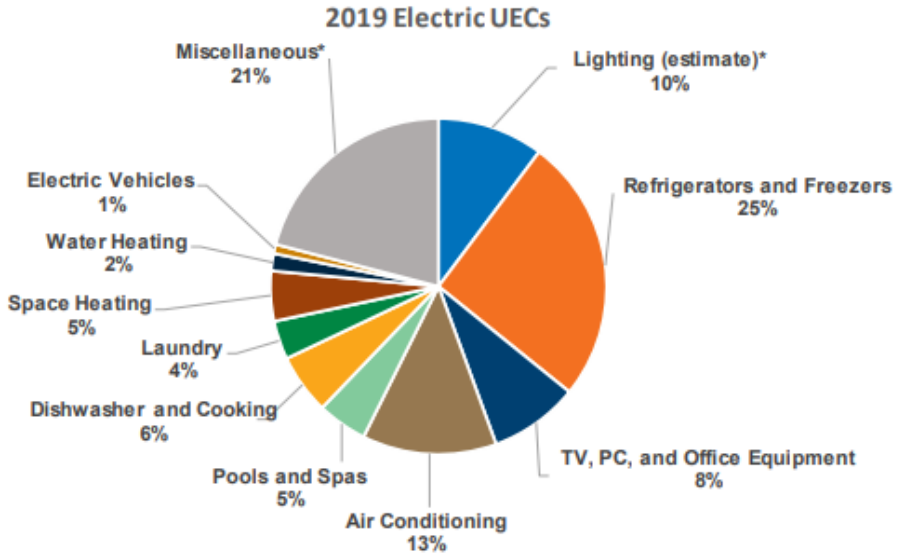

Figure 1: Electricity Consumption by End-use

Source: (DNV GL Energy Insights USA 2021)

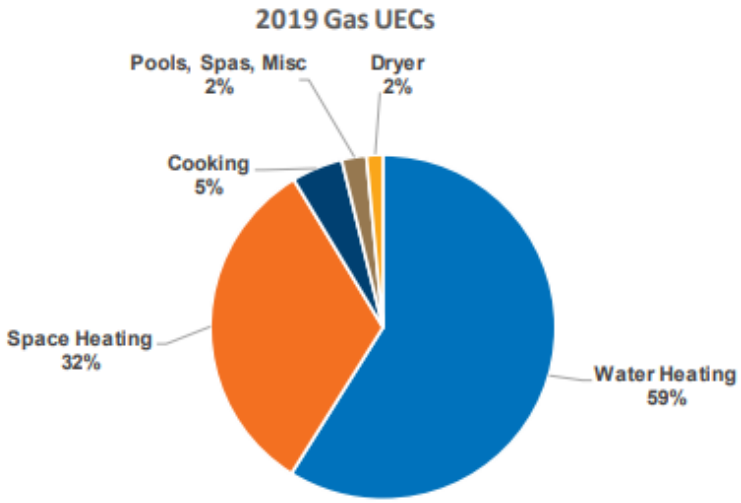

Figure 2: Natural Gas Consumption by End-use

Source: (DNV GL Energy Insights USA 2021)

The 2019 California Residential Appliance Saturation Study estimated that multifamily households consume about 4,022 kWh of electricity and 226 therms of natural gas annually (DNV GL Energy Insights USA 2021). The projected statewide energy impact of emerging technology was estimated by multiplying the rate at which both central plant and central DHW system co-exists by end-use energy percent consumption and applying a 10 percent design and feasibility factor. Based on this approach, the potential market share of the emerging technology in California is estimated at 357 GWh and 20 MTherms, as shown in Table 5.

Table 5: Multifamily Sector Annual Energy and Impacted Energy Consumption

	Electric (GWh)	Natural Gas (MTherms)
Annual Energy Consumption	17,335	974
Potential Emerging Technology Impact (percent)	357 (2.1%)	20 (2.1%)

Source: (DNV GL Energy Insights USA 2021)

Supporting energy efficiency and electrification in multifamily buildings can have substantial energy impacts while also benefiting lower-income, hard-to-reach (HTR), renter populations which disproportionately comprise multifamily building occupants. According to the 2021 U.S. Census American Community Survey, renters occupy about 90 percent of apartments in buildings with three or more dwellings in California. This is compared to less than 45 percent of the total residential population. Thus, a focus on end-uses and energy systems in multifamily buildings can benefit these underserved communities, especially when measures can impact whole buildings and bridge the split renter-owner incentive.

Emerging Technology: Multipurpose Hydronic CO_2 Heat Pump Systems

The product explored in this study is a multipurpose heat pump that uses CO_2 refrigerant (R-744) that can singularly replace a hydronic system with chillers, boilers, and DHW equipment. Thus, the packaged solutions can provide all-in-one electrifications of existing natural gas with increased efficiency. Since the emerging technology consolidates three or more distinct equipment into one, it is simpler to install, operate, and maintain. The multipurpose hydronic CO_2 heat pump can apply to both new construction and for retrofitting existing hydronic CHW, HHW, and DHW systems.

Characteristics of CO_2 R-744 Refrigerant and Transcritical Refrigeration

Many commercially available air-to-water heat pumps use R-410A refrigerant although some systems are moving to R-32 or R-454B as lower-GWP alternatives. However, these refrigerants still have notably high GWP values of 2,256, 771, and 531, respectively, CO_2 has a GWP value of 1. CO_2 is also natural, non-flammable, and non-toxic with an ozone depletion potential (ODP) of zero. These properties of CO_2 future-proofs the emerging technology as higher GWP refrigerants continue to be phased out through regulatory measures.

CO_2 as a refrigerant can operate in outside air temperature (OAT) ranging from -15°F to 120°F, making it feasible to operate in most climates in the U.S (O'Neill, Spielman and Heller 2024). For regions with excessively hot ambient temperatures, the emerging technology provides the option to add an adiabatic gas cooler to optimize efficiency. CO_2 is a high-density refrigerant, which allows systems to have smaller pipe diameters and reduced compressor volume versus a hydrofluorocarbon (HFC) system.

The CO_2 refrigerant also presents some limitations. CO_2 systems operate at higher pressures compared to traditional HFC systems such as R-410A, requiring greater attention to system design and operational safety. This can lead to higher component costs, despite the refrigerant itself being significantly cheaper than its synthetic counterparts. Additionally, CO_2 heat pump performance can be negatively influenced by the inlet water temperature; COP can decrease dramatically with higher heat pump inlet temperatures. To mitigate this, the technology incorporates a built-in heat exchanger that allows for heat recovery.

The emerging technology operates on a transcritical CO_2 refrigeration cycle, operating above the refrigerant's critical temperature of 87.8°F. This transcritical operation allows the system to achieve simultaneous heating and cooling without a reversing valve. Additionally, transcritical refrigerants can accommodate decoupled pressure and temperature and higher discharge temperatures that can enable greater, more efficient heat recovery. The refrigerant cannot be condensed, but the refrigerant circuit has a gas cooler that acts as a condenser to cool down the transcritical CO_2 refrigerant gas to provide heat (O'Neill et al. 2024).

Figure 3 illustrates the schematic diagram of the technology. In order, flash gas from the flash tank receiver enters the inlet of the high temperature upper compressor, high-pressure gas passes through a bypass valve upstream of the high-grade and low-grade hot water heat exchangers which may be used individually or in series, depending on the application and instantaneous loads. Warm gas then enters the gas cooler assembly and becomes a lower-temperature gas as heat is rejected. The gas expands through the pressure reducing valve to become a liquid-vapor mixture which then enters the flash tank receiver. From the flash tank, the liquid is sent through the chilled water heat exchanger, expanded to a gas, and enters the medium temperature lower compressor before combining with the hot compressed gas from the upper compressor, thereby restarting the cycle.

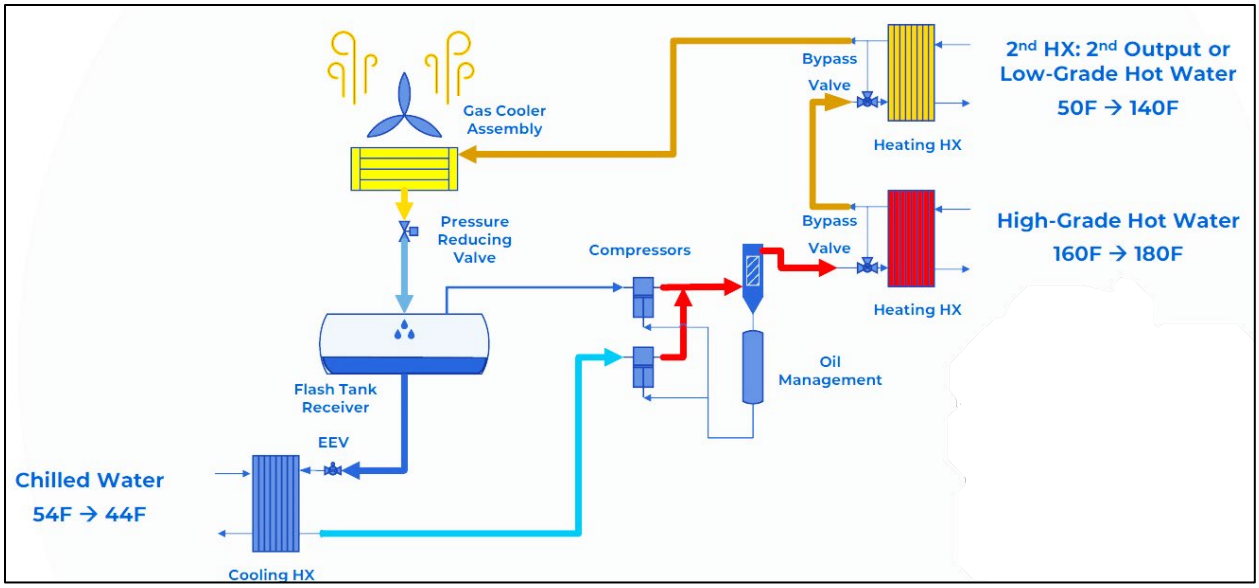

Figure 3: Multipurpose CO_2 HP refrigeration circuit[1].

Source: Manufacturer

The emerging technology has not been demonstrated in the field, yet. However, Ecotope completed a feasibility study of the product and provided an in-depth overview of key components including the equipment, costs, availability, operation, and maintenance (O'Neill, Spielman and Heller 2024). A summary of the technology is shown in Table 6. The technology is offered in split-system and packaged configurations from 30 to 120 tons, which can be modularly combined for larger capacities in a single system.

In the split-system configuration, the gas cooler is remotely located and separate from the heat pump. Split-systems may require field-installed refrigerant piping, which can increase the risk of leaks. On the contrary, packaged systems place the heat pump directly next to the gas cooler, reducing the amount of required piping and thus reducing costs. Packaged systems do have a larger footprint and considerable weight, which can both pose a challenge to install on existing rooftop configurations. Outdoor installations may also require additional protection against weather impacts. Regardless, the different configurations make it suitable for installations and retrofits in a variety of building conditions.

[1] Not all components of the system are shown.

Table 6: Emerging Technology Equipment Specifications

	Specification	Details
System	Nominal Size (tons)	30 to 120, which can be modularly combined for larger systems
	Installation Types	Split Packaged
	Operation Modes	Cooling Only Heating Only Simultaneous Heating and Cooling
	System Lifespan	20 to 30 years (estimated)
Refrigerant	Type	R-744 (CO_2)
	GWP	1.0
	Critical Point	87.8°F
	Operating Range	-15°F to 120°F
	Operating Range at Full Design Capacity	0°F to 116°F
Cooling	Supply Water Temperature	38°F to 75°F (down to 0°F with antifreeze)
Heating	Supply Water Temperature	90°F to 180°F

Source: (O'Neill, Spielman and Heller 2024) and Manufacturer

Since the technology can simultaneously produce CHW, HHW, and DHW, it is well suited to replace existing hydronic systems using chillers, boilers, and DHW service equipment with a single product. The technology, which can support supply water temperatures up to 180°F, also provides a solution for decarbonization through electrifying high-temperature water heating systems. Additionally, if the system is designed with sufficient thermal storage, it can support load shifting for additional benefits to energy savings, energy cost mitigation, and GHG emissions reduction.

Currently, the product requires custom engineering to a specific site and its applications. Additionally, the manufacturer does not provide ancillary equipment such as buffer tanks and pumps that are required for the hydronic systems and to support DHW functions. However, the manufacturer does provide engineering guidance to help with sizing and selection of any necessary ancillary equipment. Adequate structural and electrical capacity also needs to be considered when

evaluating the technology for retrofit applications. If infrastructure is already in place for hydronic distribution systems such as chillers, the technology may be able to use existing connections and wiring for operation, consequently avoiding additional electrical infrastructure upgrade costs. Alternatively, for buildings without sufficient electrical capacity or without an equivalent-sized chiller that needs to be replaced, the fuel switching or added load electrical infrastructure costs will need to be considered. In terms of availability, the estimated lead time for this technology is six months. While this is not expected to impede new construction projects, it may be a limiting factor in the feasibility for emergency or short timeline retrofit applications.

Ecotope also conducted limited applications testing on a 60-ton split-system prototype unit to assess its functionality under all three operational modes. The testing revealed that the unit performed reliably when in operated in heating or cooling only mode but demonstrated highest efficiencies when it simultaneously produced hot and chilled water. The test did not include DHW due to the lack of corresponding heat exchanger in the prototype unit even though that heat exchanger would be a part of commercially available units. As a result, the performance of this function is unclear. The study recommended that the system should heat DHW using a double-walled, low-grade heat exchanger in a single pass return-to-primary configuration. This configuration increases system efficiency by allowing the heat pump to simultaneously provide DHW (O'Neill et al. 2024).

Objectives

The study objectives are:

- Quantify the potential California market size.
- Establish market readiness and availability of commercial sized low-GWP multipurpose heat pump systems.
- Identify and select two potential early adopter host sites for the technology, located in California investor-owned utility (IOU) territories to participate in feasibility and design study objectives.
- Characterize the energy performance of multipurpose hydronic CO_2 heat pump technology at variable heating, cooling, and DHW loads through modeling.
- Develop building energy models for each host site with in-situ equipment, code, or industry standard baseline and the multipurpose hydronic CO_2 heat pump technology.
- Assess baseline and proposed energy, costs, TSB, and GHG savings relative to existing baseline systems.
- Conduct feasibility and design study of the combined heating, cooling, and DHW performance of the emerging technology at the two host sites including implementation costs, controls, materials estimates, electrical infrastructure needs, equipment sizing, space constraints and structural impacts.
- Develop conclusions and recommendations for manufacturers, designers, utilities, and program administrators towards increased market adoption.

