CalNEXT
ENERGIZING CALIFORNIA'S FUTURE

Nonresidential Heat-Recovery Chiller and Air-to-Water Heat Pump Measure Package Development

Final Report

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Disclaimer

Executive Summary

To fulfill California's ambitious goal of decarbonizing the built environment by midcentury, Energy Solutions has partnered with the California investor-owned electric utilities (Pacific Gas & Electric, Southern California Edison, and San Diego Gas & Electric) to expand the California Electronic Technical Reference Manual (eTRM) by adding measure packages that focus on hydronic air-to-water heat pump and heat-recovery chiller (HRC) technologies. These technologies are commercially available and being leveraged by designers and are ready for addition to the utility portfolio to boost visibility and market share.

This report documents the snapshots of the detailed literature review of the existing studies and manufacturer literature related to hydronic electric space heating equipment, including air-to-water heat pump (AWHP) and heat-recovery chiller (HRC) equipment. This included published articles and reports from the Department of Energy (DOE), CalNEXT, ASHRAE, equipment designers and consultants, and other stakeholders. This research helped the project team to converge on some specific systems that are useful in certain situations and helped us to decide on the base cases and the measure cases.

The project team reviewed several case studies of the field installations of AWHPs and HRCs as retrofit studies that were extremely helpful in understanding the underlying issues, motivation, challenges, energy and cost savings and the application of such systems. Based on the market research regarding the level of maturity of such products, their market availability, and the status of modelling approaches, the team developed a set of possible measure offerings that can be pursued in the near term. As a result, the team has tentatively concluded that it is appropriate to pursue one measure package covering hydronic fuel substitution offerings at this stage, however, based on the developments in this emerging field, it may expand to 2 or more measure packages in the future to accommodate other possible designs and options.

The current approach considers large commercial buildings with multizone Heating, Ventilating and Air-Conditioning (HVAC) systems and natural gas fired boilers that can be retrofitted either partially or fully with AWHPs and/or Water-to-Water Heat Pump Heat Recovery Chiller (WWHRC) systems with the following attributes-

- In partial decarbonization, we intend to impose requirements to monitor the remaining boiler runtime hours so the building owner can effectively plan out the second phase to complete electrification,
- For full electrification, the site should be ready, e.g., the electric panel capacity doesn't need to increase, the site uses water-to-air heat pumps (WAHPs) for zone conditioning, measures that include simultaneous mechanical heat recovery.

The team engaged with the stakeholders, e.g., the California Technical Forum (Cal TF) and equipment manufacturers/distributors, during the course of investigation. The team presented the findings of their research along with the thoughts of proposed measures to the Measure Screening Committee (of Cal TF) meeting on September 19, 2024. The committee's feedback was very encouraging, and the committee wished to review the complete measure plan on AWHPs next year. The team shared the slide deck with all stakeholders after the meeting.

Based on the market assessment and feedback from stakeholders, the team is proposing to carry out a total of 14 measures in three phases. Phase I (near-term), Phase II (mid-term), and Phase III (long-term) may possibly undertake about three measures, six measures and five measures respectively.

Abbreviations and Acronyms

Acronym	Meaning
AC	Air Conditioner
ACC	Air Cooled Chiller
AHRI	Air Conditioning. Heating and Refrigeration Institute
AHU	Air Handling Unit
ASHP	Air-Source Heat Pump
AWHP	Air-to-Water Heat Pump
BMS	Building Management System
CA	California
Cal TF	California Technical Forum
CBECC	California Building Energy Code Compliance
CEE	Consortium of Energy Efficiency
CET	Cost Effectiveness Tool
CHW	Chilled Water
COP	Co-efficient of Performance
CPUC	California Public Utilities Commission
DAC	Disadvantaged Communities
DEER	Database for Energy Efficient Resources
EE	Energy Efficiency
EIR	Energy Input Ratio
ER	Electric Resistance

Acronym	Meaning
ET	Emerging Technologies
eTRM	California Electronic Technical Reference Manual
EXV	Electronic Expansion Valve
FCU	Fan Coil Unit
GHG	Green House Gas
GLHE	Ground Loop Heat Exchange
GWP	Global Warming Potential
HP	Heat Pump
HR	Heat Recovery
HRC	Heat-Recovery Chiller
HTR	Hard-to-reach
HVAC	Heating, Ventilating and Air Conditioning
HW	Hot Water
IMC	Incremental Measure Cost
IOU	Investor-Owned Utility
kW, kWh	kilowatts, kilowatt-hours
MPP	Measure Package Plan
PA	Program Administrator
PG&E	Pacific Gas & Electric
PLR	Part Load Ratio
SCE	Southern California Edison

Acronym	Meaning
SDGE	San Diego Gas & Electric
TES	Thermal Energy Storage
TPM	Technology Priority Map
TXV	Thermostatic Expansion Valve
UES	Unit Energy Savings
VAV	Variable Air Volume
VFD	Variable Frequency Drive
WAHP	Water-to-Air Heat Pump
WCC	Water-Cooled Chiller
WH	Water Heater
WSHP	Water-Source Heat Pump
WWHP	Water-to-Water Heat Pump
WWHRC	Water-to-Water Heat Pump Heat-Recovery Chiller

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Introduction

This project seeks to expand the California eTRM by adding measure packages that focus on hydronic air to water heat pump (AWHP) and heat recovery chiller (HRC) offerings. This research will also determine whether the scope of AWHP and HRC can be combined into one measure package or would require two independent measure packages.

HRCs can provide significant energy savings over traditional central plant arrangements by reusing the energy within the system before it is rejected into the atmosphere. However, their utility is maximized in buildings where cooling and heating needs are simultaneously present. AWHPs are ideas for supporting electrification by providing either chilled water or hot water, plus space heating for a building. On the other hand, there is the potential to misapply both technologies if the use case isn't appropriate, so an element of the research will be devoted to identifying these poor use cases and ensure that the measure package does not inadvertently push the market in the wrong direction. The team will exercise a well thought out strategy to screen out the poor cases and focus on the preferred cases. The strategy will include defining some attributes such as building size, heating and cooling load shapes, and energy efficiency. These technologies are commercially available and being leveraged by designers and are ready for addition to the utility portfolio to boost visibility and market share.

2-pipe AWHP is generally considered only for retrofits for smaller sites without coincident cooling & heating loads that use a boiler for a variable air volume (VRV) reheat, and for any size building that currently uses a boiler to support a Water Source Heat Pump (WSHP) system. On the other hand, HRC, partial fuel substitution, retrofits for any size building with highly overlapping cooling and heating loads. However, larger buildings with simultaneous overlapping heating and cooling loads may benefit from systems that include both AWHPs and HRCs. Therefore, both technologies can complement each other pointing to an array of offerings that leverage both technologies.

The overall objectives of the project are to accomplish research into a measure package framework for commercial air-to-water heat pumps and heat-recovery chillers. The research will be broader and wider, involving several elements, including:

- Performing a market assessment to inform program design and close any knowledge gaps regarding how systems are specified,
- Developing a program design, collecting or developing measure package inputs, including cost and energy impacts, working with Cal TF and the California Public Utilities Commission (CPUC) staff (via standard protocols such as engaging with the Cal TF measure screening committee and creating measure package plan(s)) to share the working plans for the measures, and,
- Wapping up the project by identifying a clear handoff strategy for the investor-owned utilities (IOUs) to assume responsibility for the final addition to the eTRM.

The specific objectives achieved in 2024, however, include deciding on which AWHP and HRC measure offerings to pursue, reviewing chosen strategies with the market and developing program rules and network with Cal TF, IOUs, and the CPUC.

Background

Obviously, there is a tremendous opportunity to be more efficient and reclaim some of the rejected heat from chiller systems while generating hot water as a by-product. In situations with simultaneous demand for chilled water and hot water, these chillers can operate in the heat-recovery mode. This improves the overall energy efficiency and reduces the energy consumption in buildings. A major chiller manufacturer has several water-cooled heat-recovery chillers with varying capacities, e.g., 15 to 180 tons with the possibility of up-to-eight modules, hot temperature at 140°F, a variable-speed scroll compressor and a low global-warming-potential (GWP) refrigerant, R32.

Raftery et al. (2024) studied 259 buildings across 56 US organizations and found that boilers operate in low part conditions and tend to be oversized relative to the building loads. They noted that 30 percent of the maximum measure load could serve up to 84 percent of the annual energy consumption for the median building. In other words, the space heating plant can be partially retrofitted with a very small heat pump, resulting in a significant reduction in greenhouse gas (GHG) emissions, while preserving the boiler to handle the remaining space heating needs during low ambient temperature conditions.

The U.S. Energy Information Administration (EIA) 2018 Commercial Buildings Energy Consumption Survey (CBECS) states that although only 24 percent of the nonresidential building floor space is served by space heating boilers in the Pacific region (i.e., California, Oregon, Washington, Alaska, and Hawaii, though California represents about 73 percent of the population of this region), boilers are responsible for 44 percent of the total natural gas consumption in this region (EIA 2022). Another study indicates that multizone HVAC systems (typically with gas boilers) are responsible for 37 to 75 percent of the urban GHG emissions (Redwood Energy 2022). Moreover, large buildings are significantly more complex and harder to decarbonize than small residential and light commercial buildings. While there is ample of information available related to unitary or variable refrigerant flow (VRF) systems (e.g., indoor unit, outdoor unit, controls, installation guides, all components as one package etc.), hydronic heat pump HVAC (particularly heat -recovery) equipment lacks in these areas.

An air-source heat pump (ASHP) is a piece of equipment that includes an air-source heat exchanger that can be used to draw or reject heat to the ambient environment. An air-to-water heat pump is a type of ASHP that extracts or rejects heat from ambient air and removes or delivers that energy into a water stream. Air-source heat pumps are an important component to a fully electrified space heating system but are typically best deployed with a combination of water source heat pumps (also known as heat recovery) and ideally thermal energy storage to create a complete system. Water-to-water heat-recovery chillers (WWHRC) and sometimes referred to as water-to-water heat pumps (WWHP). This terminology can vary across the industry and relates to aspects such as the presence of a reversing valve. WWHRCs can move heat from one water stream to another, enabling them to simultaneously cool one stream while heating another. This technology is especially useful for nonresidential buildings that have cooling and heating demanding energy end uses occurring simultaneously. The WWHP or HRC can satisfy the cooling and heating needs in one piece of equipment.

Both types of equipment are expected to play an important role in decarbonizing nonresidential buildings. The current state of the market is that the major hydronics manufacturers offer equipment in these categories and are regularly introducing more offerings as demand steadily increases.

There is an urgent need for hydronic gas to electric fuel substitution measures targeting nonresidential buildings in the eTRM. Currently, there are no deemed HRC or AWHP offerings in eTRM, while both these technologies are mature (from a technical perspective), show significant potential of energy savings and stand out as the prime candidates in commercial buildings electrification in California. While our intention, in the long term, is to steer the market toward systems that leverage thermal energy storage (TES) equipment in some capacity, we will ensure that our near-term offerings will not undercut the long-term TES+HR vision.

Objectives

Each measure package follows a unique path during the development process but there are several standardized steps that need to be taken, as listed here.

- Conduct market outreach to share the initial incentive measure concept, gather initial insights and data, and identify any pitfalls to be avoided. This initial engagement will shape the rest of the measure development process.
- Determine the measure package framework, offerings, and overall design. Determine whether AWHP and HRC should be one or two measure packages, what the offerings and tiers should look like, and the baseline systems that are being targeted for retrofit.
- Collect comprehensive energy and cost data needed to perform energy savings and incremental measure cost (IMC) analysis.
- Develop program requirements and efficiency tiers to create a program design for the measure package, using information learned from the market and an understanding of the technology.
- Engage with Cal TF measure screening committee to solicit feedback on the proposed measure package framework.
- Conduct parametric building energy modeling, using collected data and developed tier design. The project team will conduct a full parametric modeling effort to generate unit energy savings (UES) values for the measure package, touching all appropriate climate zones, building types, and building vintages.
- If appropriate to this CalNEXT effort and authorized by California Public Utilities Commission (CPUC), populate eTRM entry – once all required UES values have been generated, cost data collected, and program requirements created, this information will be added to the eTRM entry (including measure characterization, Cost Effectiveness Tool (CET) runs, cover letter, and other required steps).

To achieve this, the project team engaged with market entitles including manufacturers, distributors, California Building Energy Code Compliance (CBECC) team, industry experts, CPUC, Cal TF and IOUs. The project's key outcome is a framework that outlines one or two measure packages that cover AWHP and HRC technologies.