Methodology & Approach

Host Sites

The project team leveraged preexisting end-user relationships, internal program networks, IOU peers, industry and advocate partners, and manufacturer contacts as well as a targeted social media outreach campaign to identify potential host site partners. From the many entities contacted, two sites with the most potential for successful participation and interest in decarbonization were selected. Site 1 is a commercial building in the Los Angeles metropolitan area and Site 2 is a low-income senior multifamily building in the San Francisco Bay Area. A summary of host site characteristics is provided in Table 7.

Table 7: Host Sites

Criteria	Site 1	Site 2
Building Type	Office	Multifamily
California Climate Zone	6	4
Utility	SCE	PG&E
Year built	1969	1981
Building size	113,000 ft^2	130,000 ft^2
Occupancy	Monday – Friday, 7 a.m. to 6 p.m. Saturday, 8 a.m. to 1 p.m.	Residence building: 24/7 Admin building: Monday – Friday, 7 a.m. to 6 p.m.
HVAC System	Dual duct variable air volume system	Fan coil units
CHW Equipment	Water-cooled DX	Air-cooled chiller
HHW Equipment	Natural gas boiler	Natural gas boiler
DHW Equipment	Natural gas storage water heater	Indirect Heating by HHW Loop with Solar Thermal Preheat
HVAC Operating Hours	Monday, 4 a.m. – 6 p.m. Tuesday – Friday, 5:30 a.m. – 6 p.m. Saturday, 7 a.m. – 1 p.m.	24/7

Site 1 Existing Equipment

Site 1 is a six-story, plus basement, multi-tenant commercial office building originally constructed in 1969. It has approximately 113,000 ft^2 of office space and a 43,000 ft^2 parking area. As of April 2025, there is approximately 40,000 ft^2 of leasable space that is vacant. Approximately 230 employees occupy the building from 7 a.m. to 6 p.m. Monday through Friday and 8 a.m. to 1 p.m. Saturday.

One 200-ton dual duct variable air volume (VAV) air handling unit (AHU) provides HVAC to the building. The AHU has design flow of 50,000 cubic feet per minute (CFM) and consists of cold deck with DX cooling coil, hot deck with HHW coil, and two 75 hp supply fans controlled by a variable frequency drive (VFD). The system also has four relief fans, each rated at 3 hp, to maintain a slightly positive building pressure. Mixing boxes in each zone are controlled by individual thermostats and blend the warm and cool air supplied by the AHU to maintain comfort. First stage cooling is designed to use an outdoor air economizer, allowing the AHU to draw in cooler outdoor air when available. However, economizer functionality could not be confirmed during the site visit. Cooling is provided by two lead/lag 100-ton variable-speed screw compressors located in the rooftop penthouse.

Figure 4: Site 1 Water-cooled screw compressors.

There are two evaporative condensers located on the roof. They include condenser coils that are evaporatively cooled using 0.75 hp spray pumps and 10 hp condenser fans, controlled by VFDs.

Figure 5: Site 1 evaporative condensers.

Two Raypak boilers provide HHW to the air handler. The boilers are 84 percent efficient and have a rated output capacity of 1,285 MBH each. The units are housed in a dedicated room on the roof which allows for combustion air to be sourced through existing louvers. There are no buffer tanks for the boilers. One of the boilers can meet the building's entire heating load under most conditions.

Figure 6: Site 1 boiler room.

Domestic hot water (DHW) is provided by two parallel natural gas fired storage water heaters. One domestic hot water heater is a 75-gallon unit with 76 MBH rated output, and the other is a 100-

gallon unit with 85 MBH rated output. DHW was excluded from the study for Site 1 due to minimal building demand for DHW.

Figure 7: Site 1 DHW heating equipment.

The summary of existing equipment for Site 1 can be found in Table 8.

Table 8 Host Site 1 Existing Equipment Details

Equipment	Qty	Capacity	Efficiency	Year	Control
DX Screw Compressor	2	100 tons	3.0 COP	Unknown	Variable speed
Evaporative Condenser	2	100 tons 10 hp fan	Unknown	2011	Variable speed
HHW Natural Gas Boiler	2	1,285 MBH output	0.84	2003	-
HHW Pump	2	2 hp	Unknown	2003	Variable speed
DHW storage water heater	2	75,100 gallons	0.81	Unknown	-

Site 1 Electricity Energy Usage

This site has one electricity meter and purchases its power from Southern California Edison (SCE). The team analyzed the site's electricity usage from September 2023 to August 2024 to understand the facility's electricity usage pattern. The building's total annual electricity use over this one-year period was 590,750 kWh with a maximum peak demand of 187 kW. Historical electricity consumption and peak demand are summarized in Table 9.

Table 9: Site 1 Historical Energy Consumption and Peak Demand

Month	Electricity Consumption (kWh)	Peak Demand (kW)
Sep-23	52,214	148.8
Oct-23	54,415	187.2
Nov-23	45,232	135.4
Dec-23	43,078	128.6
Jan-24	46,383	133.4
Sep-23	52,214	148.8
Feb-24	42,378	131.5
Mar-24	44,068	134.4
Apr-24	44,340	127.7
May-24	47,137	137.3
Jun-24	50,061	168.0
Jul-24	59,732	168.0
Aug-24	61,711	176.6
Total/Max	590,750	187.2

Figure 8 illustrates electricity consumption and peak demand throughout the year. Electricity consumption at this facility exhibit seasonal variability, with consumption increasing during the summer months likely due to increased chiller operation to meet the elevated demand for cooling.

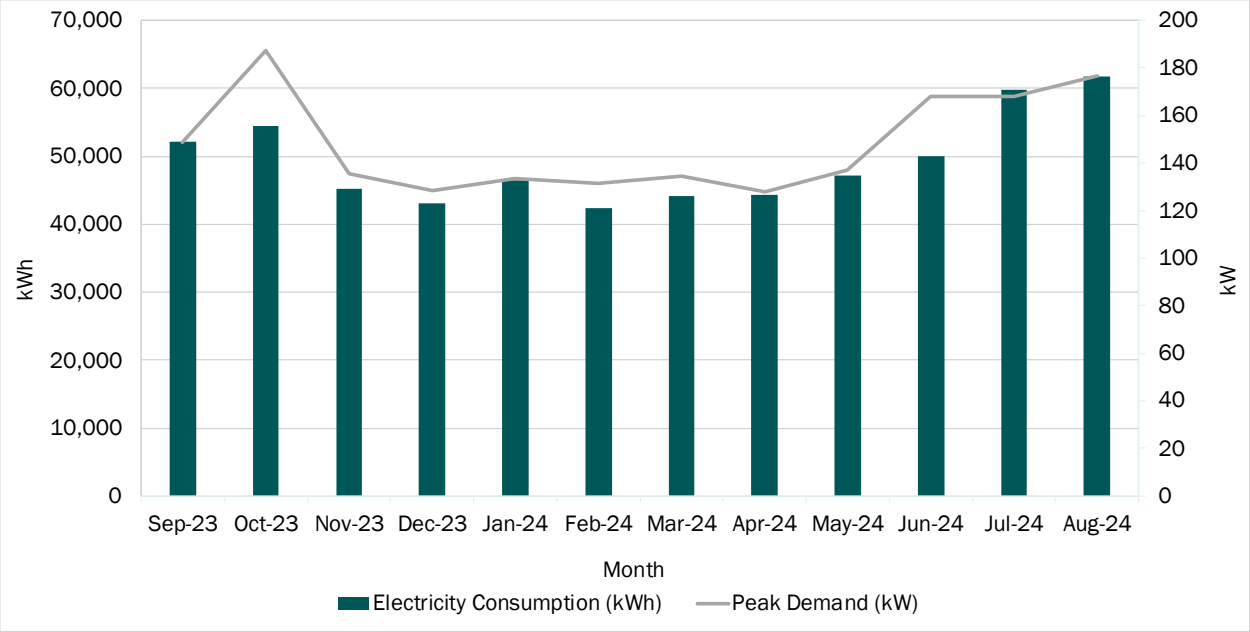

Figure 8: Site 1 electricity consumption and peak demand.

Site 1 Natural Gas Usage

This site has one natural gas meter and purchases its natural gas from Southern California Gas (SCG). The team analyzed 12 months of metered data from September 2022 through August 2023. During this period, the total annual natural gas consumption was 21,954 therms. A summary of historical gas consumption is provided in Table 10.

Table 10: Site 1 Historical Natural Gas Consumption

Month	Natural Gas Consumption (therms)
Sep-22	57
Oct-22	687
Nov-22	2,177
Dec-22	3,382
Jan-23	3,476
Feb-23	3,318
Mar-23	3,720
Apr-23	2,205
May-23	1,141
Jun-23	1,450
Jul-23	249
Aug-23	92
Total	21,954

Figure 9 shows natural gas consumption over the year. Natural gas consumption at this facility is primarily attributed to space heating and DHW heating. Usage peaks in the winter months due to heightened space heating demands. Gas consumption remains low during the summer months, with little to no space heating demands.

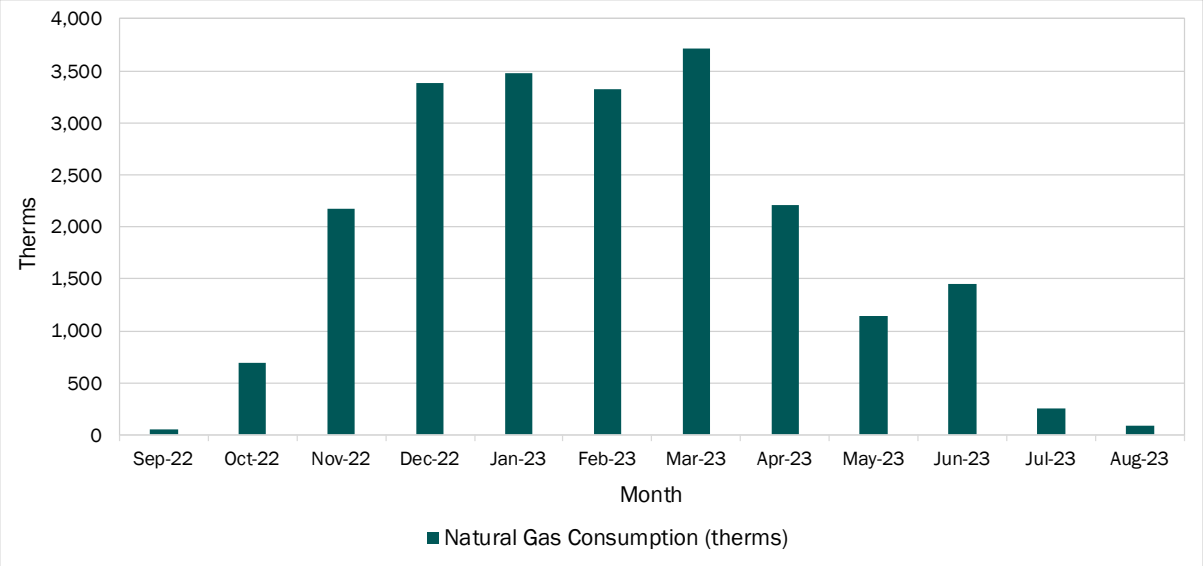

Figure 9: Site 1 natural gas consumption.

Site 2 Existing Equipment

Located in the San Francisco Bay Area, Site 2 is a multi-story senior apartment building. The project site consists of two buildings: the seven-story primary residence building and an adjacent one-story administration building, with a combined area of approximately 130,000 ft^2. The buildings include a total of 153 apartments. Tenant spaces are occupied 24 hours per day, seven days per week and the administration building is generally occupied from 7 a.m. until 6 p.m. Monday through Friday and limited hours on Saturday. Originally built in 1981, the facility underwent an extensive renovation in 2013 and 2014, which included significant upgrades to HVAC and DHW equipment.

Site 2 provide cooling and heating through a combined hydronic system. Each residence space and common area has a fan coil unit (FCU) controlled by a programmable thermostat. The thermostat activates either the HHW or CHW valves of the FCU to satisfy temperature settings. CHW is supplied by an 80-ton rooftop packaged, air-cooled chiller that has two scroll compressors, six condenser fans. A constant-speed chilled water pump (CHWP) supplies water to the FCUs.

Figure 10: Site 2 air-cooled packaged chiller.

The primary heating system includes two 942 MBH condensing boilers with a design efficiency of 94% and a rooftop solar thermal pre-heating circuit. The solar thermal system preheats DHW, and the condensing coilers are used to bring the pre-heated DHW up to the desired supply temperatures through a heat exchanger. After going through the heat exchanger, DHW is then pumped into two separate storage tanks: a 300-gallon storage tank in the primary building and 119-gallon storage tank in the administrative building. The remaining HHW is supplied throughout the buildings directly from the HHW boilers to provide space heating as needed.

Figure 11: Site 2 hot water condensing boilers and solar thermal hot water pre-heater.

Site 2 is equipped with a building management system (BMS) that monitors and controls boiler, HHW pump, air-cooled chiller, and CHWP operation.

Details of the second host site building are shown in Table 11 below.

Table 11: Host Site 2 Existing Building and Equipment Details

Equipment	Qty	Capacity	Efficiency	Year	Control
Air-cooled packaged scroll chiller	1	80 tons	15.8 IPLV	2017	Constant speed
CHW primary pump	1	5 hp	Unknown	2017	Constant speed
Condensing boiler	2	942 MBH output	0.94	2015	-
HHW primary pump	2	3/4 hp	Unknown	2015	Constant speed
HHW secondary pump	1	3 hp	Unknown	2015	Variable speed
DHW storage	2	300 gallons, 119 gallons	-	Unknown	-

Site 2 Electricity Energy Usage

This site has two electricity meters and purchases its power from Pacific Gas and Electric (PG&E). The team analyzed the site's electricity usage from August 2023 to July 2024. The facility's total annual electricity use over this one-year period was 645,345 kWh with a maximum peak demand of 85.2 kW. Historical electricity consumption and peak demand are summarized in Table 12.

Table 12: Site 2 Historical Energy Consumption and Demand

Month	Electricity Consumption (kWh)	Peak Demand (kW)

Aug-23	65,565	67.2
Sep-23	57,389	74.4
Oct-23	54,950	74.4
Nov-23	52,655	85.2
Dec-23	55,652	84.0
Jan-24	56,049	81.6
Feb-24	52,316	79.2
Mar-24	53,212	73.2
Apr-24	50,984	68.4
May-24	50,316	64.8
Jun-24	57,390	62.4
Jul-24	38,867	69.6
Total/Max	**645,345**	**85.2**

Figure 12 shows the facility's electricity consumption and peak demand relative to time of year. The facility consumes more electricity in the summer months due to increased demand for cooling. The highest peak demand is observed in November.

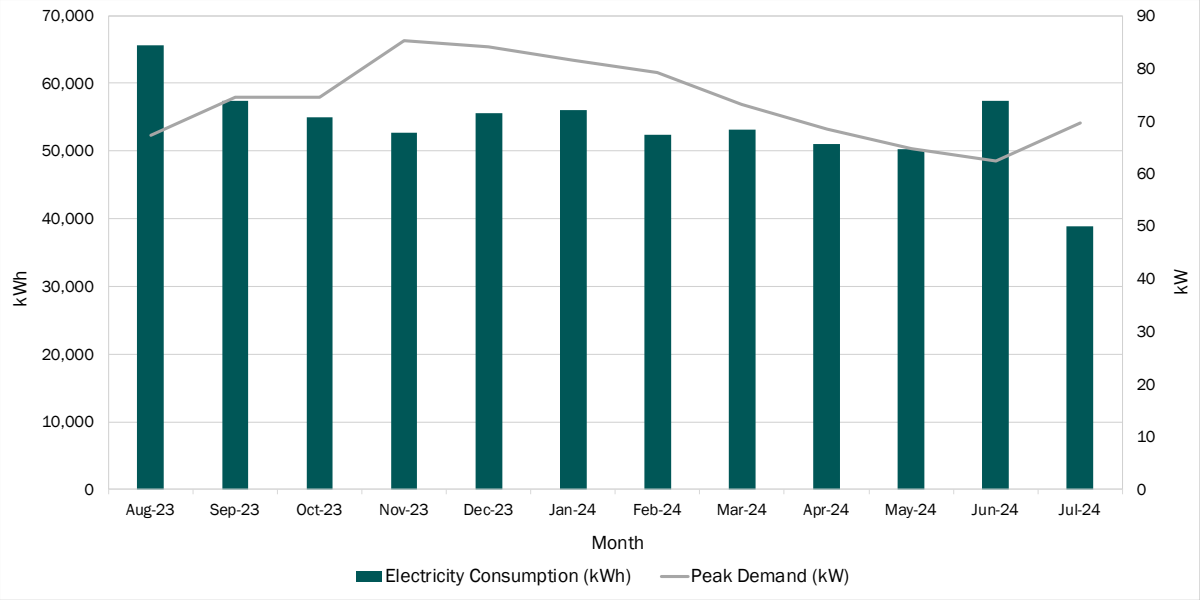

Figure 12: Site 2 electricity consumption.

Site 2 Natural Gas Energy Usage

This site has one natural gas meter and purchases its natural gas from PG&E. The team analyzed one year of data from August 2023 to July 2024. The total annual natural gas consumption during this 12-month period was 26,717 therms. Table 13 summarizes historical natural gas consumption.

Table 13: Site 2 Historical Natural Gas Consumption

Month	Natural Gas Consumption (therms)
Aug-23	1,032
Sep-23	1,299
Oct-23	1,715
Nov-23	2,582
Dec-23	3,541
Jan-24	3,775
Feb-24	3,597
Mar-24	3,010
Apr-24	2,665
May-24	1,468
Jun-24	1,081
Jul-24	952
Total	26,717

Figure 13 shows the facility's natural gas consumption over the year. Natural gas consumption at this site is primarily attributed to DHW and space heating. Usage peaks in January due to heightened space heating demands. Natural gas consumption remains low during the summer months.

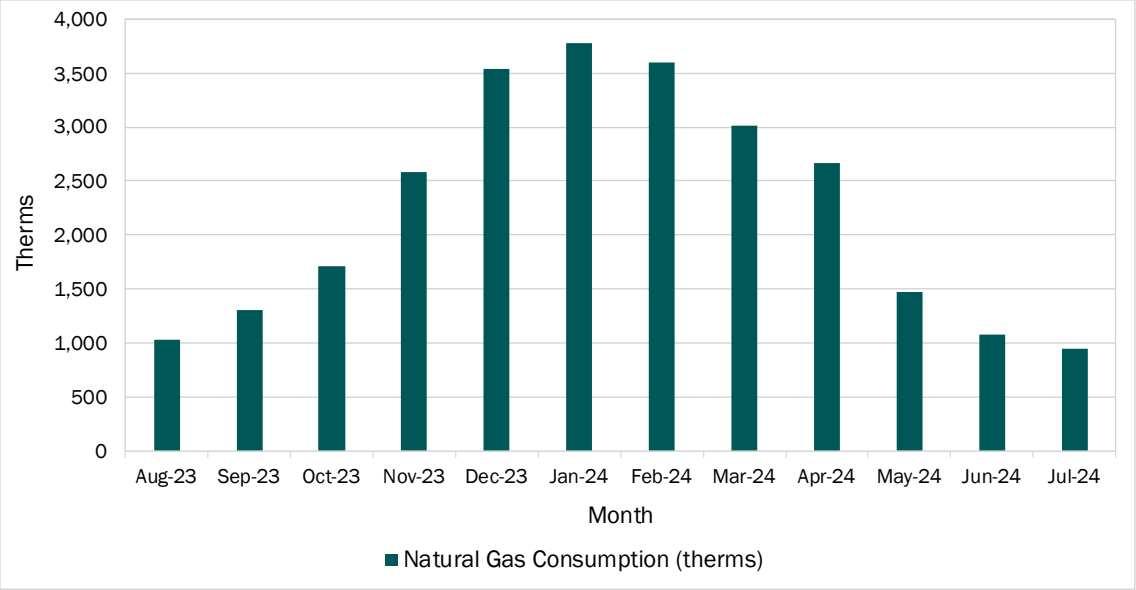

Figure 13: Site 2 natural gas consumption.

Design Analysis

The following sections detail the multifunction heat pump design for the two sites.

Site 1

SIZING

The largest available packaged heat pump model with a nominal cooling capacity of 120 tons and 1,440 MBH heating capacity was selected for Site 1 based on historical building data, design point loads, occupancy schedules, and climate conditions. The analysis excluded DHW due to the limited demand for DHW at this site. Site 1's cooling and heating demands have following characteristics:

- Cooling Demand: The building's dual-duct air handler is currently served by two 100-ton DX compressors. The compressors operate in a lead/lag configuration. The onsite staff indicated that the expected peak cooling load is approximately 100 tons. Thus, the 120-ton multifunction heat pump unit can fully service this load.
- Heating Demand: Space heating is currently provided by two 1,285 MBH Raypak boilers. The onsite staff reported that a single boiler typically meets the building's heating demand and therefore selected heat pump's heating capacity is sufficient for most conditions. However, to support potential higher heating demands and to provide redundancy, a supplementary electric boiler has been incorporated into the design.

ELECTRICAL SYSTEMS ASSESSMENT

A detailed power system assessment was performed to ensure the existing electrical infrastructure and service can support the new heat pump, backup electric boiler, and associated equipment. The evaluation confirmed that the existing electrical service had sufficient capacity, with minor panel modifications required for integration.

The existing total available capacity is approximately 1,107 amps. The new heat pump requires 342 amps at 460V/3PH and the supplemental electric boiler requires 693 amps at 480V/3PH. The following modifications would be required to accommodate these loads:

- A new 500-amp, 3-phase, 480V breaker in the existing main switchboard for the heat pump.
- A new 400-amp, 3-phase, 480V breaker in the existing main switchboard for the supplementary boiler.
- A new 208V distribution panel to provide dedicated circuits for pumps, DHW equipment, and controls.
- Individual breakers ranging from 20 to 50 amps for heating hot water and chilled water pumps.

STRUCTURAL ASSESSMENT

Two 8,000-pound boilers, two 6,000-pound screw compressors, and the 20,000-pound cooling tower will be decommissioned and removed as part of the project. The total weight of these units is about 48,000 pounds.

The replacement consists of an air-source heat pump (ASHP) section and a gas cooler in a packaged configuration. Additionally, the proposed design would add two 1,000-gallon buffer tanks for hydronic heating and cooling and a backup electric boiler for supplementary heating. The total weight of these units is about 35,400 pounds.

The project team's structural engineer assessed the existing structure to validate locations and necessary support of proposed equipment's weights. The assessment confirmed that the proposed equipment can be supported either on the main roof or the penthouse roof without altering the primary gravity or lateral resistance system of the building. No structural upgrades would be necessary for the retrofit project.

CONTROLS

The existing building management system is currently a mixture of pneumatic controls, direct digital controls (DDC), and standalone low-voltage unit controllers. A central BMS controls the existing air handler, compressors, evaporative condensers and on/off signals to the boilers. Included below are high level requirements and considerations for controls for this proposed retrofit which assume no significant upgrades to the existing BMS. The proposed equipment would be directly integrated into the existing BMS, leveraging the onboard controls that come with the packaged heat pump technology. Refer to Appendix D for detailed information regarding HHW and CHW sequences.

A summary of the proposed equipment and its details according to the design and feasibility document for Site 1 can be found in Table 14. Refer to Appendix C for further information about the equipment.

Table 14 Equipment selection and details for Site 1 proposed design

Equipment	Quantity	Size	Weight	Electrical
Packaged CO_2 heat pump	1	1,440 MBH	10,800 lbs.	460V/3PH
Hydronic cooling coil	1	100 tons, 240 GPM	Unknown.	n/a
HHW buffer tank	1	1,050 gallons	11,250 lbs. (flooded)	n/a
CHW buffer tank	1	1,050 gallons	11,250 lbs. (flooded)	n/a
CHW primary pump	1	5 hp, 240 GPM	305 lbs.	460V/3PH
CHW secondary pump	2	3 hp, 190 GPM	220 lbs.	460V/3PH
HHW primary pump	1	2 hp, 100 GPM	240 lbs.	460V/3PH
HHW secondary pump	2	2 hp, 100 GPM	160 lbs.	460V/3PH
Backup electric boiler	1	135 gallons, 1,228 MBH	2,575 lbs.	480V/3PH

COST

The total estimated cost for the retrofit system at Site 1 is $2,560,000. This cost includes preconstruction requirements, materials, construction, startup and performance testing, and training.

- Preconstruction includes acquiring stamped construction documents and procuring permits.
- Construction includes the supply and delivery of the heat pump itself as well as implementing any additional equipment, infrastructure, and systems to accommodate its use at the facility.
- Start-up and performance testing is a part of equipment commissioning to start-up the new heat pump system on-site and validate system performance.

- Training includes dedicated customer training to operate the new equipment and controls. The training component will also provide electronic manuals, test reports, and notes to provide the site with a complete transition towards the warranty phase.

The design for Site 1 includes an electric boiler to provide redundancy to ensure that rare peak heating demands that exceed the HP capacity can be satisfied. The total cost for the equipment and installation of the 360-kW electric boiler is $500,000. This cost includes the delivery and installation of the equipment, installation of supplementary components, commissioning, and training material. This brings the total project cost to $3,060,000. Refer to Appendix B for a more detailed breakdown of the cost proposal.

Site 2

SIZING

An analysis of building trend data indicated that the site's peak space heating demand is approximately 1,250 MBH. Building DHW heating requires approximately 35 therms per day. The 120-ton HP model with 1,440 MBH capacity can therefore meet typical peak heating and DHW loads but cannot replace the full existing plant capacity of 1,884 MBH with a single unit. The design includes a supplemental electric boiler to provide additional heating during occasional loads that may exceed the unit's capacity and provide emergency backup capacity for the system.

Additionally, pumps and buffer tanks are sized based on system volumes and required flow rates to ensure adequate circulation, thermal storage, and peak load management.

ELECTRICAL SYSTEMS ASSESSMENT

The project team assessed the electrical power needs to ensure the existing electrical infrastructure and service can support the new packaged CO_2 HP, electric boiler, and associated equipment. The evaluation confirmed that the existing electrical service has sufficient capacity with minor panel modifications required for integration.

The existing available capacity is approximately 1,658 amps while the new ASHP requires 342 amps at 460V/3PH and the supplemental electric boiler requires 693 amps at 480V/3PH. The following changes would be required to accommodate these loads:

- A new 1000-amp, 3-phase, 480V breaker in the existing main switchboard to serve the backup electric boiler.
- A new 500-amp, 3-phase, 480V breaker in the existing main switchboard to serve the new packaged CO_2 HP.
- A 225 kVA 480-208Y/120V transformer to step down voltage for 208V equipment loads.
- A new 800-amp, 208V distribution panel to provide dedicated circuits for pumps, DHW equipment, and controls.

STRUCTURAL ASSESSMENT

The team's structural engineer conducted an assessment to validate that the proposed locations could support the equipment without modifications or reinforcements. The assessment confirmed that the proposed equipment could be supported without altering the primary gravity or lateral resistance system of the building.

- The packaged CO_2 HP will be placed on the existing concrete pad from the previous chiller. Since the new unit is longer, the pad will be extended and adhered with epoxy to the existing structure for additional support.
- The buffer tanks, storage tanks, electric boiler, and electric water heaters will be supported by a new steel frame structure anchored to the roof slab and parapet wall using hollow structural section (HSS) steel posts and steel base plates.

CONTROLS

The existing BMS is currently inaccessible and all equipment operates on default settings. The project team's understanding is that upgrades are required to restore full user functionality to the BMS, which is outside the scope of this feasibility study. Below are high-level requirements and considerations for controls for the proposed retrofit, assuming no changes or upgrades to the existing BMS:

Multipurpose CO_2 HP

- The HP will be supplied with an integral BACNET controller capable of receiving enable/disable signals and temperature setpoints. Without access to the existing BMS, it is assumed the unit will be continuously enabled and operate based on internal logic to maintain HHW and CHW buffer tanks and DHW storage tank temperature setpoints.
- It is recommended that a third-party controller with an OAT sensor and multiple outputs is also provided and tied to the new CO_2 HP and supplemental electric boiler to provide a coordinated supply temperature reset sequence.