This effort served to provide recommendations for future measure package(s) by identifying and partially developing the necessary inputs, and by coordinating with Cal TF and CPUC to ensure the effort is headed in an acceptable direction. The long-term expected outcome is the adoption of HRC and AWHP measure package(s) into the eTRM. The finalization of the measure package(s) is anticipated to occur in coordination with SDG&E as the lead HVAC IOU in a subsequent effort.

Methodology & Approach

The project began by reviewing existing studies and manufacturer literature related to Hydronic Heat Pumps, including AWHP and HRC equipment. This included published articles and reports from the Department of Energy (DOE), CalNEXT, ASHRAE, equipment designers and consultants, and other stakeholders. This research helped the project team to converge on some specific systems that are useful in certain situations and helped to decide on the base cases and the measure cases.

In parallel, the project team also networked with several manufacturers and distributors of hydronic heat pumps to gather equipment performance data and entertained nondisclosure agreements to provide assurance that sensitive business information remains confidential.

In the process, one major OEM has shown interest in collaborating with the team in its measure efforts, while the others are defining the engagement process. Note that these engagement efforts are highly time consuming, challenging and require a higher level of perseverance and patience.

While the performance data from manufacturers will be sourced in the next phase, the project team has processed the publicly available data of an AWHP and modeled it in EnergyPlus™ with the overall goal to model the equipment in EnergyPlus and update the Database for Energy Efficient Resources (DEER) prototype equipment library.

System Configuration Research

Air-to-Water Heat Pump Systems

Commercial space heating AWHPs are an innovative technology driven out of a desire to decarbonize HVAC systems through electrified heating solutions. Heat pump technology offers coefficients of performance (COP) far exceeding the resistance-based heating systems, thus, enabling a reduced heating energy intensity. AWHPs are air-to-water refrigeration units with the ability to generate chilled or hot water with one refrigerant-to-water heat exchanger, where a reversing valve is used to switch between heating and cooling modes.

AWHPs or hydronic heat pumps, as shown in Figure 1, are based on a vapor compression cycle to generate hot water and distribute it throughout the building to radiators, variable-air-volume (VAV) boxes, and other heat exchangers to heat the surrounding area. This technology uses a building infrastructure similar to that of a fuel-fired boiler, except with electricity as the energy source. Current AWHPs can supply hot water output temperatures in the range of 120 to 130°F (Goetzler et al, 2024), although some recent designs can offer up to 140°F and even higher temperatures when operating in cascade mode.

Air-to-water heat pumps come either in 2-pipe or 4-pipe configurations and with units offering heat recovery. The efficiency and capacity of these units can vary significantly due to the outdoor ambient air temperature and the desired leaving fluid temperature. Test procedures such as AHRI 550/590[1] can provide a degree of apples-to-apples comparisons between systems.

Two-Pipe AWHP Units: Two-pipe AWHP units have one refrigerant-to-water heat exchanger that can cool or heat, but not both simultaneously. Two-pipe units have one pipe each for supply and return of the same fluid. At any given time, the units operate in only one mode, either heating or cooling, and use outdoor air as the source or sink to provide heating or cooling fluid. A refrigerant four-way reversing valve enables the switchover between the heating and the cooling modes of operation, while a Building Management System (BMS) controls the changeover over process of the unit.

They offer capacities in the range 300 to 5,000 thousand British thermal units per hour (MBH). They can be an attractive option to replace boiler in hot water distribution system and ideal for systems that have little to no cooling or chilled water demand. They contain fan coils equipped with a single coil that is fed with chilled water in summer and hot water in winter.

One of the drawbacks of AWHPs is that their coefficient of performance (COP) is not very high (e.g., 2 to 2.5) during design periods. Therefore, care must be exercised to avoid simply replacing a boiler with a 2-pipe AWHP unit without first taking steps to reduce the space heating load through energy efficiency (EE) measures or ensure that heat-recovery opportunities within the building have been maximized.

A 2-pipe AWHP can operate in either of the three modes — cooling, heating, or defrost — as described below.

Cooling Mode: As can be seen in Figure 1, the unit captures heat at the evaporator (as a refrigerant-to-water heat exchanger), producing chilled water and rejects this heat at the condenser to the ambient air as energy sink via a refrigerant-to-air heat exchanger. The unit acts like an air-cooled chiller.

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[1] The Air Conditioning. Heating and Refrigeration Institute's 2023 standard for the performance rating of water-chilling and heat pump water heating packages using the vapor compression cycle.

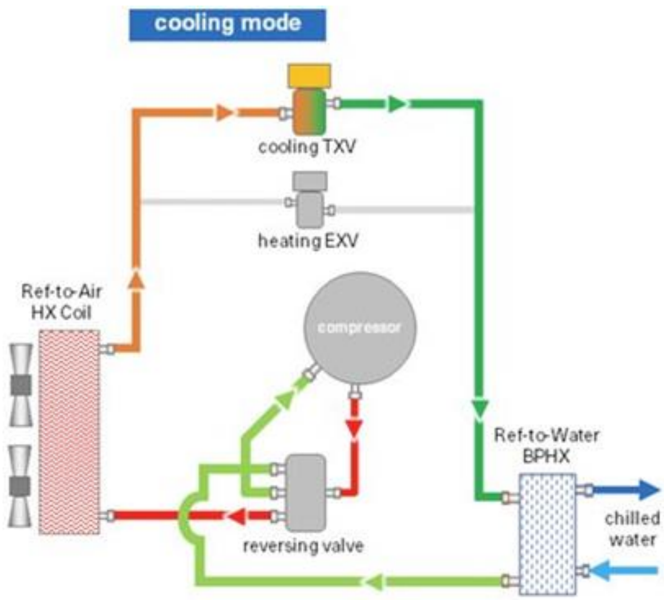

Figure 1: Cooling-mode operation of 2-pipe AWHP

Heating Mode: In this mode (Figure 2), the refrigerant-to-air heat exchanger is the energy source that absorbs energy from ambient air, while refrigerant-to-water heat exchanger is the heat sink rejecting heat to generate hot water.

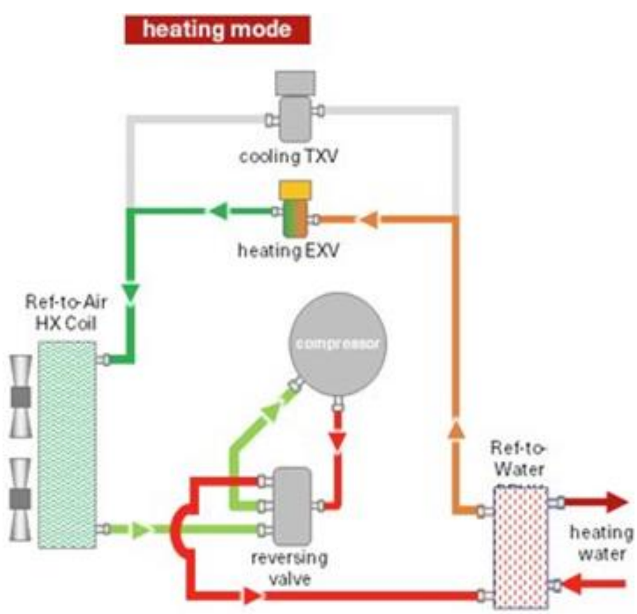

Figure 2: Heating-mode operation of 2-pipe AWHP

Defrost Mode: In this mode, the unit (Figure 3) works in the cooling mode, where return hot water from the hot water loop is the heat energy source to melt the accumulated ice on the refrigerant-to-air heat exchanger.

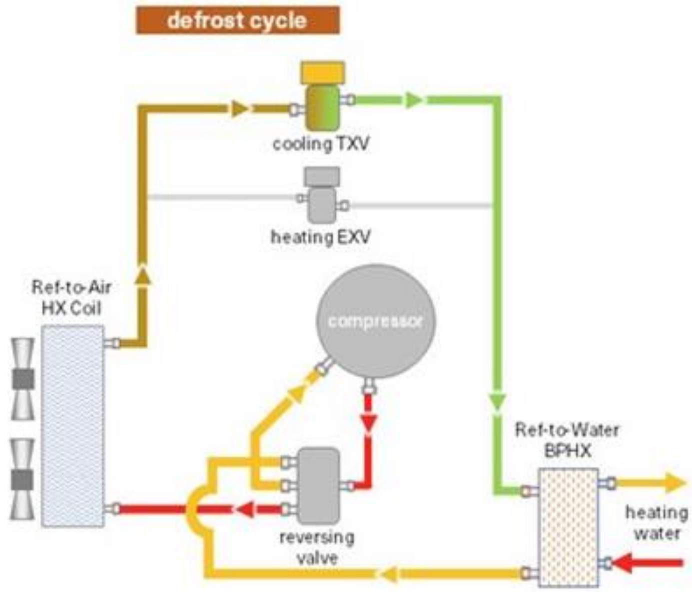

Figure 3: Defrost mode operation of a 2-pipe AWHP (Trane).

Source: Trane 2024.

Four-Pipe AWHPs without heat recovery: A 2-pipe AWHP typically features a single-load refrigerant-to-water heat exchanger that can provide either heating or cooling, but not both simultaneously. A 4-pipe air-to-water heat pump features two separate sets of pipes and coils, one each for heating and cooling. In addition, it contains three main heat exchangers, namely a condenser, an evaporator and a balancing air coil. The balancing coil works as either a condenser (in the cooling mode) or an evaporator (in the heating mode), as can be seen from Figure 4.

Four-Pipe Cooling Mode: In the cooling mode, the refrigerant-to-water heat exchanger is the energy source absorbing energy from the chilled water, while refrigerant-to-air coil is the heat sink rejecting heat to the ambient air. In this mode, the cooling water valves are open, while the heat-recovery water valves and hot water valves are closed. The 4-pipe AWHP works typically like an air-cooled chiller (ACC).

Four-Pipe Heat Mode: In the absence of cooling load, the AWHP produces hot water (HW). The refrigerant-to-air heat exchanger is the heat source absorbing energy from ambient air, while the refrigerant-to-water heat exchanger is the heat sink, rejecting heat to the hot water circuit. Note that the valves in this mode from the load heat exchanger to the chilled water loop are closed but open to the hot water loop.

Four-Pipe Defrost Mode: In this mode, the cycle works in the cooling mode where hot water is supplied to defrost the accumulated ice on the outdoor refrigerant-to-air heat exchanger. The hot water valves are open, while the heat-recovery water valves and chilled water valves are closed, as shown in Figure 5.

A number of practical and operational issues, including system sizing, are discussed by two HVAC manufacturers, Hecoclima, and Jetson, that are worth considering in the efficient and reliable operation of these units. As deemed measures are pursued, care must be exercised to not inadvertently incentivize 4-pipe AWHPs without heat recovery as if they could provide heat recovery.