Heating Hot Water Temperature Reset

- The HHW system shall be enabled at an OAT of 70°F or below and disabled otherwise.
- The HHW supply temperature shall reset based on the OAT. At the outdoor design temperature of 35°F, the supply water temperature setpoint shall be 180°F. Between 35°F and 55°F, the supply water temperature shall be linearly reset between 180°F and 140°F. Above 55°F, the supply water temperature setpoint shall be 40°F.

Chilled Water Temperature Reset

- The CHW system shall be enabled at an OAT of 60°F or above and disabled otherwise.
- The CHW supply temperature shall reset based on OAT. At the design OAT of 92°F, the supply water temperature setpoint shall be 42°F. Between 92°F and 72°F, the supply water temperature shall be linearly reset between 42°F and 54°F. Below 72°F, the supply water temperature setpoint shall be 54°F.

Primary Pumps

- A custom pump control package with a BACNET controller to interface with the new CO_2 HP controller shall be provided. The pumps will be a sensor-free type and controlled to a target flow and enabled/disabled by the new CO_2 HP controller. The primary pump shall operate whenever there is a call for heating from storage tank temperature sensors.

Secondary Pumps

- CHW/HHW secondary pumps will be controlled by differential pressure sensors in the distribution loop to maintain target differential pressure in each system.

Supplemental Electric Boiler

- The supplemental electric boiler will be programmed to start when the HHW supply temperature drops below a deadband setpoint for a defined duration (e.g., five degrees below the HHW supply temperature setpoint for five minutes).

A summary of the proposed equipment and its details according to the design and feasibility document for Site 2 can be found in Table 15. Refer to Appendix C for further information.

Table 15 Equipment selection and details for Site 2 proposed design

Equipment	Quantity	Size	Weight	Electrical
Packaged CO_2 HP	1	1,440 MBH	10,800 lbs.	460V/3PH
HHW buffer tank	1	700 gallons	7,500 lbs.	n/a
CHW buffer tank	1	850 gallons	9,000 lbs.	n/a
CHW primary pump	1	7.5 hp, 240 GPM	470 lbs.	460V/3PH
CHW secondary pump	2	7.5 hp, 135 GPM	360 lbs.	460V/3PH
HHW primary pump	1	3 hp, 124 GPM	250 lbs.	460V/3PH
HHW secondary pump	2	5 hp, 150 GPM	275 lbs.	460V/3PH
Electric boiler	1	1,474 MBH	2,575 lbs.	480V/3PH
DHW Electric Heaters	2	90kW, 150 gallons	1,900 lbs.	480V/3PH
DHW Storage Tanks	2	765 gallons	8,100 lbs.	n/a
DHW Pump	1	1.5 hp, 40 GPM	160 lbs.	460V/3PH

COST

The total project cost for the CO_2 HP at site 2 is $2,600,000. The cost includes activities for preconstruction, construction including the installation of a new back-up electric boiler, start-up, performance testing, and training. The CO_2 HP size and the scope of work for implementing the system is the same at both sites. Refer to Appendix B for a more detailed breakdown of the cost proposal.

Modeling and Calculation Methodology

The project team evaluated the performance of emerging technology through energy modeling. Baseline models were developed using OpenStudio, which utilizes the EnergyPlus simulation engine. EnergyPlus is a widely recognized tool for building energy analysis, capable of generating hourly energy consumption profiles and detailed HVAC system performance metrics. While other HVAC and DHW modeling tools were considered, EnergyPlus was selected for its ability to handle complex building system inputs and outputs required for detailed simulation and analysis.

The baseline for this evaluation was the existing equipment and conditions at each of the two sites. In other words, operational characteristics, capacities, and configurations of the existing systems served as the reference case for comparing the performance of the emerging technology. The team conducted site visits in October 2024 to gather detailed information on existing systems and equipment in consultation with building operators.

Baseline models for each building were calibrated to within ten percent of the actual annual electricity and natural gas consumption using utility billing data. Space heating and DHW were the only end-uses for natural gas and electricity consumption for space cooling was isolated from other building loads for analysis. Hourly heating and cooling load outputs from the baseline simulations were then applied to manufacturer performance maps to evaluate the emerging technology's system performance and to estimate energy usage. These performance maps, developed for the retrofit scenario at each site, considers site-specific weather and operating conditions for every hour of the year.

This modeling approach required several key assumptions:

- Baseline Operation: Existing equipment, occupancy schedules, and control settings observed during site visits and interviews with building staff were assumed to represent normal operating conditions.
- Weather Data: Typical Meteorological Year (TMY3) data for Santa Monica Municipal Airport was used for Site 1 and San Jose International Airport for Site 2.
- Baseline System Efficiency: Manufacturer-rated and documented efficiency for each existing equipment were assumed for modeling purposes.
- Proposed System Efficiency: Manufacturer-tested laboratory efficiencies and corresponding performance maps were used to simulate proposed operating conditions.

Findings

The project team focused on comparing the following variables between baseline and retrofit scenarios for each site:

- Heating and cooling loads for consistency
- Energy consumption in kWh and therms dedicated to HHW, CHW, and DHW use. DHW use was considered for Site 2 only.

From these variables, the team derived annual estimates for:

- Energy savings
- Peak demand reduction
- GHG emissions reduction
- Energy cost savings
- TSB

The team also investigated operational profiles and emerging technology system COP. The HP system always operated in either a heating or cooling priority mode. These operating modes switch to prioritize certain system output so that it can satisfy space heating and cooling demands, accordingly. The findings are presented in the following order for each site:

- Baseline modeling
- Retrofit modeling
- Results

Site 1 Results

BASELINE MODELING

The project team developed a baseline model for Site 1 incorporating a chilled water system, as the site currently uses a DX system for cooling and does not have chilled water infrastructure. This model was used to estimate the site's CHW and HHW demands for data analysis. However, to represent the actual baseline, energy consumption from the existing DX system model was used to calculate energy impacts. Note that DHW was excluded from the analysis for Site 1, making space heating the only natural gas end-use considered.

Figure 14 shows the annual heating and cooling hourly load profiles for Site 1. For visualization purposes, cooling loads are presented in negative values. The site is cooling-dominated with a greater cumulative cooling load that peaks in the summer months. During the year, Site 1 experiences a peak heating load of 542,000 Btu/hr in the winter and a peak cooling load of 706,000 Btu/hr in the summer.

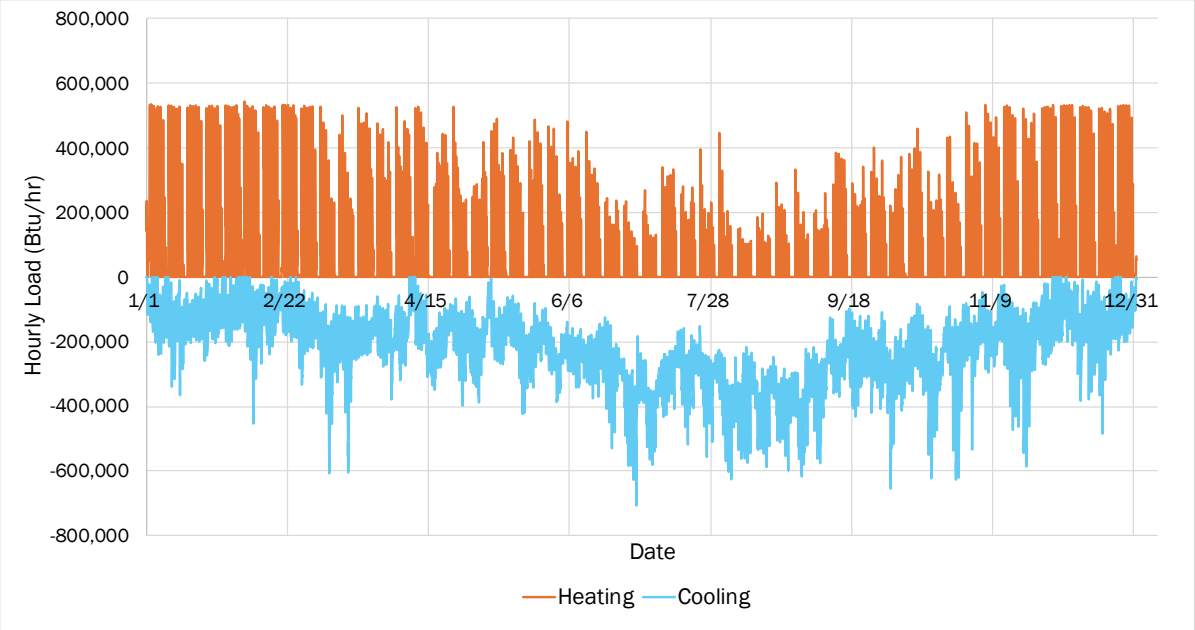

Figure 14: Site 1 annual heating and cooling load profiles

The annual average system COP, calculated as the ratio of total annual system output to total system input, including the contribution of natural gas boilers for heating, is approximately 1.7.

RETROFIT MODELING

The multipurpose CO_2 HP system alternates between heating and cooling priority modes during operation, with monthly runtime for each mode shown in Figure 15. The heating and cooling load established in the baseline model were used directly in the retrofit analysis, so they remain unchanged. At Site 1, the new system operates primarily in cooling priority mode throughout the year, consistent with the site's cooling-dominated load profile.

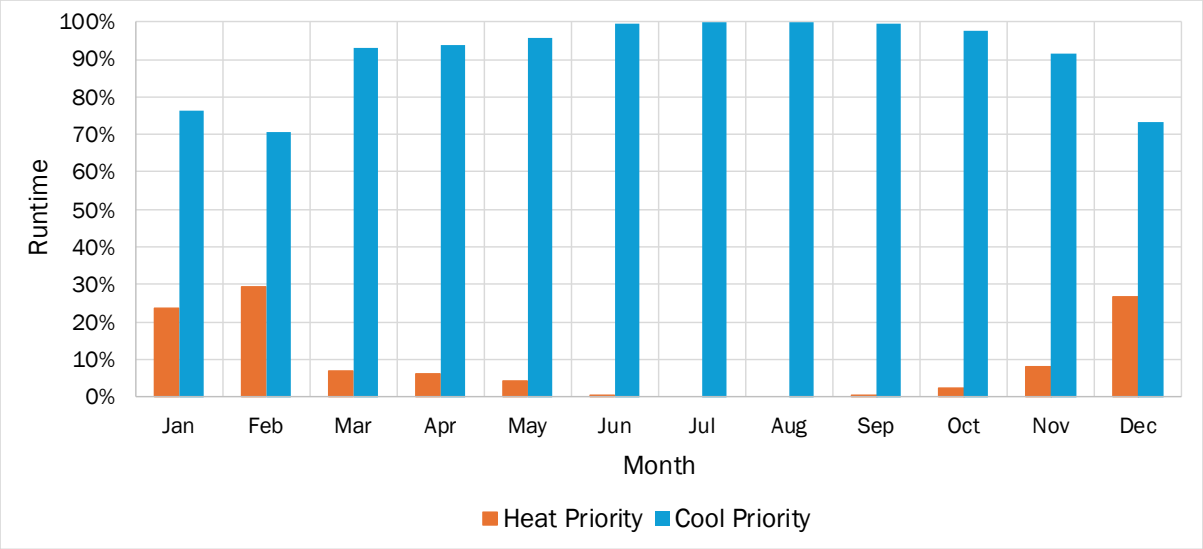

Figure 15: Site 1 monthly runtime percentage for each heat pump operating mode

Figure 16 represents average monthly COPs for the heat pump operating in heating-only, cooling-only, and simultaneous modes. In simultaneous mode, the heat pump provides both heating and cooling. As shown, the average monthly COPs during heating-only or cooling-only modes ranged between 1.2 to 1.6 while COPs during simultaneous mode ranged between 2.7 and 3.4. This indicates heat pump operated more efficiently in simultaneous mode due to its heat recovery capability. This feature is particularly advantageous for a building in moderate climate like Site 1, where simultaneous heating and cooling can occur much of the year. The annual average system COP, calculated as total annual heat pump output divided by input, was 1.9, representing an improvement over the baseline system, which had lower efficiency due to reliance on natural gas boilers.

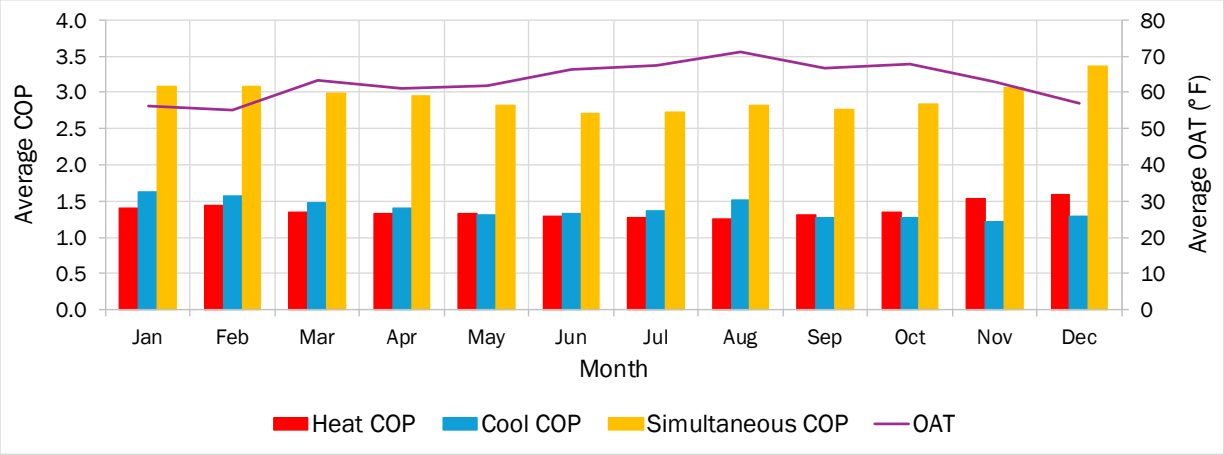

Figure 16: Site 1 average monthly COP and OAT

RESULTS SUMMARY

Table 16 presents a summary of the findings for Site 1.

Table 16: Site 1 Savings Summary

	Cooling Electricity Use (kWh/yr)	Peak Demand (kW)	Heating Gas Use (Therms/ yr)	Total Energy Cost ($/yr)	Total GHG Emissions (tons of CO_2/yr)	TSB ($/yr)
Baseline	104,714	61	4,228	$25,330	30	$16,836
Retrofit	168,188	101	0	$22,973	8	$15,408
Savings (%)	**-63,474 (-61%)**	**-40 (-66%)**	**4,228 (100%)**	**$2,357 (9%)**	**22 (73%)**	**$1,428 (8%)**

At Site 1, the retrofit system demonstrated several benefits, and the following observations were derived from the modeling analysis:

- Energy consumption: The switch from the baseline system to the hydronic multipurpose CO_2 heat pump system increased electricity usage by 61 percent, primarily due to switching the heating source from natural gas to electricity.
- Peak electricity demand: Peak demand, estimated based on maximum hourly consumption during weekday peak period between 4 p.m. and 9 p.m. rose by 66 percent, from approximately 61 kW in the baseline to 101 kW in the retrofit scenario. This increase is also attributed to fuel switching.
- GHG emissions reduction: Hourly GHG analysis indicated that the new system reduced annual emissions by 22 metric tons of CO_2-e by eliminating all natural gas emissions for space heating. The retrofit is projected to achieve a 73% reduction in site GHG emissions.
- Total System Benefit (TSB): TSB is a comprehensive cost-effectiveness metric, accounting for GHG emissions, lifecycle, and other services, and reflects avoided grid and societal costs. For Site 1, the estimated TSB is $1,428 per year, confirming that the technology delivers measurable benefits to utilities, programs, and ratepayers.
- Operational performance: The CO_2 heat pump met heating and cooling demands with ample capacity year-round. It predominantly operated in a cooling-priority mode with 100 percent runtime in this mode between June and September. The system achieved an average simultaneous COP of 2.9, with a maximum COP of 3.4. Compared to the baseline system COP of 1.7, the CO_2 heat pump offers a significant efficiency.

Site 2 Results

BASELINE MODELING

Figure 17 illustrates the annual heating and cooling load profiles for Site 2. This is a multifamily building that provides heating through a HHW loop and cooling through a CHW loop. The site has solar preheating system for DHW and HHW and the existing HHW boilers are locked out when OAT exceeds 70°F, which is reflected in the flat consumption pattern during summer months. The site's

peak heating load is approximately 899,000 Btu/hr and a peak cooling load reaches about 1.06 million Btu/hr.

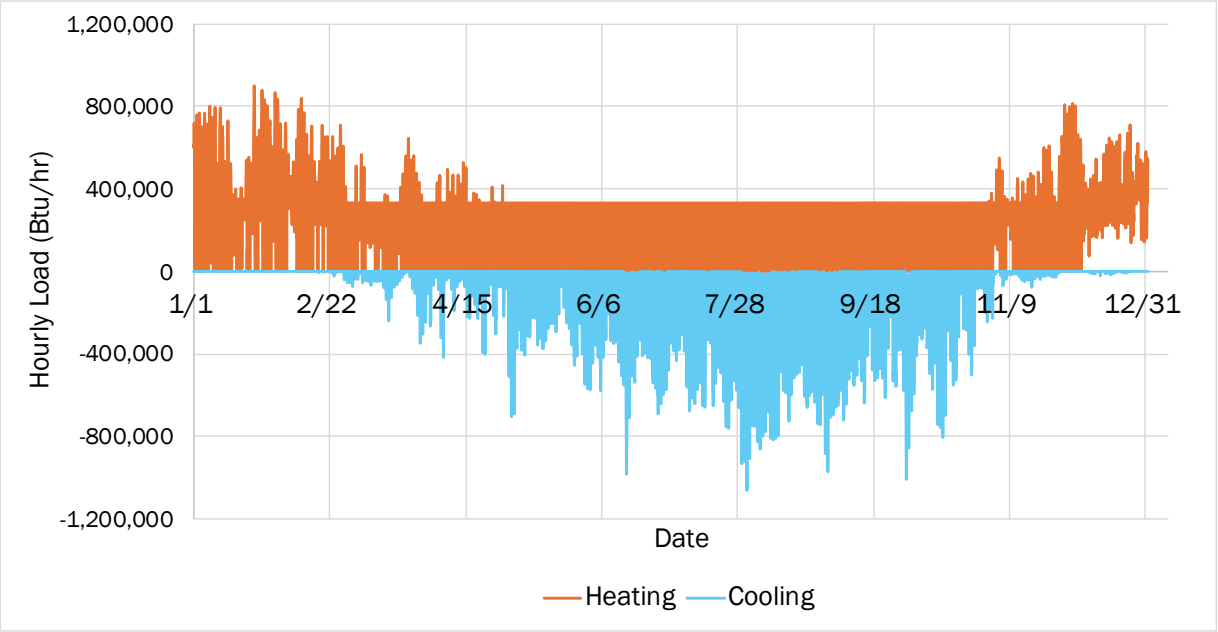

Figure 17: Site 2 annual heating and cooling load profiles

Figure 18 represents the total monthly heating and cooling loads alongside the average OAT for Site 2. Heating loads remain dominant throughout the year, with the peak occurring in January when the average OAT is at its lowest. Based on model results, Site 2's total baseline cooling load is estimated at 883,844 kBtu. The estimated annual cooling electricity consumption is 63,415 kWh with a peak demand of 36 kW. The baseline cooling system operates at an estimated COP of 4.1. When accounting for the gas-fired baseline heating system, the annual average COP is approximately 1.2, which provides a more realistic indicator of system efficiency given the significantly higher annual heating loads compared to cooling loads.

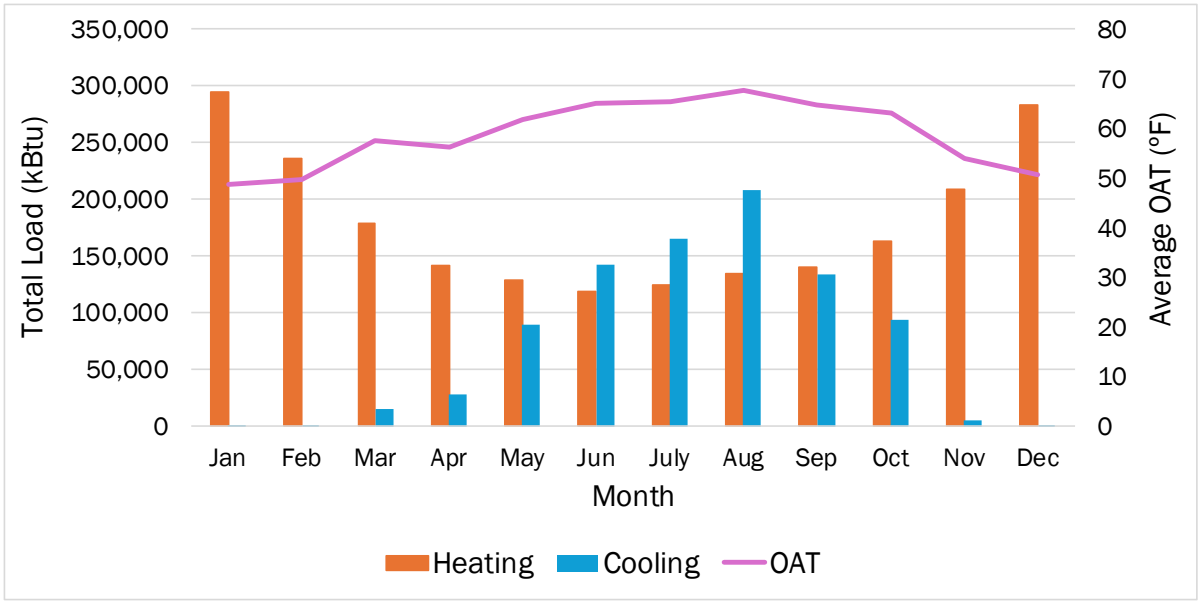

Figure 18: Site 2 monthly total building loads with average OAT

RETROFIT MODELING

The heating and cooling loads calculated in the baseline modeling were directly as inputs to the retrofit modeling at Site 2, therefore they remain unchanged. Figure 19 shows the monthly runtime distribution for the CO_2 heat pump system's operation modes. At site 2, the system predominantly operates in a heating-priority mode throughout the year, with nearly 100% operation in this mode during winter months. The proposed design for Site 2 includes redundancy through secondary HHW and CHW pumps, as well as a backup electric boiler and electric water heaters to meet DHW and HHW demands when the primary system cannot fully satisfy load requirements.

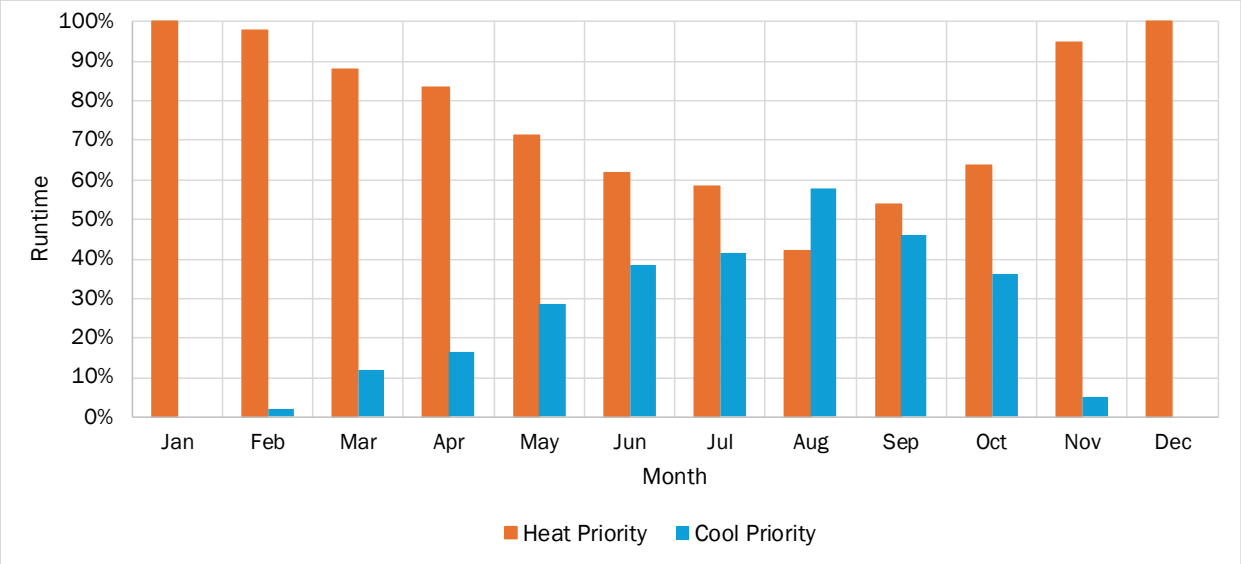

Figure 19: Site 2 monthly runtime percentage for each heat pump operating mode

Figure 20 shows the average monthly COPs for heating-only, cooling-only, and simultaneous operations at Site 2. When the heat pump operated in simultaneous mode, providing both cooling and heating, the average COP values ranged from 2.6 to 2.8. This exceeds the COPs of heating-only and cooling-only operations, highlighting improved performance through heat recovery. Compared to the baseline system's annual average COP of 1.2, the retrofit technology achieved an average COP of 1.5, demonstrating an efficiency improvement.

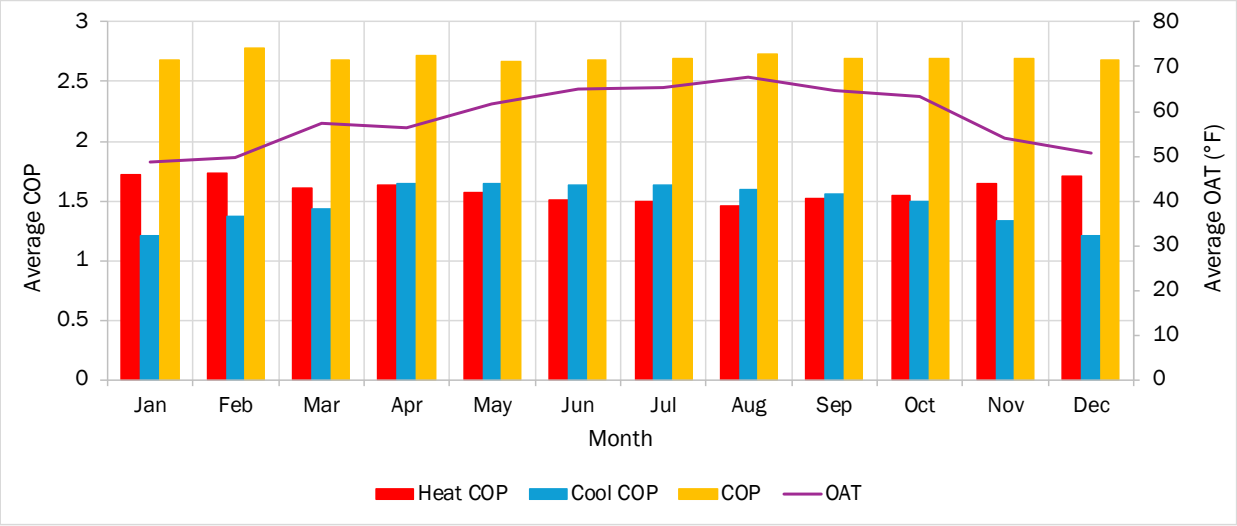

Figure 20: Site 2 average monthly COP and OAT

RESULTS SUMMARY

Table 17 presents a summary of findings for Site 2.

Table 17: Site 2 Savings Summary

	Cooling Electricity Use (kWh/yr)	Peak Demand (kW)	Heating Gas Use (Therms/ yr)	Total Energy Cost ($/yr)	Total GHG Emissions (tons of CO_2/yr)	TSB ($/yr)
Baseline	63,415	36	23,598	$83,678	132	$52,694
Retrofit	602,457	122	0	$245,381	53	$50,434
Savings (%)	**-539,042 (-850%)**	**-86 (-239%)**	**23,598 (100%)**	**-$161,703 (-193%)**	**79 (60%)**	**$2,259 (4%)**

At Site 2, the new system demonstrated the following outcomes based on modeling analysis:

- Energy consumption: Electricity use at Site 2 increased significantly with the operation of the new CO_2 heat pump, primarily because the building is heating-dominant and previously relied on natural gas boiler for space heating. On the gas side, the retrofit allowed natural gas consumption for both space heating and DHW to be fully eliminated, achieving 100% savings and approximately $58,000 in natural gas cost savings. However, these savings were partially offset by increased electricity usage and associated costs.
- Peak electricity demand: Peak demand, estimated during the weekday 4 p.m. to 9 p.m. peak period, rose by approximately 239%, from 36 kW in baseline to 122 kW in retrofit scenario.
- GHG emissions reduction: While GHG emissions from electricity increased, the retrofit eliminated all baseline natural gas emissions. Overall, the site is projected to achieve a 60% reduction in total GHG emissions.
- TSB: The estimated TSB for Site 2 is $2,358 per year, indicating that despite increase in electricity usage, the system still delivers avoided costs and benefits to the site.
- Operational performance: The system primarily operated in heating-priority mode, reflecting consistently higher heating loads throughout the year. The system design included a backup electric boiler, ensuring occupant comfort during periods of high heating demand. The heat pump achieved an average simultaneous COP of 2.7, with a maximum observed COP of 2.8, demonstrating strong efficiency improvement over the baseline.