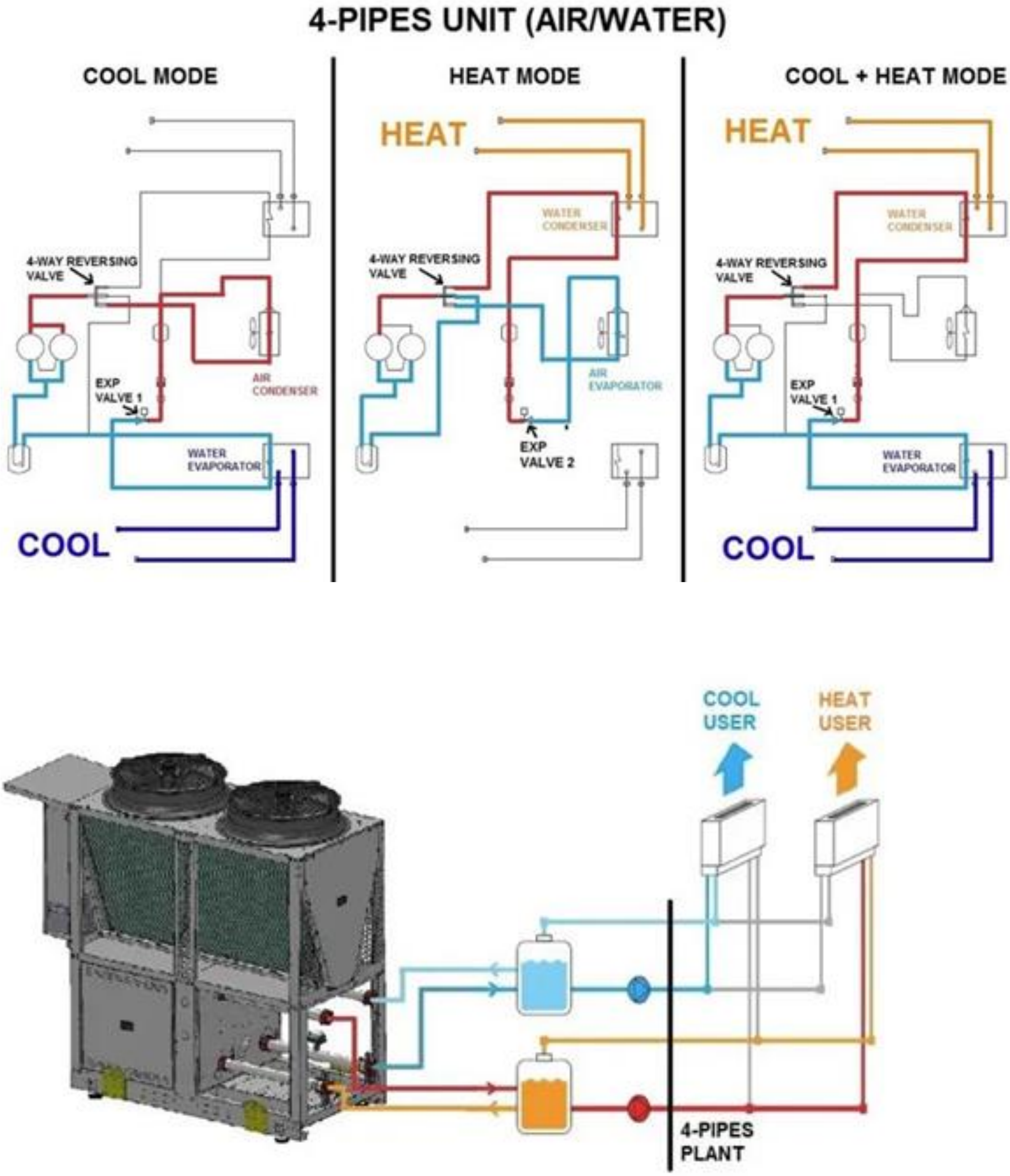

Figure 4: Heating and cooling operation from a 4-pipe AWHP Unit.

Source: Hecoclima 2024.

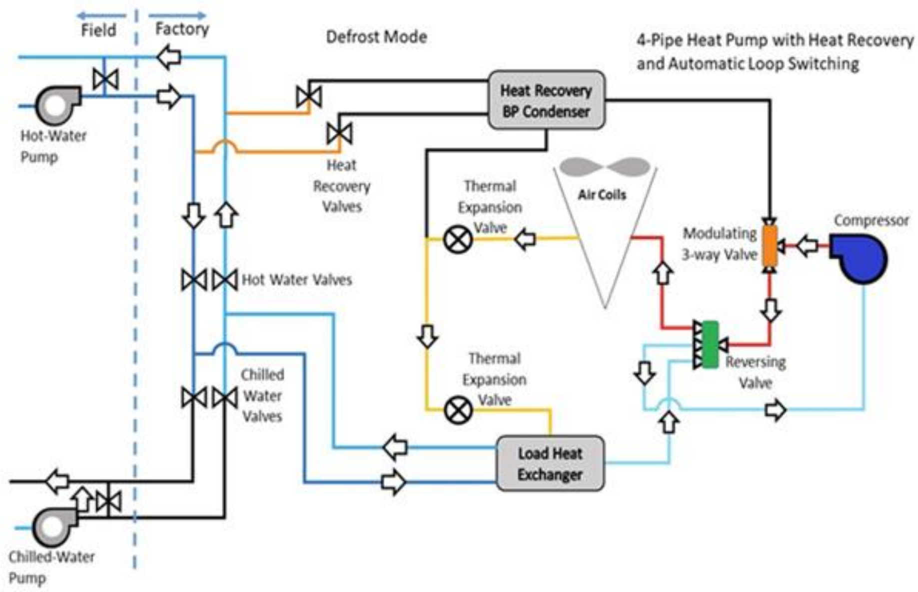

Figure 5: 4-Pipe AWHP in defrost mode.

Source: Jetson 2024.

Four-Pipe Heat-Recovery AWHPs: For a 4-pipe heat recovery option, a second refrigerant-to-water heat exchanger is incorporated alongside the load heat exchanger. This secondary heat exchanger is designed to heat a separate fluid loop while the primary load refrigerant-to-water heat exchanger is in cooling operation. In this arrangement, the heat removed from the cooling loop is not dissipated to the ambient air, but rather, repurposed to heat a separate fluid loop in a useful manner, as shown in Figure 6. Heat recovery can only be used when there is a simultaneous cooling load. The amount of energy available for heat recovery is usually about 10 to 20 percent higher than the cooling load, due to the compressor work (Jetson 2024). During the heat-recovery mode, the chilled water and heat-recovery water valves are open, while the load heat-exchanger hot water valves are closed.

In situations where cooling demand is higher and the simultaneous heat-recovery demand is low, designers customarily use modular AWHP systems with variable capacity compressors and fans. One such module, for example, may supply only chilled water demand, while the second module may supply both the chilled water and hot heating water demand. This part is described further later in the report.

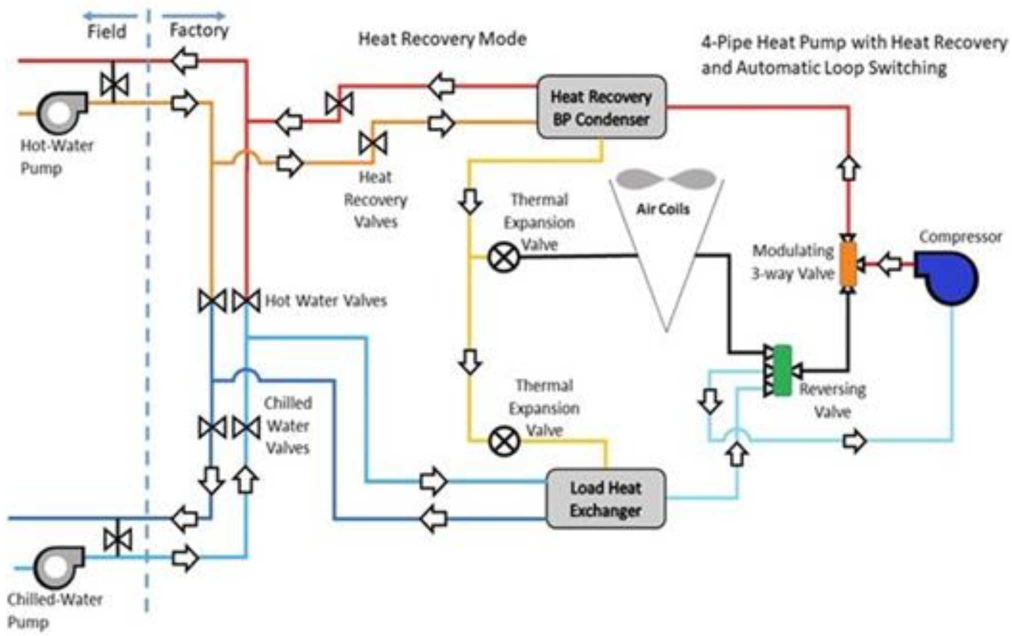

Figure 6: Four-pipe AWHP in heat-recovery mode[2].

Source: Jetson 2024.

Table 1 shows the comparative analysis of the features of 2-pipe versus 4-pipe AWHPs.

Table 1: Comparative Features of 2-Pipe vs. 4-Pipe AWHPs

Features	2-pipe AWHP	4-pipe AWHP
Heating	Yes	Yes
Cooling	Yes	Yes
Simultaneous Heating & Cooling Capability	No	Yes
Cost	Medium	High
Space constraint	High	High

4-Pipe WWHP Configuration: Heat-Recovery Chillers

There are numerous global applications of four-pipe and two-pipe water distribution systems serving room terminal units — most typically, fan coil units (FCUs) comprised of a filter, coils, possibly some condensate drainage, and a fan — that provide room heating and cooling.

Four-pipe systems have two independent water circuits — one with chilled water for room cooling, the other with hot water for heating. All terminal units in four-pipe systems are equipped with two independent coils and can cool or heat according to space requirements. Four-pipe systems are extensively used in temperate climates such as California, particularly where there is no clearly defined seasonal operation. No summer or winter changeover is required, as cooling or heating can be produced at all times, and the control of each room's temperature is independent of others.

A four-pipe system is typically served by either a chiller and boiler combination or a heat pump arrangement. In commercial buildings, cooling and heating loads often overlap that can be accomplished by a heat-recovery chiller (or a hybrid heat pump) that allows this energy potential to be recovered and usefully applied.

Each unit is equipped with three heat exchangers: the 'main heat exchanger' supplying chilled water; the heat recovery or 'secondary heat exchanger' supplying only hot water; and the 'balancing heat exchanger' used as a condenser or evaporator, rejecting or absorbing heat. This last heat exchanger can be a finned coil in the air-cooled units, or a refrigerant-to water heat exchanger in the water-cooled unit. In each operating mode, only two heat exchangers are activated, as described below:

- **Mode 1: Generation of chilled water only (as a chiller, shown in blue color).** When chilled water is required, the unit operates like a normal chiller, where the heat is removed (i.e., chilled water is produced) from the main heat exchanger and heat is rejected at the condenser to the ambient. This process is shown by dotted blue lines in Figure 7.
- **Mode 2: Generation of chilled and hot water simultaneously (shown in red color).** In this mode, the unit switches to heat-recovery mode, where heat is removed (i.e., chilled water is produced) at the main heat exchanger, while the heat is rejected at the secondary HX to produce hot water. This process is shown by solid red lines in Figure 7.
- **Mode 3: Generation of hot water only (shown in green color).** If the chilled water is not needed anymore but there is still demand for hot water, the unit switches to heat pump mode. The heat is absorbed at the evaporator, while high temperature heat is utilized either at the secondary heat exchanger or at main heat exchanger to produce hot water. This process is shown by dotted green solid lines in Figure 7.

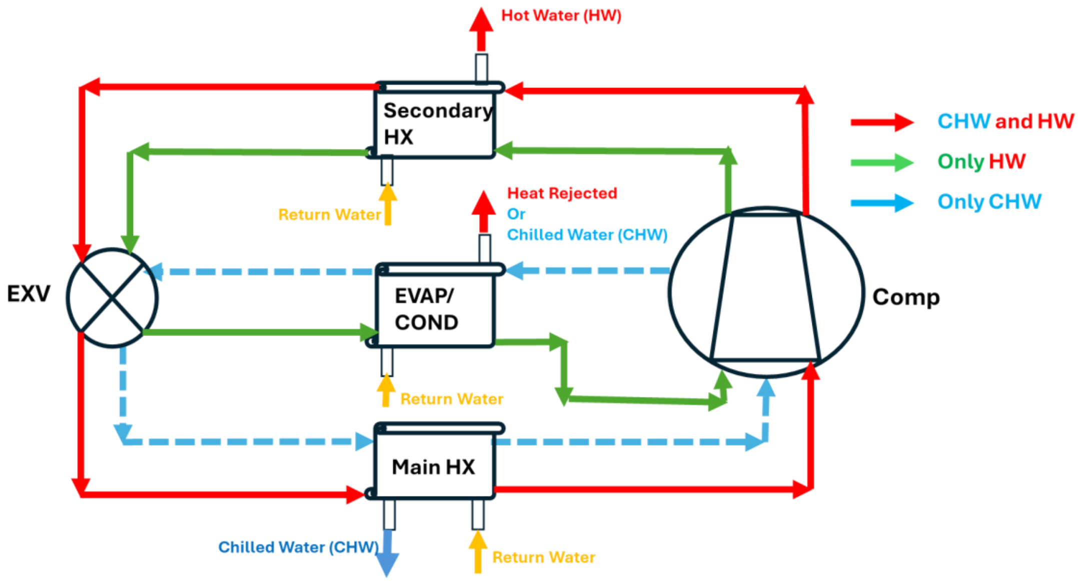

Figure 7: 4-pipe WWHP in heat-recovery mode.

Source: CIBSE Journal, 2015.

Water-to-Air Heat Pumps

Water-to-air heat pumps (WAHPs) are a very established technology that has been in the market for decades. Many WAHP systems (in fact, the umbrella term 'WSHP', or water-source heat pump, usually refers to WAHPs since WAHPs are the most common type of WSHP) have been installed throughout California.