Discussion

The modeling analysis for two sites demonstrated the potential of the multipurpose hydronic CO_2 heat pump to eliminate natural gas use while efficiently meeting heating, cooling, and DHW demands. Site 1, a commercial office building, has an existing DX system for space cooling, natural gas boilers for space heating, and natural gas water heaters for DHW. The modeling and analysis showed that replacing the cooling and space heating systems with the CO_2 heat pump would

increase electricity consumption from 104,714 kWh to 168,188 kWh, a 61 percent increase, while fully eliminating natural gas use for space heating. The total estimated project cost for Site 1 included an electric boiler for redundancy during peak heating demand; however, its performance was not reflected in the analysis. Additional electrical infrastructure upgrades would be necessary to support the new system, further increasing capital costs.

Site 2, a multifamily building, uses existing air-cooled chiller to provide CHW for space cooling and natural gas condensing boilers and a solar thermal preheating system supplementing the HHW for space heating and DHW. The results indicated that the retrofit would increase electric energy use from 63,415 kWh to an estimated 602,457 kWh. Site 2 had significantly higher baseline heating loads than cooling, likely contributing to the higher electricity consumption after the retrofit. Site 2's retrofit design also included multiple backup systems for HHW, CHW, and DHW, increasing cost. Despite this, the site achieved GHG emissions reductions and total system benefit (TSB) by eliminating natural gas use.

Estimated energy savings at both sites would not offset total capital costs for a full cost retrofit replacement within the system's lifetime. However, in a new construction situation or for incremental costs over a more conventional system replacement, the cost-benefit analysis would be markedly different. Also, several non-energy benefits warrant further investigated at scale:

- Low GWP and strong performance characteristics of CO_2 as a refrigerant
- High-efficiency heating, cooling, and DHW, including heat recovery opportunities
- Compact, packaged design for simpler installation, operation, and maintenance

It is important to note that existing systems at both sites are nearing their end of their service life and will require a replacement, regardless. The technology's ability to consolidate multiple heating and cooling systems into a single solution may make it cost-competitive, especially when energy efficiency and decarbonization benefits are considered. Incremental cost, defined as the difference between the retrofit technology cost and a comparative code-compliant or industry-standard system cost, should be evaluated to determine customer value for future projects. Also, real-world performance data and optimization approaches should be further investigated through follow-up field demonstrations across a broader range of buildings types.

Despite the large energy saving and GHG potential and associated benefits, the widespread adoption of the technology needs additional study and demonstration that can address the following uncertainties and thus lend confidence to early-adopters:

- High retrofit costs, particularly when a full system conversion is required (e.g., replacing a distributed refrigerant system with a hydronic system).
- Limited familiarity with CO_2 refrigerant in hydronic central plants.
- Need for empirical, proven performance in real-world, in situ settings.
- Cost savings due to central plant equipment consolidation, reduced electrical infrastructure needs, and simpler on-site installation.
- Lack of field demonstrations and case studies.
- Unknown long-term performance and useful life.
- Lack of well-defined best practices for installation, operation, and maintenance.

Recommendations

This study provides an initial perspective on emerging technology's application-specific system costs, controls integration, sizing, and impacts for retrofit installations and equipment operation, based on two host sites: an office building and a multifamily building. Through building energy modeling and analyses, the study provides deeper insight into potential energy savings, decarbonization benefits, and cost impacts with this technology in retrofit applications. However, to address remaining uncertainties, further investigation through field demonstrations, testing, and validation is needed to support early adoption.

The following recommendations are proposed to improve as next steps for the adoption of multipurpose CO_2 heat pumps:

- Validate performance data with laboratory results: Manufacturer-supplied performance curves were used to estimate energy usage for the proposed retrofit. A third-party national lab is currently validating these curves with laboratory testing, though this was not completed within the project timeline. Completing this validation should be a priority to confirm findings and identify future research needs.
- Design considerations: A primary benefit of CO_2 heat pumps is their ability to produce 180°F water, making them suitable for retrofitting buildings that require high-temperature water for their hydronic systems. Since efficiency improves with lower entering water temperatures, designers should incorporate strategies to reduce these temperatures, such as outdoor air temperature-based supply reset and increasing temperature differentials across terminal equipment.
- Expand pilot programs and demonstrations: Conduct pilot field demonstrations in diverse buildings and climate zones to validate real-world performance. A small-scale study in California could provide more accurate estimates of total system benefit (TSB), GHG emissions reduction, energy cost impacts, and energy savings. Field testing should also explore optimization strategies for COP, heat recovery opportunities, and best practices for utility programs and customers pursuing electrification and decarbonization.
- Define and compare incremental costs: Compare retrofit costs of this emerging technology to code-compliant alternatives, focusing on incremental costs rather than total system costs. Energy cost savings relative to baseline systems may justify additional upfront investment, which warrants further analysis.
- Standardize technology cost and implementation: Collaborate with manufacturers to standardize equipment sizing and installation costs. Engage utilities to develop rebate and incentive programs as more data on energy impacts and cost-effectiveness becomes available.
- Education and training: Disseminate study findings through publications, conferences, and utility-sponsored outreach to close knowledge gaps among HVAC designers and building owners. Support initiatives that provide training and resources for contractors, which can reduce costs and improve accessibility for customers.

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Appendix A: Manufacturer Product Data

The multipurpose HP referenced throughout this report uses CO_2 as a refrigerant and can produce HHW, CHW and DHW simultaneously. Figure 21 and Figure 22 detail the multipurpose HP product data.

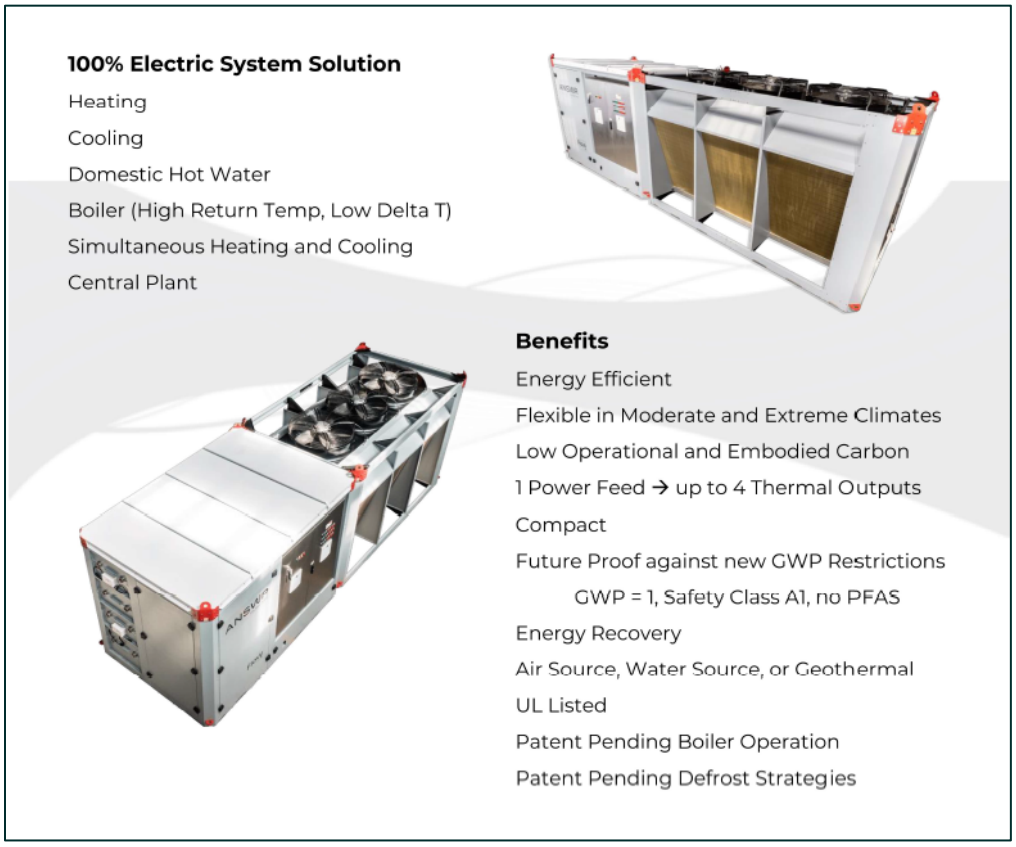
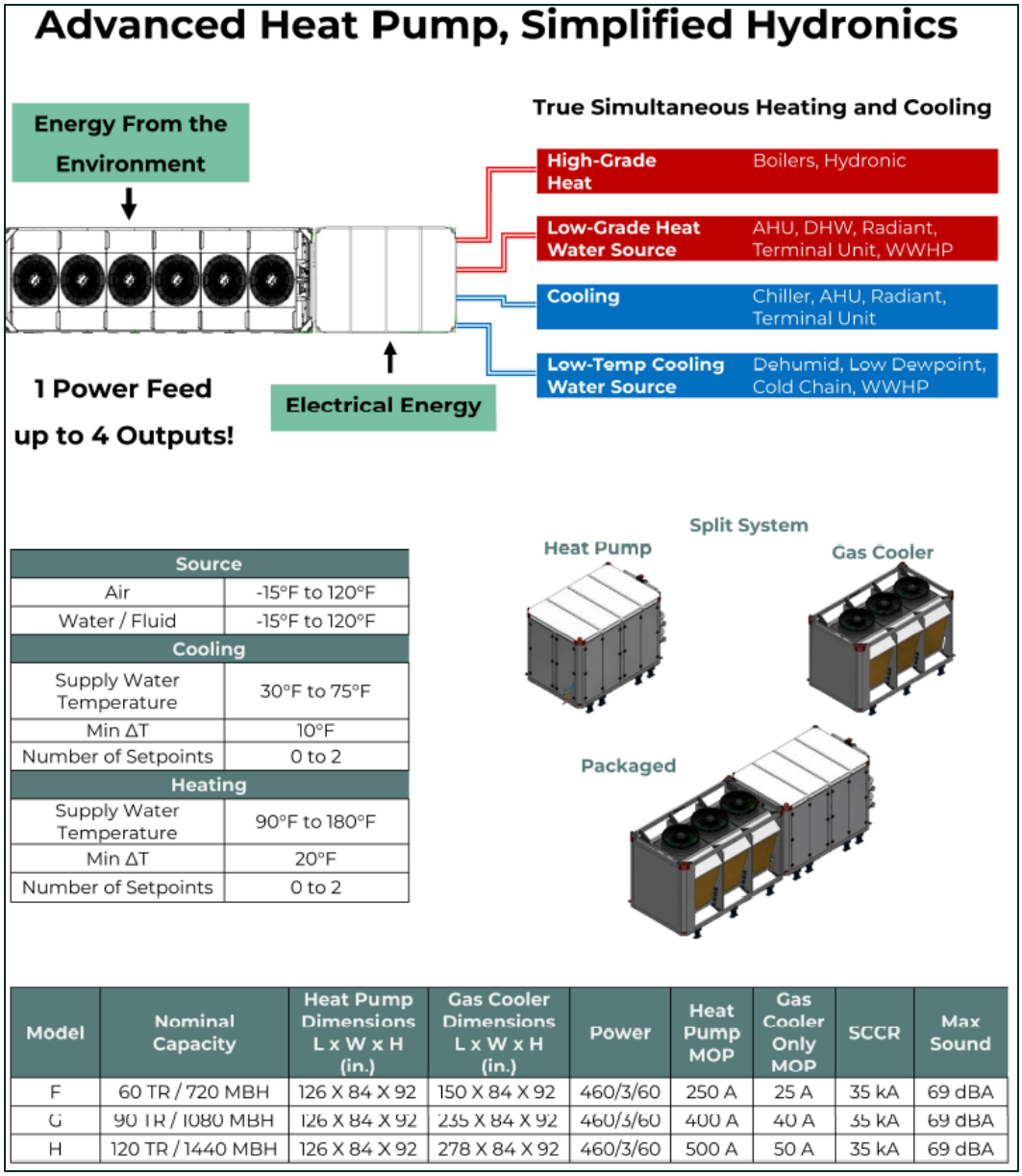


Figure 21: Multipurpose CO2 HP product details.

Source: Manufacturer



Source	
Air	-15°F to 120°F
Water / Fluid	-15°F to 120°F
Cooling	
Supply Water Temperature	30°F to 75°F
Min ΔT	10°F
Number of Setpoints	0 to 2
Heating	
Supply Water Temperature	90°F to 180°F
Min ΔT	20°F
Number of Setpoints	0 to 2

Model	Nominal Capacity	Heat Pump Dimensions L x W x H (in.)	Gas Cooler Dimensions L x W x H (in.)	Power	Heat Pump MOP	Gas Cooler Only MOP	SCCR	Max Sound
F	60 TR / 720 MBH	126 X 84 X 92	150 X 84 X 92	460/3/60	250 A	25 A	35 kA	69 dBA
G	90 TR / 1080 MBH	126 X 84 X 92	235 X 84 X 92	460/3/60	400 A	40 A	35 kA	69 dBA
H	120 TR / 1440 MBH	126 X 84 X 92	278 X 84 X 92	460/3/60	500 A	50 A	35 kA	69 dBA

Figure 22: Multipurpose CO2 HP product specifications.

Source: Manufacturer

Appendix B: Detailed Cost Proposals

Host Site 1

Scope of Work

EcoCosm shall provide the labor and material an perform the work as described in this Agreement.