WAHPs are available in capacities ranging from less than one to around 20-25 tons. Carrier's Aquazone line goes up to 20 tons (Carrier 2024), Daikin's Large Capacity Water-Source Heat Pump line goes up to 25 tons (Daikan 2024), and Trane's Axiom line (Trane 2022) goes up to 25 tons. As shown in Table 2, along with WAHP efficiency requirements, DOE appliance standards only cover up to 135,000 Btu/h (11.25 ton) equipment.

Table 2: Water-to-Air Heat Pump DOE Federal Minimum Efficiency Requirements

Size Category (Btu/h)	Cooling Efficiency (EER)	Heating Efficiency (COP)
<17,000	12.2	4.3
≥17,000 and <65,000	13.0	4.3
≥65,000 and <135,000	13.0	4.3

Source: 10 CFR 431.97 Table 3 and 4.

The current default system design involving WAHPs is to locate them in the building interior, serving one or several zones, and to have a water loop running throughout the building, either accepting or rejecting heat to the individual WAHPs depending on if the zones require cooling or heating. The water loop also includes a boiler and cooling tower to provide trim heating or cooling if the overall building demands it, as shown in Figure 8. The fuel substitution measure involving this system would consist of replacing the boiler with an AWHP, as shown in Figure 9. If the cooling tower is eliminated for the measure case, then additional water savings could be claimed. Opportunities to retrofit existing non-WAHP systems to WAHPs are also possible. However, as noted above, all water source equipment requires additional equipment such as an AWHP (or AWHP and cooling tower) to form a complete system.

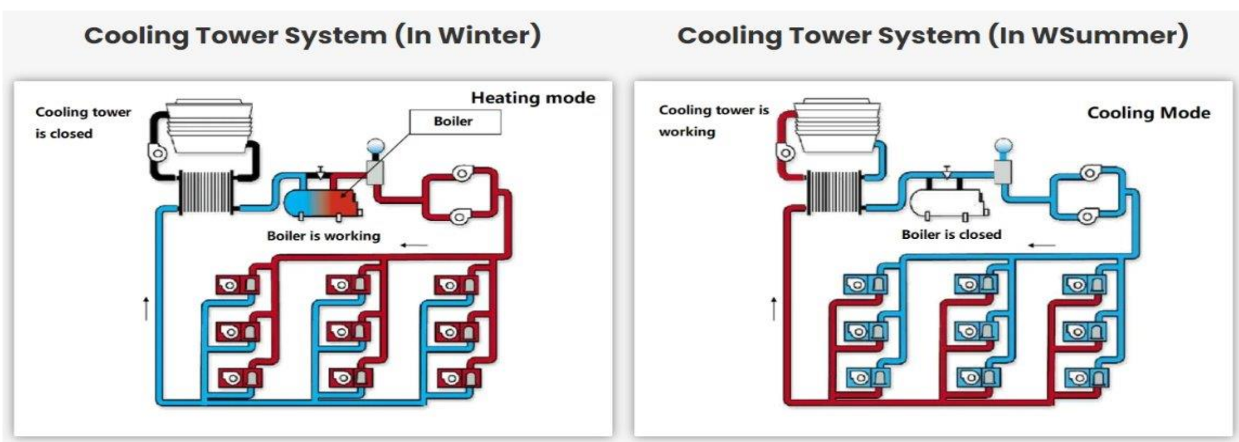

Figure 8: Schematics of a WAHP system in heating and cooling mode.

Source: Glenwin 2024.

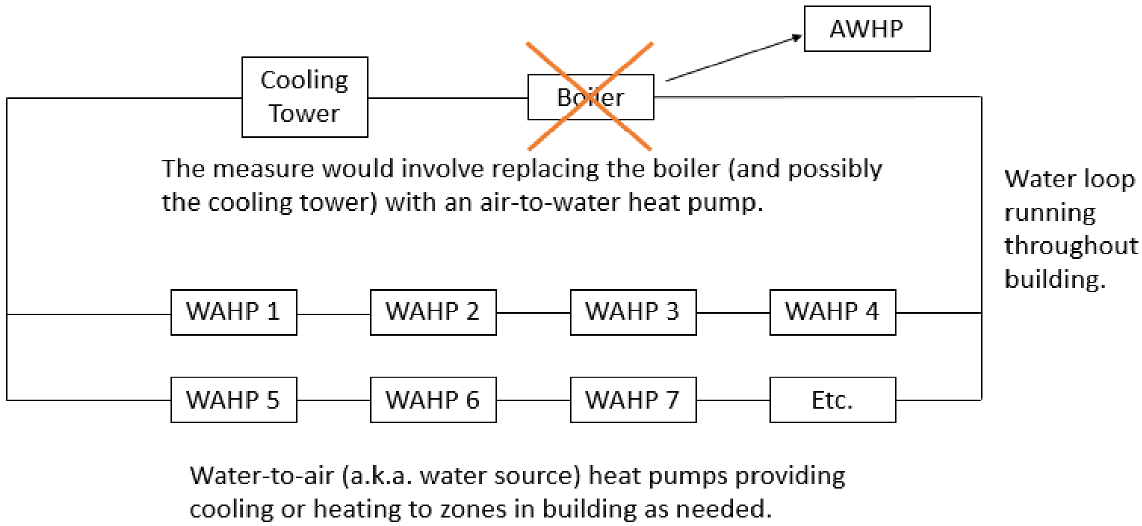

Figure 9: Water-to-air heat pump (i.e., water source heat pump) providing cooling or heating in buildings as needed.

Integrating Heating and Cooling Through Heat-Recovery Chillers

The primary difference between a heat pump and a heat-recovery chiller is that a heat pump uses a reversing valve on the refrigeration side and keeps the same water connections to a heat sink and a heat source. A HRC, however, uses the fixed refrigeration circuit and its evaporator, and does not use a reversing valve, while its condenser may reject heat to a heating hot water (HHW) system or an external heat sink (e.g., geothermal wellfield or a cooling tower).

The application of HRCs requires an instantaneous balance of heating and cooling load, or a source or sink acting as a storage system to handle load mismatches. For example, a geothermal wellfield can work as a long-term storage to improve the efficiency of the HRCs.

Effective electrification and decarbonization can be achieved by reducing overall energy use. One of the most effective ways to reduce energy use, particularly in large commercial buildings, is by integrating the heating and cooling production and distribution through the proper use of heat pumps and heat-recovery chillers. Estimating simultaneous heat loads using a peak load, total annual cooling and heating loads or even a bin analysis is not practical, because these energy estimating methods cannot capture the coincidentally of the loads. Such a calculation may rather be based on a 365 days (== 8,760-hour) analysis for the building or system, served to take advantage of more recovered energy (2021). Heat-recovery chillers are highly efficient systems that help reduce energy consumption and operating costs by utilizing waste heat for heating purposes, making them environmentally friendly and cost-effective solutions for both commercial and industrial applications.

Double Bundle Heat-Recovery Chillers: The term ‘double bundle’ refers to a system having two ‘condensing coils’, one for rejecting excess energy via the cooling tower, and the other for extracting energy from the condensing heat exchanger to a separate heating hot water loop to the building. The chiller can also operate as a ‘cooling’-only chiller at normal condensing temperatures.

Sometimes this equipment is called in the industry as a “6-pipe” unit or double bundle heat-recovery chiller, as shown in Figure 10 and Figure 11. A rapidly growing category of heat-recovery chillers can be classified as “dedicated” or “modular” equipment, as shown in Figure 12.

The team’s intention is to limit the eligibility of any eTRM measure offerings to equipment that cannot modulate its condenser head pressure to efficiently deliver hot or condenser water to the building’s heating demand or cooling tower, respectively.

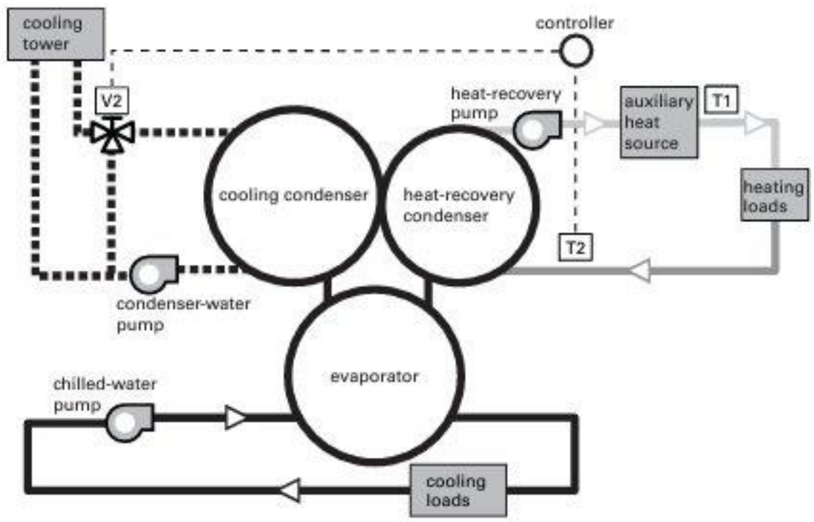

Figure 10: Schematics of a double-bundle HRC

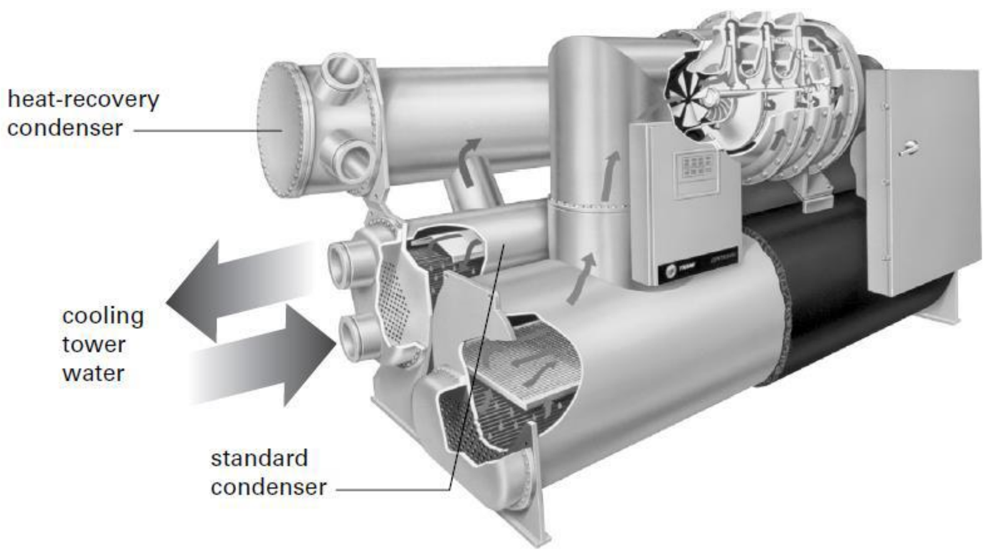

Figure 11: Double-bundle HR centrifugal chiller.

Source: Trane 2007.

Figure 12: Modular air-cooled or water-cooled heat pump.

Source: Multistack 2024.

Innovations in Hydronic Heat Pumps

Novel designs of water-sourced heat pumps[3] are appearing in the market that feature variable-speed technology, allowing the compressor and fan to operate at reduced speeds to match demand, minimizing on/off cycling, temperature swings, noise and energy use. These features can save up to 60 percent of energy costs compared with older systems. Some systems are integrated with technologies to maximize indoor comfort by removing airborne contaminants, reducing humidity and minimizing system noise. Such systems can offer unique features to supply simultaneous needs of heating and cooling in different zones of the same building. A heat-recovery process can transfer excess heat from where it is not needed to where it is, increasing the overall system efficiency. Some commercial systems are available in the capacity range five to 20 tons.

The soon-to-be released AquaForce 23XW chiller and the 23XQ heat pumps are drawing attention, due to their following special features:

- Offers enhanced seasonal efficiency and load matching with Scroll compressor fitted with variable frequency drive (VFD),
- Optimized for ultra-low global warming potential, with HFO-1234ze[E] and A1-rated R-515B refrigerants,

[3] One such example is Trane Technology's water-sourced heat pumps, as seen on their website at WSHP-SLB039-EN_02272024.pdf (tranetechnologies.com).

- Optimized for part-load performance, delivering high efficiency at off-design conditions,
- Delivers 140°F (60°C) heating capability,
- Offers a coefficient of performance (COP) around 10, and
- Remote connectivity for enhanced service delivery and diagnostics.

Modular systems designs[4] are becoming increasing popular in AWHPs with two or more heat pump units in a system that offer several advantages, including the following:

- Improved system turn-down capability, particularly, at low loads,
- Offering enough capacity to meet simultaneous heat and cooling loads, without the added complexity of heat-recovery systems, meaning that one unit can operate in cooling and the other in heating mode,
- Use of two separate AWHPs requires a four-pipe distribution system that can be optimized for the supply temperatures, flows, and temperature changes, as required by the air-side design,
- Decoupling greatly simplifies the system design and allows for an array of sizes and types of heat pump units that can be applied to best match building load requirements.

Monoblock systems, on the other hand, use self-contained sealed refrigeration loop located outside the home, eliminating the risk of potential refrigerant leaks. The outdoor unit is connected to the heat distribution system via hydraulic connections. These systems are ideal to save space while promoting and facilitating the use of hydrocarbon refrigerants (i.e., R290).

Modelling of Heat Chillers (Wang and Boyce, 2023)

Double-Bundle Water-Cooled Heat-Recovery Chillers: As per EnergyPlus engineering reference, the chiller object (Chiller:Electric:EIR) can model heat recovery where part of its condenser section is connected to a heat-recovery loop for what is commonly known as a double-bundle chiller or single condenser with split bundles. The heat-recovery chiller is simulated as a standard vapor compression refrigeration cycle with a double-bundle condenser. A double-bundle condenser involves two separate flow paths through a split condenser, as can be seen in Figure 13. One of these paths is condenser water, typically connected to a standard cooling tower. The other path is hot water connected to a heat-recovery loop. After leaving the compressor, the refrigerant is condensed to liquid in a refrigerant-to-water condenser. In a split bundle, the chiller's internal controls will direct a part of the refrigerant to the heat-recovery condenser bundle, or to the tower water condenser bundle, depending on the chilled-water load, the condenser inlet temperatures, and internal chiller controls (and possibly a leaving hot water temperature setpoint). The refrigerant pressure is then dropped through a throttling valve so that fluid can evaporate at a low pressure that provides cooling to the evaporator.

[4] Jetson has several examples of modular system designs on its website, JET17-300_Jetson-Heat-Pump-Application-Guide.pdf (jetsonhvac.com)

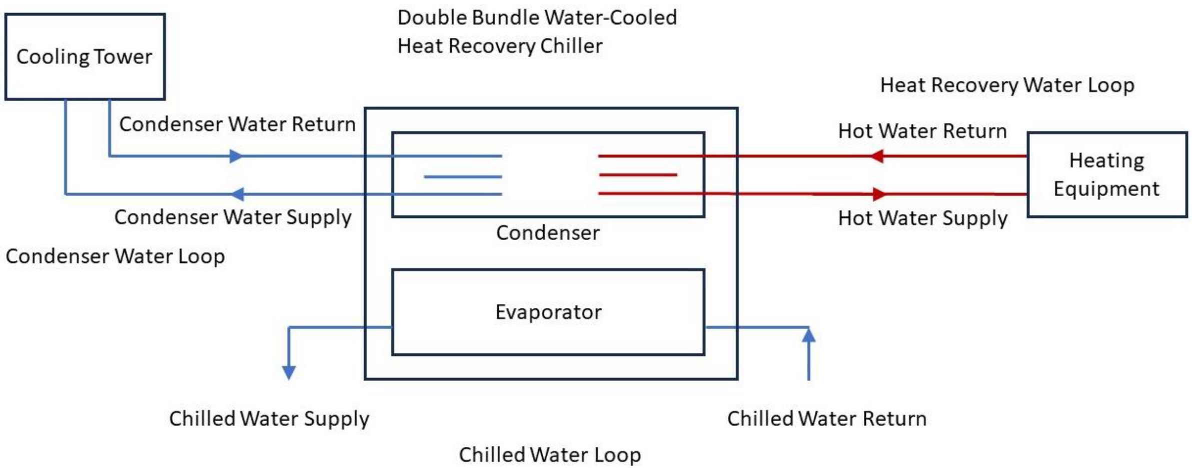

Figure 13: Schematic for double-bundle water-cooled heat-recovery chiller.

Dedicated Heat-Recovery Chiller: The EnergyPlus object (CHILLERHEATERPERFORMANCE:ELECTRIC:EIR) simulates the performance of a chiller heater, which can receive pre-cooled or pre-heated water from the source loop, and provide cooling, heating, or simultaneous cooling and heating, as shown in Figure 14, Figure 15 and Figure 16 respectively. The object needs to work with the Central Heat Pump System object to be controlled properly. This model does not simulate thermal performance or the power consumption of associated pumps or cooling towers. The Central Heat Pump System object holds the input and output nodes connection of the chiller heater and its control scheme once the chiller heater is properly referred.

The model uses user-input performance information at design conditions along with three performance curves (curve objects) for cooling capacity and efficiency to determine chiller operation at off-design conditions. Three additional performance curves for heating capacity and efficiency are used when the chiller is operating in a heating-only mode or a simultaneous cooling and heating mode.

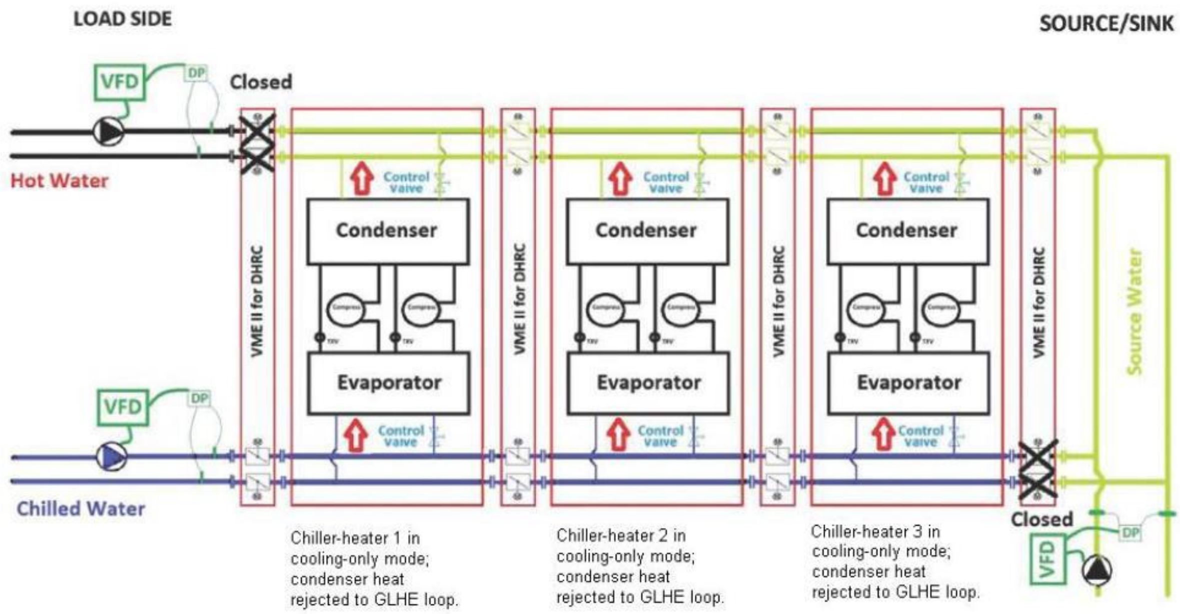

Figure 14: Schematic of a central heat pump system with three chiller-heaters in cooling-only mode (condensers reject heat to ground loop heat exchanger).

Heating-only mode and Simultaneous cooling-heating mode: , and Figure 17 depict the schematics of heating only model and simultaneous cooling-heating mode for dedicated heat-recovery chiller.

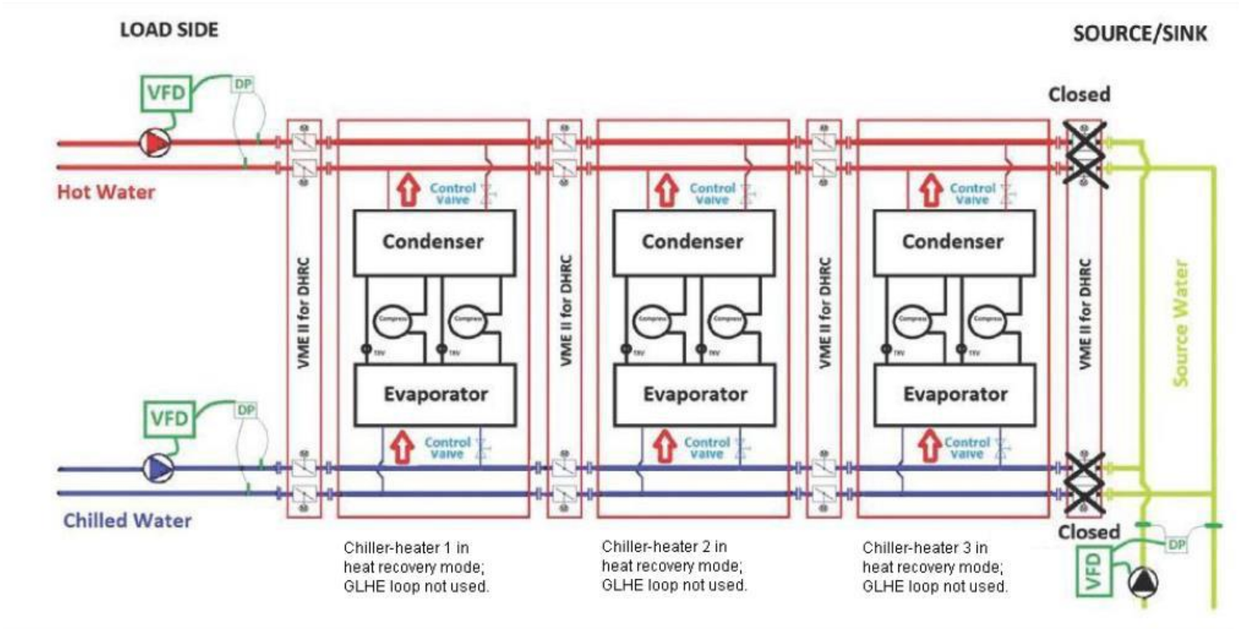

Figure 15: Schematic of a central heat pump system with three chiller-heaters in heat-recovery mode. (No heat is exchanged with the ground source loop.)

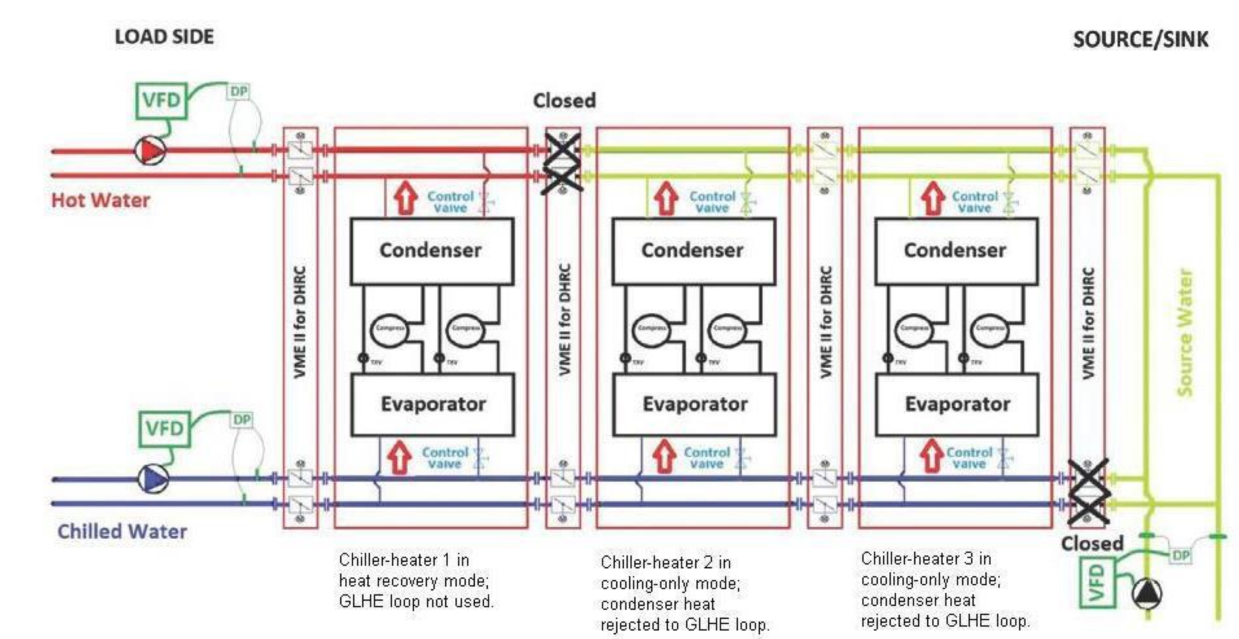

Figure 16: Schematic of a central heat pump system with one chiller-heater in heat-recovery mode and two chiller-heaters in cooling-only mode.