Preconstruction

Provide constructions documents stamped by a Professional Engineer
Procure permits

Construction

Supply and deliver the [redacted] 120 ton heat pump
Storage, transport, and rig the heat pump to the roof
Supply up to two crane lifts to remove old equipment and deliver new equipment to the roof. Street closure and traffic control
Isolate, disconnect and remove old equipment, piping, DX coils
Supply and install a new steel support frame to support the heat pump. Provide shop drawings
Anchor the steel frame to the roof joists and secure the heat pump to the frame
Patch the roof around the frame
Supply new pumps, buffer tanks and coils. Secure pumps and tanks new housekeeping pads
Supply & install new chilled water and hot water piping. Test new piping
Install new condensate drain piping and other piping accessories.
Insulate new piping, valves, and equipment.
Provide power for new equipment including circuit breakers, conduit and wire, and a new 208V/3-phase distribution panel
Label the new equipment, valves, piping, and electrical circuits.
Integrate controls and sequences into the existing BMS. Installation of new low voltage conduit and wire. Update the BMS graphics and set up data logs
Participate in startup and functional performance testing. Support commissioning provided by EcoCosm
Provide closeout permits, issue equipment warranties, start up and test reports and as-built drawings

Startup and Performance Testing

Start-up package and O&M manuals need to be provided in advance of start-up work
Provide factory authorized start-up of the new chiller.
Provide (64) hours of commissioning functional performance testing
Commissioning

Training and Turnover

Provide eight hours of customer training in the operation of the new equipment and controls
Provide customer training in the operation of the new equipment and controls.
Issue closeout package including O&M manuals, start-up reports, as well as commissioning report, and training notes with guidance on warranty and service to provide a complete transition to warranty phase. Material provided in electronic format

Total	**$2,560,000**

Alternate-1 Supply & Install Electric Boiler

Supply and install one 1228 MBH (360 kW) Aerco Electric Boiler
Supply and install a new 500A/3P, 480V breaker in the main switchboard
Piping, insulation, jacketing, valving, labeling, and controls
Factory start-up and testing
Closeout package: as-builts, start-up & test reports, O&M manual, & warranties

Pricing assumes leveraging the crane lifts and other economies of scale with the heat pump installation.

Total	**$500,000**

Host Site 2

Scope of Work

EcoCosm shall provide the labor and material an perform the work as described in this Agreement.

Preconstruction

Provide constructions documents stamped by a Professional Engineer
Procure permits

Construction

Supply and deliver the [redacted] 120 ton heat pump
Storage, transport, and rig the heat pump to the roof
Supply up to two crane lifts to remove old equipment and deliver new equipment to the roof. Street closure and traffic control
Isolate, disconnect and remove old equipment, piping, DX coils
Supply and install a new steel support frame to support the heat pump. Provide shop drawings
Anchor the steel frame to the roof joists and secure the heat pump to the frame
Patch the roof around the frame
Supply new pumps, buffer tanks and coils. Secure pumps and tanks new housekeeping pads
Supply & install new chilled water and hot water piping. Test new piping
Install new condensate drain piping and other piping accessories.
Insulate new piping, valves, and equipment.
Supply and install new Aerco Electric Boiler
Provide power for new equipment including circuit breakers, conduit and wire, and a new 208V/3-phase distribution panel
Label the new equipment, valves, piping, and electrical circuits.
Integrate controls and sequences into the existing BMS. Installation of new low voltage conduit and wire. Update the BMS graphics and set up data logs
Participate in startup and functional performance testing. Support commissioning provided by EcoCosm
Provide closeout permits, issue equipment warranties, start up and test reports and as-built drawings

Startup and Performance Testing

Start-up package and O&M manuals need to be provided in advance of start-up work
Provide factory authorized start-up of the new chiller.
Provide (64) hours of commissioning functional performance testing
Commissioning

Training and Turnover

Provide eight hours of customer training in the operation of the new equipment and controls
Provide customer training in the operation of the new equipment and controls.
Issue closeout package including O&M manuals, start-up reports, as well as commissioning report, and training notes with guidance on warranty and service to provide a complete transition to warranty phase. Material provided in electronic format

Total	**$2,600,000**

Appendix C: Proposed Design Equipment Details

Host Site 1

The heat pump ratings for Site 1 can be found in Figure 23. Capacities and system COP are highlighted in green.

Special Notes	Model H ASHP 120TR nom.					
Application Rating						
Condition Number		1	2	3	4	5
ID	**Condition Name**	**Heat #1 Only**	**Cool #1 Only**	**Cool #1 Only**	**Cool #2 Only**	**0.0**
Source	OAT DB or Water Supply Temp (°F)	35.0	35.0	94.0	94.0	0.0
	OAT WB or Water Return Temp (°F)	0.0	0.0	70.0	70.0	0.0
Cool #1	Evaporator Capacity (MBH)	0	0	1,239	1,213	0
	Cooling COP (W/W)	0.0	0.0	3.6	3.5	0.0
	Cooling EER (MBH/KW)	0.0	0.0	12.4	11.8	0.0
	Cooling (KW/Ton)	0.0	0.0	1.0	1.0	0.0
	IPLV	0.0	0.0	0.0	0.0	0.0
	Cooling Media #1	Water	Water	Water	Water	0.0
	Cooling Inlet Water Conditions (°F)	0.0	0.0	54.0	54.0	0.0
	Cooling Outlet Water Conditions (°F)	0.0	0.0	44.0	42.0	0.0
	Cooling #1 Flow Rate (GPM)	0	0	248	202	0
	Cooling #1 Min Pipe Size (in.)	0.0	0.0	4.0	4.0	0.0
	Adiabatic Water Flow Rate (gpm)	0.0	0.0	3.7	3.6	0.0
Heat #1	Heating Capacity #1 (MBH)	1,105	896	0	0	0
	Heating Media #1	PG 20%	PG 20%	PG 20%	PG 20%	0.0
	Heating #1 Inlet Water Conditions (°F)	140.0	150.0	-	-	0.0
	Heating #1 Outlet Water Condition (°F)	180.0	180.0	-	-	0.0
	Heating #1 Flow Rate (GPM)	55	60	0	0	0
	Heating #1 Min Pipe Size (in.)	2.0	2.0	0.0	0.0	0.0
Heat #2	Heating Capacity #2 (MBH)	0	0	0	0	0
	Heating Media #2	Water	Water	Water	Water	0.0
	Heating Inlet #2 Water Conditions (°F)	0.0	0.0	0.0	0.0	0.0
	Heating Outlet #2 Water Condition (°F)	0.0	0.0	0.0	0.0	0.0
	Heating #2 Flow Rate (GPM)	0	0	0	0	0
	Heating #2 Min Pipe Size (in.)	0.0	0.0	0.0	0.0	0.0
Total Heat	COP Total Heating (W/W)	1.6	1.3	0.0	0.0	0.0
	COP Simultaneous (W/W)	1.6	1.3	3.6	3.5	0.0
Electrical	Power (KW)	205	205	100	102	0
	MCA System (HP+subfed GC) (A)	383	383	297	298	0
	MOP System (HP+subfed GC) (A)	400	400	400	400	0
	MCA Heat Pump Only (A)	354	354	269	270	0
	MOP Heat Pump Only (A)	400	400	400	400	0
	MCA GC Only (A)	29	29	29	29	0
	MOP GC Only (A)	50	50	50	50	0

	Heat Pump Physical	Gas Cooler Physical
Electrical Supply	460V / 3PH / 60 Hz	460V / 3PH / 60 Hz
SCCR (kA)	35	35
Dimensions L X W X H (inches)	126 X 84 X 92	278 X 84 X 92
Weight Dry (lbs)	5,700	4,524
Weight Wet (lbs)	6,200	4,599
Sound (dBA)	67	69

Figure 23: Multipurpose CO_2 HP rating for Site 1

The backup boiler specifications for Site 1 are outlined in blue in Figure 24.

Equipment Tag: EB-1

Specifications and Dimensions

	Benchmark E				
	216 kW (737 MBH)	360 kW (1228 MBH)	432 kW (1474 MBH)	576 kW (1965 MBH)	684 kW (2334 MBH)
Boiler Category	ASME Sect.IV				
Max. Allowed Working Pressure	150 PSIG				
Electrical Req. 480V/3PH/60Hz	260 A	433 A	520 A	693 A	823 A
Electrical Req. 600V/3PH/60Hz	208 A	347 A	416 A	555 A	659 A
Number of Elements	12	20	24	32	38
Number of Stages	6	10			
Water Connect. (Flanged)	4"				
Max. Water Flow (GPM)	350				
Water Volume Gallons	140				
Temp. Control Range	50°F to 220°F				
Ambient Temp. Range	0°F to 130°F				
Standard Listings & Approvals	ASME, UL-834, CSA-C22.2 No. 165, CSD-1				
Dry Weight	1450 lb				
Shipping Weight	1700 lb				
Width	34"				
Depth	56"				
Height	78"				

Figure 24: Backup boiler specifications for Site 1

Portions of the roof plans at Site 1 are included in Figure 25 to show existing equipment demolition and in Figure 26 and Figure 27 to show new equipment installation.

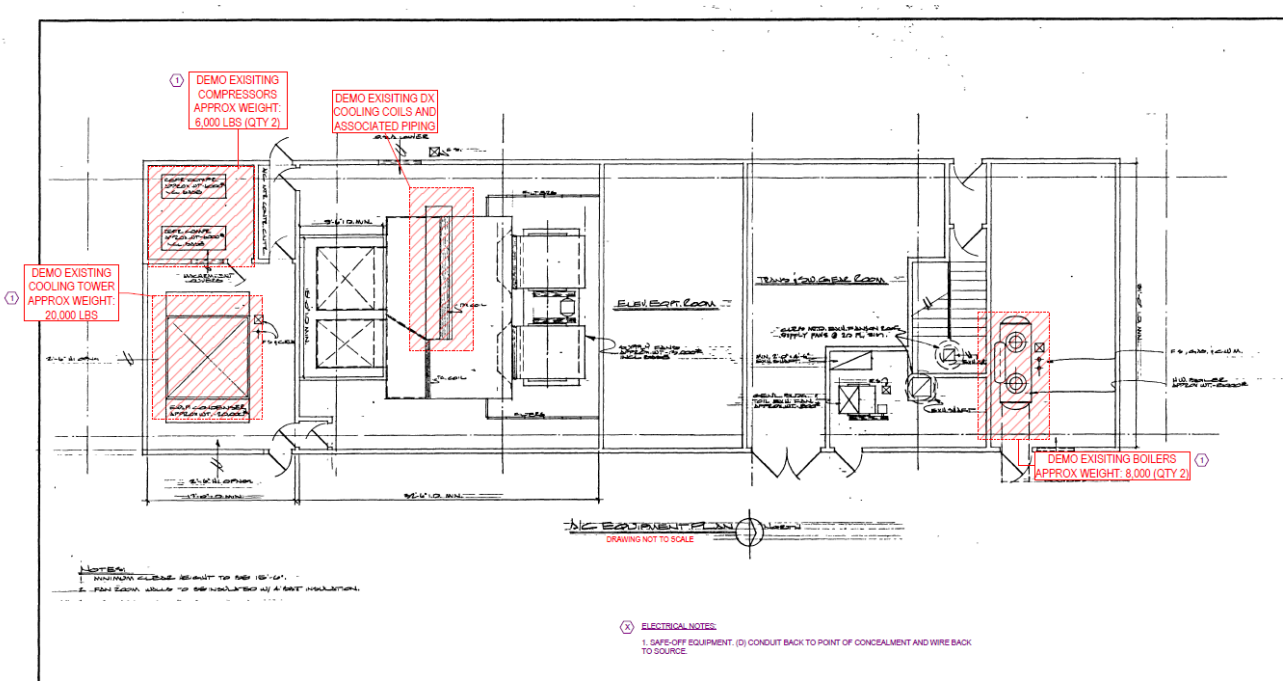


Figure 25: Existing equipment demolition plan for Site 1

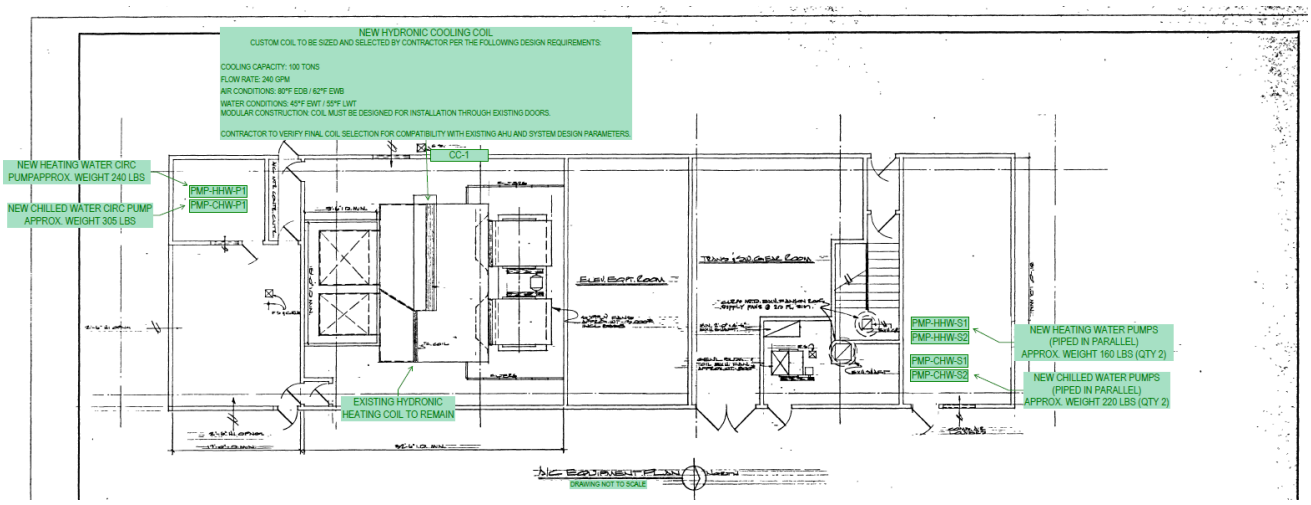


Figure 26: Proposed equipment plan for Site 1

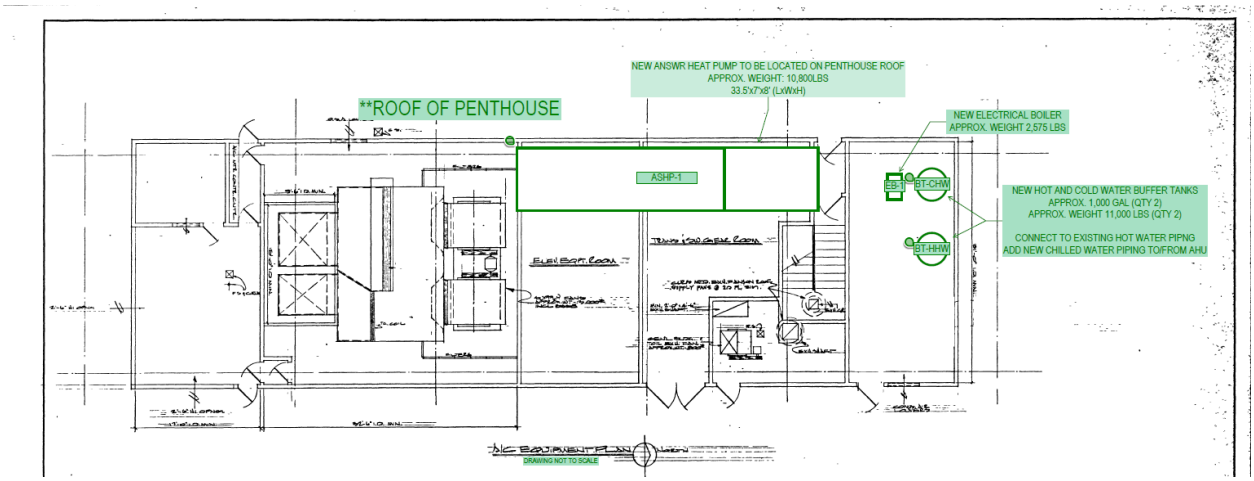


Figure 27: Proposed equipment plan for Site 1 – additional detail

Host Site 2

The heat pump ratings for Site 2 can be found in Figure 28. Capacities and system COP are highlighted in green and are the same for both sites.