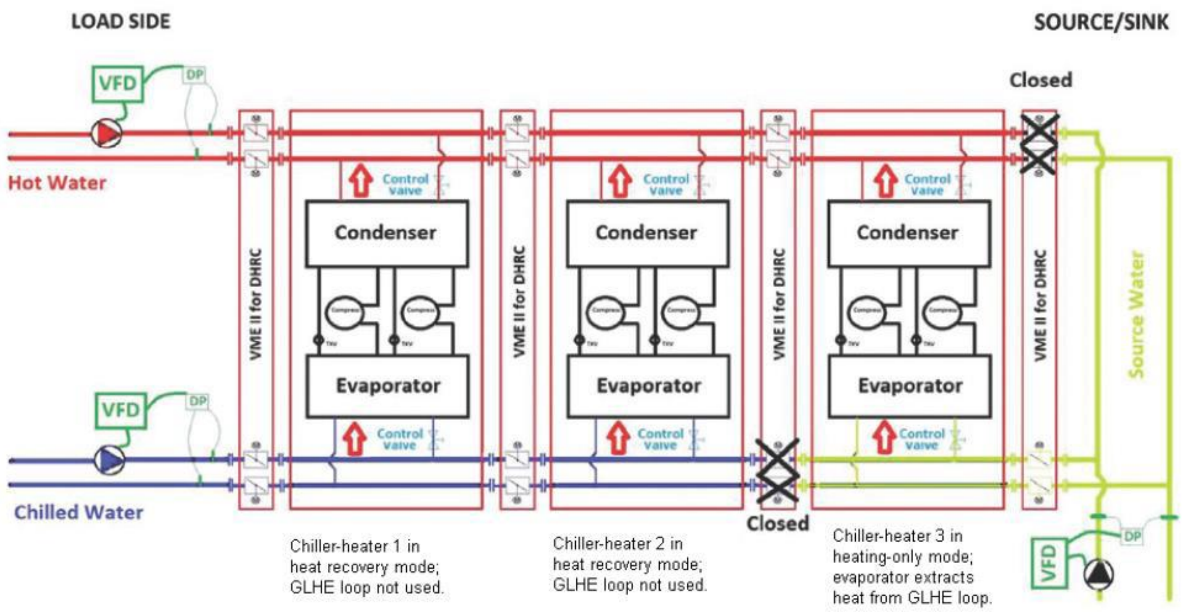

Figure 17: Schematic of a central heat pump system with two chiller-heaters in heat-recovery mode and one chiller-heater in heating-only mode.

Market Assessment and Case Studies of Retrofit Hydronic Heat Pump Installations

Potential of recovering waste heat: DOE estimates 35 percent of industrial energy input for process heating, amounting to nearly 1500 to 3000 trillion Btu per year, is lost as waste heat in the form of exhaust gases, cooling water and heat loss from product heating. This heat can be reclaimed via heat-recovery chillers. Although there is no one silver bullet solution to decarbonize the world, heat pumps offer a great pathway for industries to achieve their carbon reduction targets (Vairamohan et al. 2023).

The project team performed a literature search and found case studies illustrating the retrofits of a boiler, chiller or both, with hydronic heat pumps. These are summarized below, and a synopsis is also presented in Table 3.

- Retrofit of Boiler and Chiller with AWHPs in Office Bldg., Palo Alto, CA, 2023: The gas boiler and an old chiller plant in an existing 3-story, 50,000 ft^2 office building and library in East Palo Alto, CA were retrofitted with two all-electric AWHPs. One of the AWHPs was 2-pipe system, supplying either chilled water or hot water, while the other one was a 4-pipe heat recovery-recovery AWHP supplying both chilled and hot water simultaneously. The project was an example of meeting the goals of the State of California of electrification, sustainability and decarbonization.
- Retrofit of a boiler with an AWHP in Office Bldg., Mountain View, CA, 2022: The five-story and 125,000 ft^2 office building In Northern California at Mountain View had an aging natural gas

boiler that provided hot water serving the VAV reheat terminal units for heating and direct expansion package air-conditioning units for cooling. This boiler was retrofitted with an AWHP while the existing direct expansion package air-conditioning units continued to provide cooling. This was a partial effort to decarbonize and provide an all-electric design.

- Partial Retrofit of Gas Fired Boiler and Cogeneration Plant at University of Stanford Campus, 2016: The aging 50 MW natural gas-fired cogeneration plant has served 11 million ft^2 area at the University of Stanford by supplying electricity, steam and chilled water to its campus since 1987. This system was retrofitted with a new advanced system consisting of i) three 2500-ton AWHPs; ii) four 3,000-ton chillers, iii) two chilled tanks (9.5M gals) and a hot water tank (2.3M gallons), iv) 180 MMBtu boiler; boiler that supplies peak load from November to February annually (10 percent of annual heating load), while AWHP serves the remaining 90 percent load.
- Retrofit of a Boiler with Heat Recovery Chiller at Medical Center, University of Alabama, 2023**:** The aging two gas-fired hot water boilers at the University of South Alabama (USA) Medical Center in Mobile, Alabama, were replaced with a 350-ton modular heat-recovery chiller heat pump. The heat-recovery chiller heat pump reclaimed low temperature heat (from cooling tower) to produce (120 to 180ºF), comprising of five 70-ton, dual compressor stage modules. The operating average power and the condenser temperature of the heat-recovery chiller were 75 kW and 134 °F, respectively, contributing close to 800,000 Btu/h to hot water needs. The average heating COP was 3.3.
- Retrofit of a chiller with a Heat Recovery Chiller at Hospital, 2020**:** A new heat-recovery chiller (HRC) was integrated into the existing plan to deliver 400-ton process cooling load in a new 875,000 ft^2 hospital. This HRC supplies up to 6,200 MBH of heating that allows switching off the boiler during the cooling season and the main chiller plant during the heating season, while all central equipment operates during the shoulder months. The central utility plant for this hospital includes six 8,000 MBH hot water heating boilers, three 1,200-ton centrifugal chillers, and one 482-ton heat -recovery chiller.
- Retrofit of Boilers and Chiller with Heat Recovery Chiller at HSBC Office Bldg., Vancouver, Canada, 2022: The 24-story HSBC office building occupies approximately 711,624 ft^2 that was served with hot water from 90 to 147ºF and cooling by two 480-ton chillers. Each chiller had a dedicated cooling tower with two fans- one with a variable frequency drive and one without. A new 120-ton modular HRC was selected to reclaim waste heat from the existing chiller plant's cooling tower condenser loop in a cascaded or dedicated configuration. HRC raises the temperature of this water and injects it into the heating loop. It typically runs between 25 percent and 50 percent of the total capacity, resulting in steam and electrical consumption decreasing by 20 percent.

Table 3: Synopsis of Some Retrofit Case Studies of Hydronic Heat Pump Installations

Reference	Base Case	Measure Case	Building Type	Project Details
Goetzler et al. (2024)	Boiler and chiller	2 AWHPs	3-story 50,000 ft^2 Office Building, East Palo Alto, CA	2-pipe AWHP supplied either chilled or hot water, 4-pipe HR AWHP supplied chilled and hot water simultaneously
Goetzler et al. (2024)	Boiler	AWHP	Office Building, Mountain View, CA	AWHP provides hot water; DX package AC units continue to provide cooling
Stagner (2016)	Boiler, chillers and gas-fired CHP	AWHPs provide base load- partial replacement	Stanford University Campus Bldg, CA	Advanced system features-a) three 2500-ton AWHPs; b) four 3,000-ton chillers, c) two chilled tanks (9.5M gals) and a hot water tank (2.3M gals), d) 180 MMBtu boiler
Vairamohan et al. (2023)	Boilers, chillers	HRC HP	University of South Alabama (USA) Medical Center in Mobile, Alabama	Replaced gas boilers with a 350-ton modular HRC HP to produce (120-180°F), comprising of five 70-ton, dual compressor stage modules.
Battles et al. (2020)	Boilers, chillers	482-ton HRC	875,000 ft^2 replacement new Hospital	Central utility plant includes- a HRC providing 400-ton cooling and 6,200 MBH heating load, six 8,000 MBH boilers, and three 1200-ton chillers
SES Consulting (2022)	Boiler	A new 120-ton modular HRC	711,882 ft^2, HSBC Office Bldg, Vancouver, Canada	HRC typically runs between 25 and 50% of total capacity, resulting in steam and electrical consumption decreasing by 20%.

Energy Code Considerations

1. As stipulated by Boyce et al. (2023), the setpoint of design water temperature should be lowered to 130°F to make the application of hydronic heat pumps more relevant, efficient and cost effective.
2. Further research may be necessary to establish the level of simultaneous heating and cooling required for different building types to cost-effectively justify four-pipe heat pumps and two-pipe heat pumps (Bulger, 2023).
3. System sizing and area constraints to install the equipment in different building types should be evaluated for effective use of AWHPs.

Large Building Decarbonization Principles

There are certain fundamentals and ground rules that need to be exercised in the overall framework of large building decarbonization, as illustrated below.

- Energy efficiency and heat-recovery opportunities should be maximally leveraged before heat pumps are considered.
- Electric panel upgrades can be prohibitively expensive for commercial buildings, and steps should be taken to avoid this.
- Pair electrification with energy efficiency measures such as HVAC controls retrofits (terminal unit supply airflow minimum setpoints).
- Partial electrification measures to grab the low hanging fruit of first stage boiler plant operation.
- Waste-heat thermal energy storage is a long-term strategy for large buildings that these near-term measure offerings should build towards.

Common Traits for Measures

The current approach considers large commercial buildings with multizone HVAC systems with natural gas fired boilers that can be retrofitted either partially or fully with AWHPs and/or WWHRC systems with the following attributes:

- In offerings where partial decarbonization is considered, the team intends to impose requirements to monitor the remaining boiler runtime hours so the building owner can effectively plan out the second phase to complete electrification.
- The team is considering full electrification for scenarios where it is relatively confident that the site is ready (e.g., the electric panel capacity does not need to increase, the site uses WAHPs for zone conditioning, measures that include simultaneous mechanical heat recovery).
- The new retrofit systems may have several constraints, including first cost, capacity of AWHPs, availability of space, system performance at low ambient, varying heat demands, and that the water temperature requirements be limited to 130°F.

Stakeholder Engagement

The team engaged with several stakeholders (e.g., Cal TF and equipment manufacturers and distributors) and invited their comments on the research findings and the resultant proposal on measures. Notably, the team presented the findings of their research along with the thoughts of proposed measures to the Measure Screening Committee of Cal TF on September 19, 2024. The committee's feedback was very encouraging, and the committee wished to review the complete measure plan on AWHPs next year. In particular, the concept of phased or partial decarbonization for large buildings with multizone HVAC systems served by gas boilers was well received as a realistic pathway to decarbonize this type of system. The team shared the slide deck with the committee members after the meeting.

The project team conducted market interviews with three major manufacturers early in the project's launch, then followed up to gather feedback on the team's proposed measure offerings. Early engagement aimed to understand available units on the market, assess market share, and identify industry best practices. This input was pivotal in shaping key decisions regarding measure offerings. After receiving positive feedback from the measure screening committee, the team re-engaged manufacturers for additional input. In the first follow-up interview, one manufacturer emphasized that the team's proposed offerings aligned well with a primary configuration strategy for their HRC units. Another manufacturer highlighted that, based on designer and user feedback, control strategies must consider both loops simultaneously in a 4-pipe configuration. All manufacturers agreed that retrofitting older buildings poses significant challenges for HRC electrification, as common issues like pneumatic controls and extreme heating demands often necessitate a complete system overhaul and cost millions of dollars. These older buildings comprise a significant fraction of the market.

Based on the market assessment and feedback from stakeholders, the team is proposing to carry out up to 14 measures in three phases. Phase I captures the near term, Phase II captures the mid term, and Phase III captures the long term. Each Phase would develop three measures, six measures and five measures, respectively.

Preliminary Measure Offerings

Based on market assessment and case studies, the following possible measure offerings were developed. Table 4 presents the pertinent EnergyPlus objects for base and measure cases for each offering for Phase I, while Phase II and Phase III offerings are still under scoping.

Phase I: Near-Term, High-Priority Deemed Measures

- Full electrification: A two-pipe AWHP retrofitting a boiler and/or a cooling tower in an existing water-to-air heat pump system (with a water loop).
- Partial electrification: A modular four-pipe AWHP with HR added to system or replacing existing equipment to provide a portion of cooling and/or heating loads. The boiler remains in place in this offering, and monitoring equipment is installed to capture remaining boiler load for future AWHP retrofit.
- Partial electrification: A WWHRC replaces an existing water-cooled chiller unit and can serve either condenser water or hot water loads, depending on building demand. Four- or six-pipe units may be used, but the key requirement is that the HRC can modulate its head pressure to efficiently deliver cold water or hot water as needed. The boiler remains in place and is monitored for the remaining load and future electrification measure.

Phase II: Potential Mid-Term Ideas[5]

- Full electrification: A modular four-pipe AWHP (perhaps with some 2-pipe AWHP if the site has significant excessive cooling or heating loads) replaces the existing cooling and heating

[5] These mid-term ideas were deprioritized by the team for Phase I and may not make sense to move forward with.

system, and the boiler is fully decommissioned. This is basically the full electrification version of measure 2 listed above.

- Full Electrification: A modular or multiple water-to-water heat-recovery chiller (WWHRC) system retrofitting both boilers and water-cooled chillers. In situations where cooling demand is higher and the simultaneous heat-recovery demand is low, designers may use modular WWHRC systems with variable capacity compressors and fans. One such module, for example, may supply only chilled water demand (while rejecting typical condenser water temperature water to the cooling towers) while the second module may supply both the chilled water and hot heating water demand. An AWHP would be installed to account for any excessive cooling or heating loads that cannot be handled by the WWHRC and cooling tower system. This is basically the full electrification version of measure 3 listed above.
- Partial electrification: A 2-pipe AWHP equipment replaces air-cooled chillers, monitors how much boiler load is offset, and that the project does not result in an electric panel capacity increase. Additionally, consider an upper size limit for buildings such as 25,000 ft^2.
- Full electrification: Install two-pipe AWHPs enough to fully replace air-cooled chillers and boiler loads. Ensure that the project does not result in an electric panel capacity increase. Additionally, consider an upper size limit for buildings such as 10,000 ft^2.
- Partial electrification: Install some heating only two-pipe AWHP equipment to offset boiler, install monitoring equipment to determine remaining boiler loads. Consider requirement that project does not increase electric panel requirements.
- Full electrification: Install heating only 2-pipe AWHP enough to fully replace the existing boiler loads. Consider strict limitations on building eligibility criteria considering electric panel upgrade necessity, building size, and possibly other factors.

Phase III: Long-Term, Future Heat-Recovery and Thermal Energy Storage Related Measure Offering Concepts

- Partial electrification: Add thermal energy storage tank to HVAC system. If thermal energy storage is hot water, then perhaps heat-recovery equipment would not be required. If ice, cold-water, or chilled-water thermal energy storage is used, then pair it with water-to-water heat-recovery chiller equipment to deliver hot water to the building.
- Partial electrification: Use a wastewater heat-recovery system with mechanical heat recovery to deliver process or space heating hot water to the building.
- Full electrification: Complete the electrification process for a system that had previously partially electrified by decommissioning the boiler and replacing it with the appropriate amount of two-pipe AWHP. Add thermal energy storage as well.
- Full electrification: Enhanced version of offering #1, the retrofit would include thermal energy storage as well as a two-pipe AWHP so that the building can potentially install less AWHP equipment.
- Enabling electrification: Energy efficiency measures (to be studied or fleshed out at a later date) that are able to reduce the building's space heating loads for future decarbonization efforts.

Additional measure offerings are anticipated to be developed as research into these hydronic technologies and systems continues.

Table 4: EnergyPlus/DEER Modelling Strategy for Initial Offerings During Phase I

Measure Offerings	Operation Mode	Base Case	EnergyPlus Object for Base Case	Measure Case	EnergyPlus Object for Measure Case
1	Cooling / Heating	WAHP	Coil:Heating:WaterToAirHeatPump:EquationFit Coil:Cooling:WaterToAirHeatPump:EquationFit	WAHP	Coil:Heating:WaterToAirHeatPump:EquationFit Coil:Cooling:WaterToAirHeatPump:EquationFit
		Natural gas boiler	Boiler:HotWater	2-pipe AWHP	HeatPump:PlantLoop:EIR:Heating
		Cooling tower	CoolingTower:VariableSpeed	2-pipe AWHP	HeatPump:PlantLoop:EIR:Cooling
2	Simultaneous cooling and heating	ACC	Chiller:Electric:EIR with air-cooled	4-pipe modular AWHP	HeatPump:PlantLoop:EIR:Cooling
3	Cooling Heating Simultaneous Heating and Cooling	WCC	Chiller:Electric:ReformulatedEIR	4-pipe WWHRC	HeatPump:WaterToWater:ParameterEstimation:He

Practical Considerations: System Sizing, Backup Supplemental Heating, and Building Management System

Recognizing the significance and complexity of the issues addressed in this report, it is important to note that while the proposed solutions provide a strong foundation, they may not yet address all related questions and concerns. Ongoing work and further research will continue to refine these concepts and address the remaining challenges.

Determining Load Profiles: Some caution may need to be exercised while determining the heat load profiles of existing buildings and to properly size air-to-water heat pump or heat-recovery chillers. In a future task, the team will carefully understand the design and sizing practices of the equipment before it performs modelling to generate ex-ante saving values. The team will also work with some key designers to check its understanding.

Backup Supplemental Electric Resistance (ER) Heating: In a fully electric space heating system, there may be instances where demand surges and may require backup and supplemental resistance heating. However, partial decarbonization that focuses primarily on using the four-pipe AWHP and WWHRC heat recovery capabilities should avoid this issue. This negates the possibility of any supplemental electric heating in the measure cases, since after a partial retrofit, the original boiler is still in place to provide space heating if the recoverable heat from the chilled water system is insufficient to meet the space heating loads. At the same time, for measures with an AWHP, it is available in heat pump heating mode and would have a COP greater than 1.0 (i.e., more efficient than an electric resistance or a gas boiler), but if the ambient temp is too low or there is not enough AWHP capacity, then the gas boiler can add more heat to the system. And therefore, supplemental electric resistance heating should not factor in with the measure offerings.

Necessity of Building Management System and Resultant Cost Buden on Measure Cost: In applications where the system would need a building management system, the recommendation would be to target sites that already have that capability so that it is not an incremental cost. For sites without a building management system, the offerings would target equipment that does not need to go into a building with it. This is because, for example, if a small building with a boiler and an air-cooled chiller is going to be retrofitted to a four-pipe AWHP unit, then presumably the air-cooled chiller was able to function without a building management system, and hence, the measure case should be able to work as well. Our approach would be similar for all other aspects such as infrastructure cost for retrofit design where multiple designs or equipment changes are incorporated. Such costs would be outside the scope of the incremental measure cost exercise. However, the team will investigate this question further as work continues.

The team recognizes that there may be several other such considerations that may require additional research to provide further insights.

Air-to-Water Heat Pump Performance Data and EnergyPlus Modelling

The DEER prototype does not currently have an AWHP model available. The EnergyPlus AWHP model (object name HeatPump:PlantLoop:EIR:Cooling and HeatPump:PlantLoop:EIR:Heating) uses performance information at reference conditions

along with three curve fits for cooling/heating capacity and efficiency to determine AWHP operation at off-reference conditions. The following sections describe the method to generate AWHP performance curves by fitting manufacturer's catalog data. Two set of the manufacture's performance curves are listed in Table 5 and
Table 6.

Cooling Capacity Function of Temperature Curve

Cooling capacity performance curve is a biquadratic performance curve that parameterizes the variation of the cooling capacity as a function of the leaving chilled water temperature and the entering condenser fluid temperature. The data utilized to model these curves was supplied by the distributors and manufacturers that the team had socialized with during the project. This curve's output is multiplied by the reference capacity to give the cooling capacity at specific temperature operating conditions. The reference capacity is listed in the manufacturer's catalog under the AHRI rated conditions (AHRI 550/590).

$$CoolCapFTemp = a + b(LChWT) + c(LChWT)^2 + d(ECWT) + e(ECWT)^2 + f\,(LChWT)(ECWT)$$

Equation 1: Cooling Capacity as Function of Temperature

where:

$CoolCapFTemp$ is cooling capacity factor, equal to 1 at reference conditions.

$LChWT$ is leaving chilled water setpoint temperature (°C).

$ECWT$ is entering condenser fluid temperature (°C). For a water-cooled condenser this will be the water temperature returning from the condenser loop (e.g., leaving the cooling tower).

Electric Input to Cooling Output Ratio Function of Temperature Curve

The first energy input to cooling output ratio (EIR) performance cure is a biquadratic performance curve that parameterizes the variation of the EIR as a function of the leaving chilled water temperature and the entering condenser fluid temperature.

$$CoolEIRFTemp = a + b(LChWT) + c(LChWT)^2 + d(ECWT) + e(ECWT)^2 + f\,(LChWT)\,(ECWT)$$

Equation 2: Electric Input to Cooling Output Ratio Function of Temperature

where:

$CoolEIRFTemp$ is Energy input to cooling output factor, equal to 1 at reference conditions.

Electric Input to Cooling Output Ratio Function of Part Load Ratio Curve

The second energy input to cooling output ratio (EIR) performance curve is a quadratic performance curve (ref: Performance Curves) that parameterizes the variation of the EIR as a function of the part-load ratio.

$$CoolIRFPLR = a + b\,(PLR) + c\,(PLR)^2$$

Equation 3: Electric Input to Cooling Output Ratio

where:

$CoolEIRFPL$ is the energy input to cooling output factor, equal to 1 at reference conditions.

$PLR = (cooling\ load) \ / \ (AWHP's\ available\ cooling\ capacity)$

Heating Capacity Function of Temperature Curve

As same as cooling capacity performance curve, heating capacity performance curve is a biquadratic performance curve that parameterizes the variation of the cooling capacity as a function of the leaving hot water temperature and the entering condenser fluid temperature.

$$HeatCapFTemp = a + b(LHWT) + c(LHWT)^2 + d(ECWT) + e(ECWT)^2 + f\ (LHWT)(ECWT)$$

Equation 4: Cooling Capacity as Function of Temperature

where:

$HeatCapFTemp$ is Heating capacity factor, equal to 1 at reference conditions.

$LHWT$ is Leaving hot water setpoint temperature (°C).

$ECWT$ is Entering condenser fluid temperature (°C). For a water-cooled condenser this will be the water temperature returning from the condenser loop (e.g., leaving the cooling tower).

Electric Input to Cooling Output Ratio Function of Temperature Curve

The first EIR performance curve is a biquadratic performance curve that parameterizes the variation of the energy input to cooling output ratio (EIR) as a function of the leaving chilled water temperature and the entering condenser fluid temperature.

$$HeatEIRFTemp = a + b(LHWT) + c(LHWT)^2 + d(ECWT) + e(ECWT)^2 + f\ (LHWT)\ (ECWT)$$

Equation 5: Electric Input to Cooling Output Ratio Function of Temperature

where:

$HeatEIRFTemp$ is Energy input to cooling output factor, equal to 1 at reference conditions.

Electric Input to Cooling Output Ratio Function of Part Load Ratio Curve

The second energy input ratio (EIR) performance curve is a quadratic performance curve (ref: Performance Curves) that parameterizes the variation of the EIR as a function of the part-load ratio.

$$HeatEIRFPLR = a + b\ (PLR) + c\ (PLR)^2$$

Equation 6: Electric Input to Cooling Output Ratio

where:

$HeatEIRFPLR$ is the energy input to cooling output factor, equal to 1 at reference conditions.

$$PLR = (heating\ load) / (AWHP's\ available\ heating\ capacity)$$

Findings

Table 4 presents the performance curve coefficients for model 1 from the sample manufacturer's software equipment library, including those for cooling or heating capacity, energy input ratio, and part load ratio. The performance curve coefficients in Table 5 are generated by curve fitting, based on the collected manufacturer data.