Special Notes	Model H ASHP 120TR nom.					
Application Rating						
Condition Number		1	2	3	4	5
ID	**Condition Name**	**Heat #1 Only**	**Cool #1 Only**	**Cool #1 Only**	**Cool #2 Only**	**0.0**
Source	OAT DB or Water Supply Temp (°F)	35.0	35.0	94.0	94.0	0.0
	OAT WB or Water Return Temp (°F)	0.0	0.0	70.0	70.0	0.0
Cool #1	Evaporator Capacity (MBH)	0	0	1,239	1,213	0
	Cooling COP (W/W)	0.0	0.0	3.6	3.5	0.0
	Cooling EER (MBH/KW)	0.0	0.0	12.4	11.8	0.0
	Cooling (KW/Ton)	0.0	0.0	1.0	1.0	0.0
	IPLV	0.0	0.0	0.0	0.0	0.0
	Cooling Media #1	Water	Water	Water	Water	0.0
	Cooling Inlet Water Conditions (°F)	0.0	0.0	54.0	54.0	0.0
	Cooling Outlet Water Conditions (°F)	0.0	0.0	44.0	42.0	0.0
	Cooling #1 Flow Rate (GPM)	0	0	248	202	0
	Cooling #1 Min Pipe Size (in.)	0.0	0.0	4.0	4.0	0.0
	Adiabatic Water Flow Rate (gpm)	0.0	0.0	3.7	3.6	0.0
Heat #1	Heating Capacity #1 (MBH)	1,105	896	0	0	0
	Heating Media #1	PG 20%	PG 20%	PG 20%	PG 20%	0.0
	Heating #1 Inlet Water Conditions (°F)	140.0	150.0	-	-	0.0
	Heating #1 Outlet Water Condition (°F)	180.0	180.0	-	-	0.0
	Heating #1 Flow Rate (GPM)	55	60	0	0	0
	Heating #1 Min Pipe Size (in.)	2.0	2.0	0.0	0.0	0.0
Heat #2	Heating Capacity #2 (MBH)	0	0	0	0	0
	Heating Media #2	Water	Water	Water	Water	0.0
	Heating Inlet #2 Water Conditions (°F)	0.0	0.0	0.0	0.0	0.0
	Heating Outlet #2 Water Condition (°F)	0.0	0.0	0.0	0.0	0.0
	Heating #2 Flow Rate (GPM)	0	0	0	0	0
	Heating #2 Min Pipe Size (in.)	0.0	0.0	0.0	0.0	0.0
Total Heat	COP Total Heating (W/W)	1.6	1.3	0.0	0.0	0.0
	COP Simultaneous (W/W)	1.6	1.3	3.6	3.5	0.0
Electrical	Power (KW)	205	205	100	102	0
	MCA System (HP+subfed GC) (A)	383	383	297	298	0
	MOP System (HP+subfed GC) (A)	400	400	400	400	0
	MCA Heat Pump Only (A)	354	354	269	270	0
	MOP Heat Pump Only (A)	400	400	400	400	0
	MCA GC Only (A)	29	29	29	29	0
	MOP GC Only (A)	50	50	50	50	0

	Heat Pump Physical	Gas Cooler Physical
Electrical Supply	460V / 3PH / 60 Hz	460V / 3PH / 60 Hz
SCCR (kA)	35	35
Dimensions L X W X H (inches)	126 X 84 X 92	278 X 84 X 92
Weight Dry (lbs)	5,700	4,524
Weight Wet (lbs)	6,200	4,599
Sound (dBA)	67	69

Figure 28: Multipurpose CO2 HP rating for Site 2

The backup boiler specifications for Site 2 are outlined in blue in Figure 29.

Specifications and Dimensions

	Benchmark E				
	216 kW (737 MBH)	360 kW (1228 MBH)	432 kW (1474 MBH)	576 kW (1965 MBH)	684 kW (2334 MBH)
Boiler Category	ASME Sect.IV				
Max. Allowed Working Pressure	150 PSIG				
Electrical Req. 480V/3PH/60Hz	260 A	433 A	520 A	693 A	823 A
Electrical Req. 600V/3PH/60Hz	208 A	347 A	416 A	555 A	659 A
Number of Elements	12	20	24	32	38
Number of Stages	6	10			
Water Connect. (Flanged)	4"				
Max. Water Flow (GPM)	350				
Water Volume Gallons	140				
Temp. Control Range	50°F to 220°F				
Ambient Temp. Range	0°F to 130°F				
Standard Listings & Approvals	ASME, UL-834, CSA-C22.2 No. 165, CSD-1				
Dry Weight	1450 lb				
Shipping Weight	1700 lb				
Width	34"				
Depth	56"				
Height	78"				

Figure 29: Backup boiler specifications for Site 2

Portions of the roof plans at Site 2 are included in Figure 30 and Figure 31 to show existing equipment demolition and new equipment installation respectively.

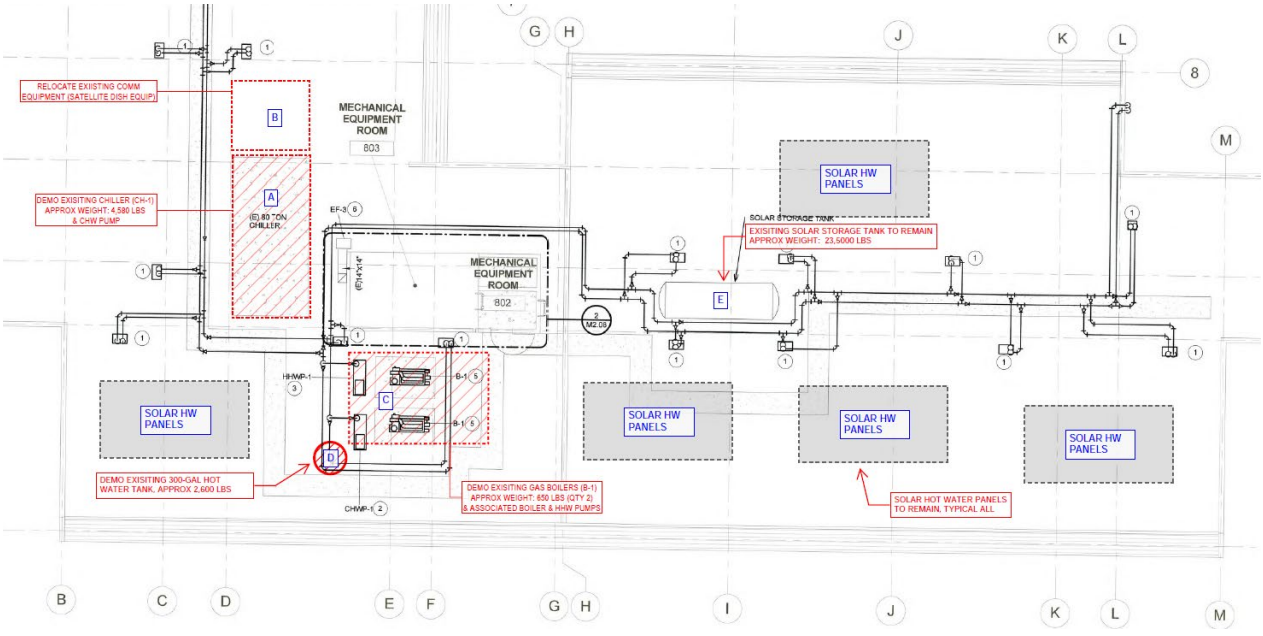


Figure 30: Existing equipment demolition plan for Site 2

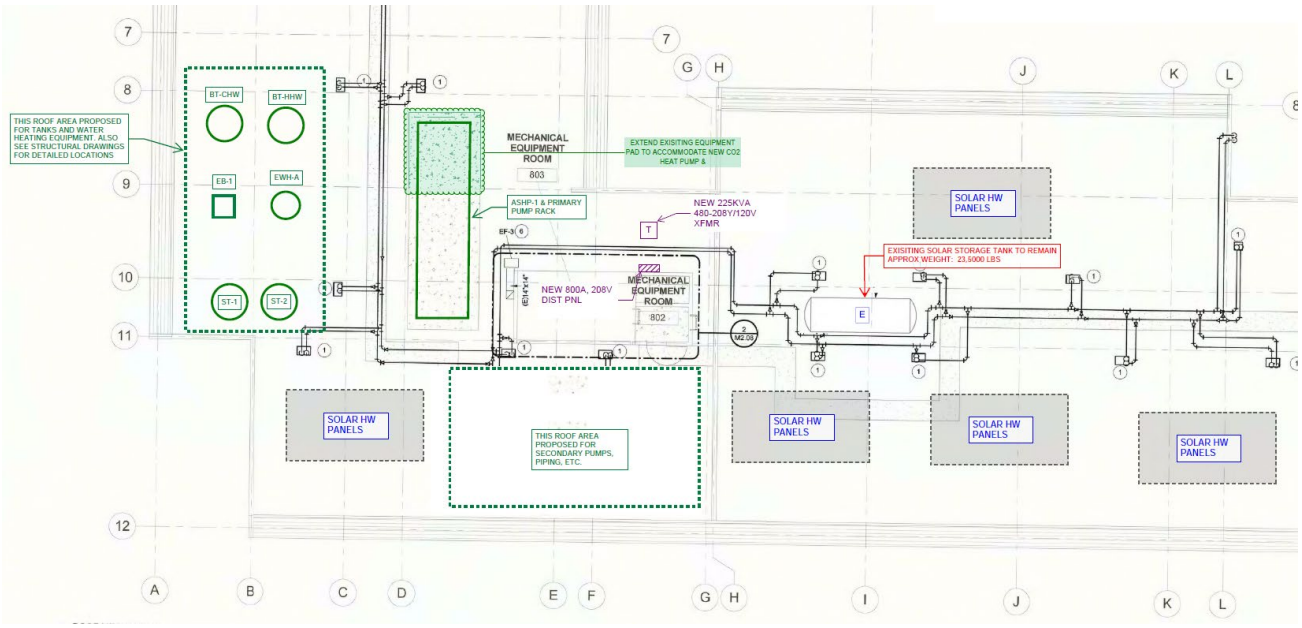


Figure 31: Proposed equipment plan for Site 2

Appendix D: Site 1 Control Sequences

Control sequences for heating hot water and chilled water at Site 1 are the following:

Heating Hot Water Sequences

- All setpoints and time delays included in this sequence shall be adjustable.
- The HHW system shall be enabled based on a call for heating from the AHU. A call for heating shall be interpreted as a HHW valve command of five percent or greater. The HHW system shall be disabled if the valve position is less than five percent.
- The initial and minimum HHW supply temperature setpoint shall be 140°F.
- The HHW supply pump speed shall start at 25 percent and modulate to maintain the AHU hot deck supply air temperature setpoint, as a first stage.
- If the HHW supply pump speed command reaches 100 percent, a second stage control shall increase the HHW temperature setpoint.
    - For every minute the hot deck supply air temperature is more than 1°F below the setpoint, increase the HHW temperature setpoint by 1°F. The maximum HHW temperature setpoint shall be 180°F.
    - If the hot deck supply air temperature is within 1°F of the setpoint, maintain the HHW temperature setpoint.
    - For every minute the hot deck supply temperature is more than 1°F above the setpoint, decrease the HHW temperature setpoint by 1°F.
    - Once the HHW temperature setpoint has been at 140°F for more than ten minutes, the HHW pump speed shall modulate to control the hot deck supply air temperature setpoint, returning to first stage operation.

Chilled Water System Sequences

- All setpoints and time delays included in this sequence shall be adjustable.
- The CHW system shall be enabled based on a call for cooling from the AHU. A call for cooling shall be interpreted as a CHW valve command of five percent or greater. The CHW system shall be disabled if the valve position is less than five percent.
- The initial and maximum CHW supply temperature setpoint shall be 54°F.
- The CHW supply pump speed shall start at 25 percent and modulate to maintain the AHU cold deck supply air temperature setpoint, as a first stage.
- If the CHW supply pump speed command reaches 100 percent, a second stage control shall decrease the chilled water supply temperature setpoint.
    - For every minute the cold deck supply temperature is more than 1°F above the setpoint, decrease the CHW temperature setpoint by 1°F. The minimum supply water temperature setpoint shall be 44°F.
    - If the cold deck supply air temperature is within 1°F of the setpoint, maintain the CHW temperature setpoint.
    - For every minute the cold deck supply temperature is more than 1°F below the setpoint, increase the CHW temperature setpoint by 1°F.

- Once the CHW temperature setpoint has been at 54°F for more than ten minutes, the CHW supply pump speed shall modulate to control the cold deck supply air temperature setpoint, returning to first stage operation.