Table 5: Model 1 Air-to-Water Heat Pump Performance Curve Coefficients

Curve	Curve Coefficient					
	a	b	c	d	e	f
CoolCapCurveFuncTemp	1.067227	0.046068	0.000346	-0.00697	-2.9E-05	-0.00048
CoolEIRCurveFuncTemp	0.440306	-0.02413	0.000538	0.011872	0.000306	-0.00062
EIRCurveFuncPLR	0.072877	0.551967	0.375156	NA	NA	NA
HeatCapCurveFuncTemp	0.794901	0.003885	-5.8E-05	0.027811	0.000318	-0.00013
HeatEIRCurveFuncTemp	0.530730	0.006552	0.000264	-0.036207	0.001266	-0.000791
EIRCurveFuncPLR	0.0473	0.8643	0.0884	NA	NA	NA

Table 6: Model 2 Air-to-Water Heat Pump Performance Curve Coefficients

Curve	Curve Coefficient					
	a	b	c	d	e	f
CoolCapCurveFuncTemp	1.079190	0.036738	0.000438	-0.005267	-5.85E-05	-0.000372
CoolEIRCurveFuncTemp	0.559515	-0.005373	0.000309	0.002054	0.000427	-0.000558

Curve	Curve Coefficient					
	a	b	c	d	e	f
EIRCurveFuncPLR	NA	NA	NA	NA	NA	NA
HeatCapCurveFuncTemp	0.445592	0.017429	-0.000193	0.009277	-0.000102	0.000164
HeatEIRCurveFuncTemp	1.498303	-0.033439	0.000484	-0.148831	0.002551	0.001976
EIRCurveFuncPLR	NA	NA	NA	NA	NA	NA

Data Analysis, Energy Modeling, and Findings

The manufacturer performance data was analyzed and curve fitting was conducted to determine curve coefficients as shown in Table 4 and Table 5. Six performance curves from model 1 were plotted in **Error! Reference source not found.** through Figure 23. The cooling capacity of the air-to-water heat pump decreases at higher entering condenser air temperatures, due to the increasing temperature lift between the evaporator and the condenser. Consequently, the energy input ratio of the air-to-water heat pump increases with increasing entering condenser air temperature and part load ratio. However, as expected, the heating performance curves show the oppose trend with the increasing temperature of the entering condenser air.

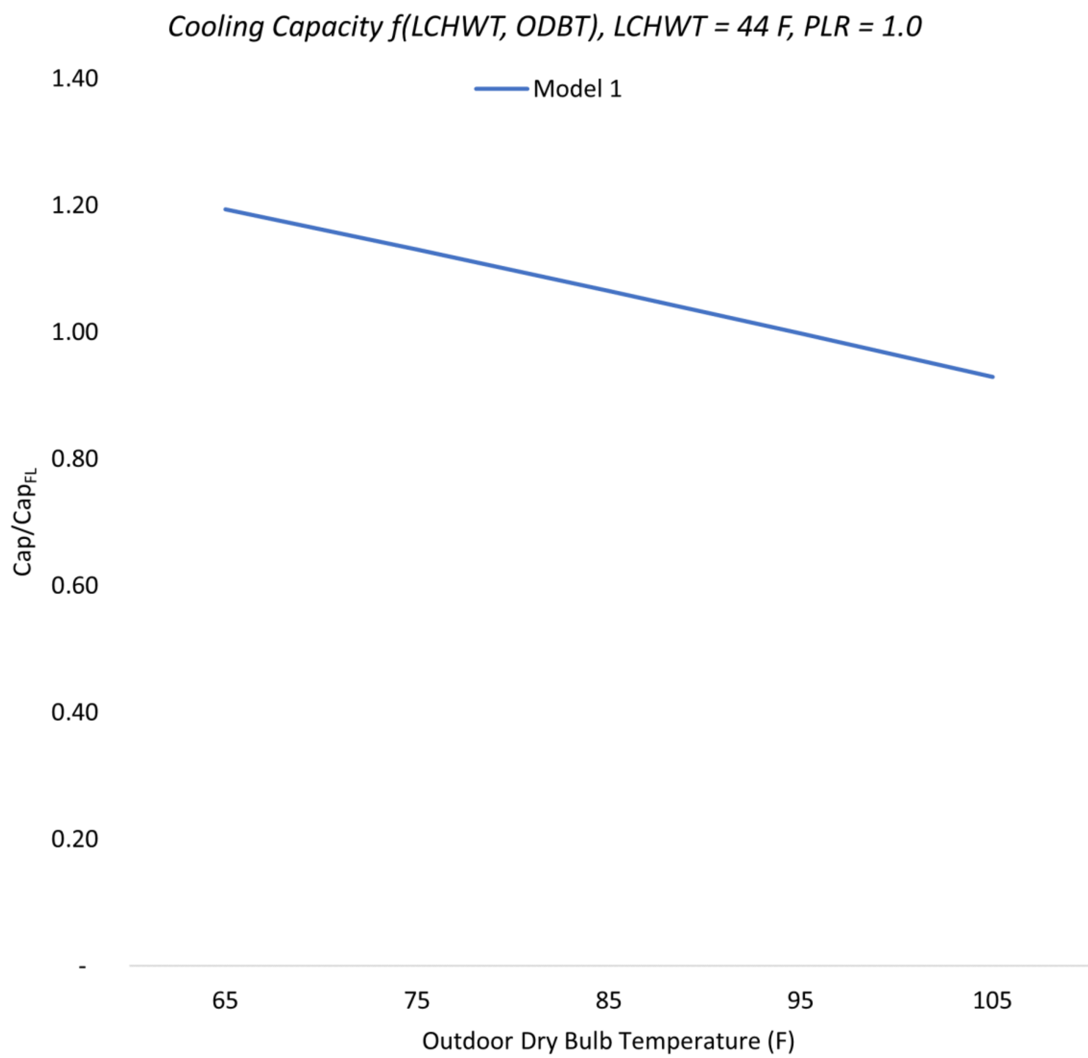

Figure 18: Model 1 cooling capacity as function of temperature curve.

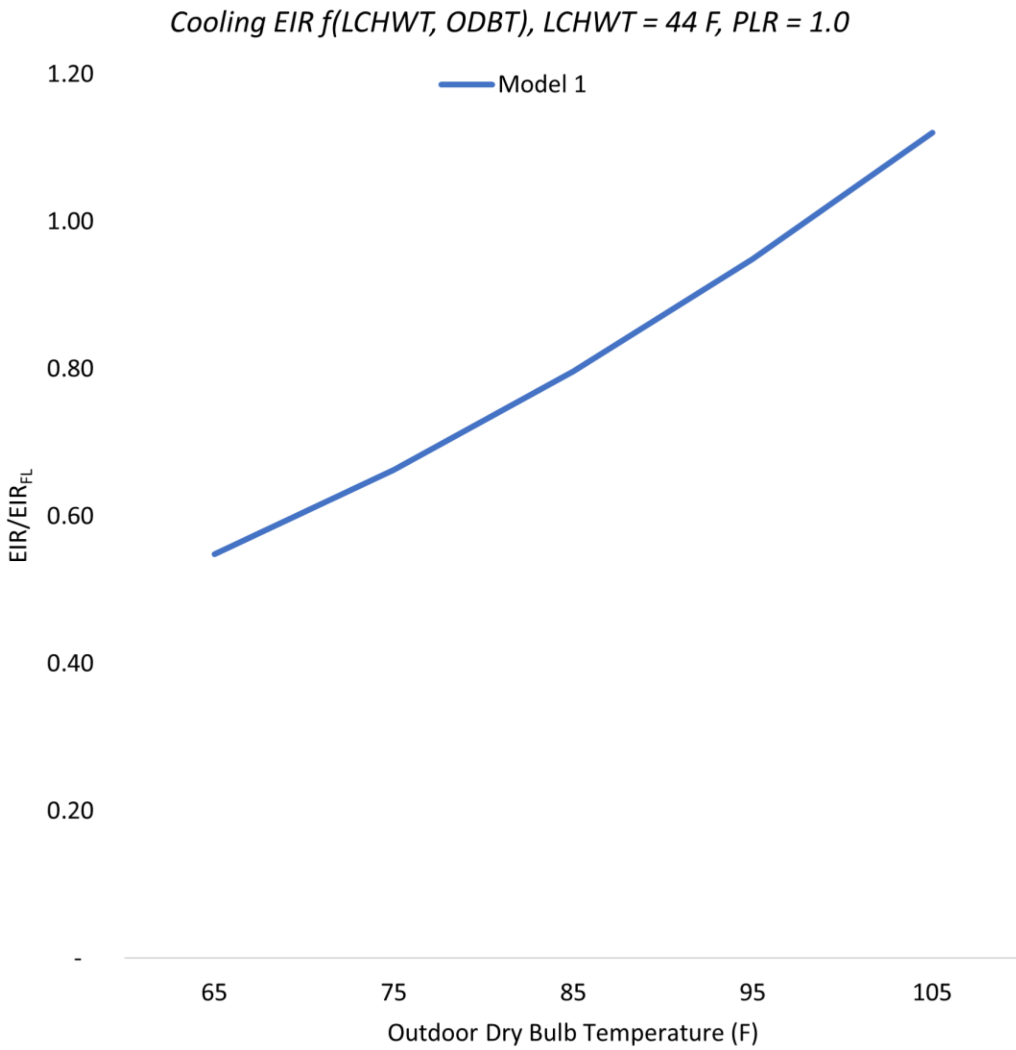

Figure 19: Model 1 electric input to cooling output ratio function of temperature curve.

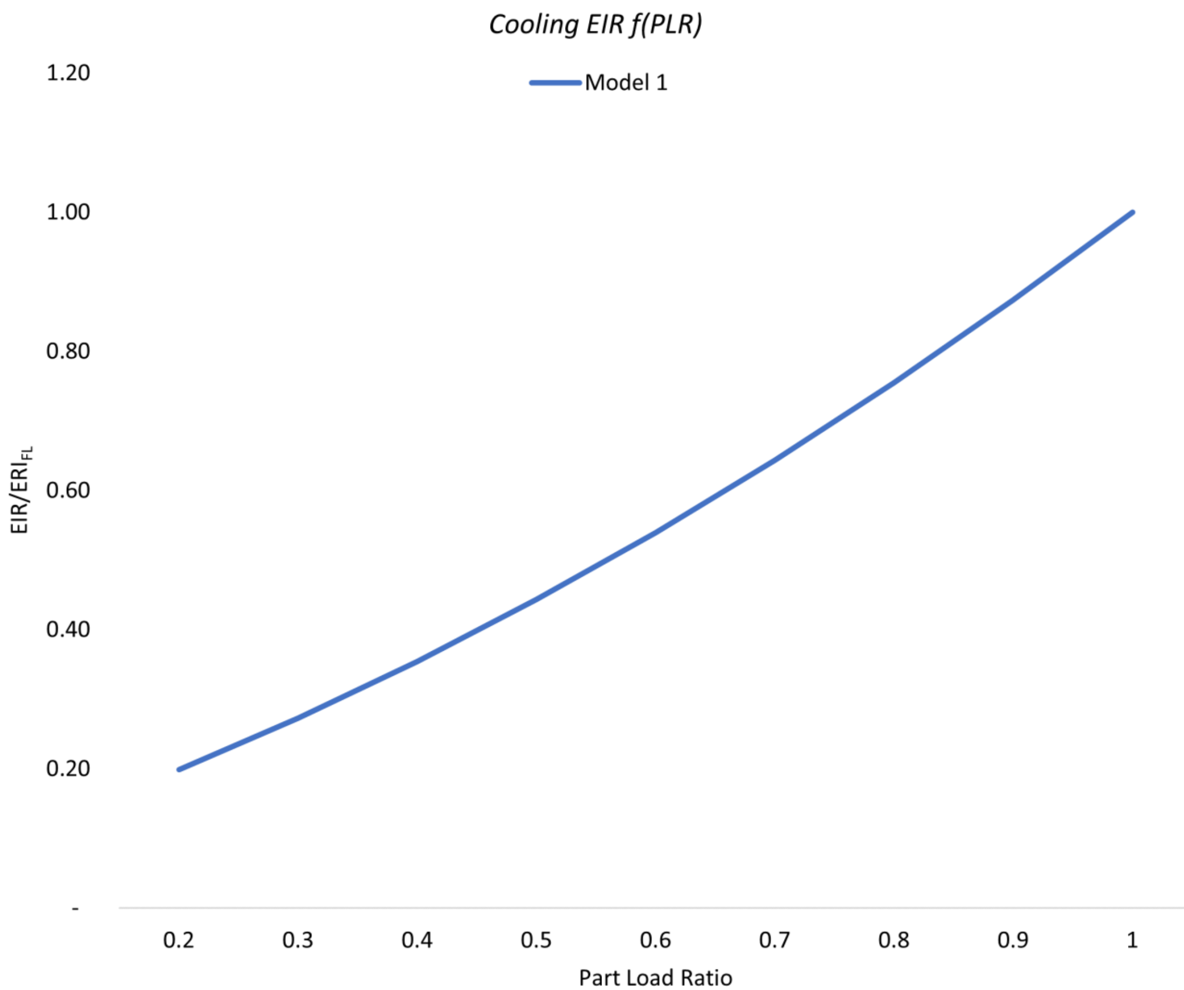

Figure 20: Model 1 electric input to cooling output ratio function of part load ratio curve.

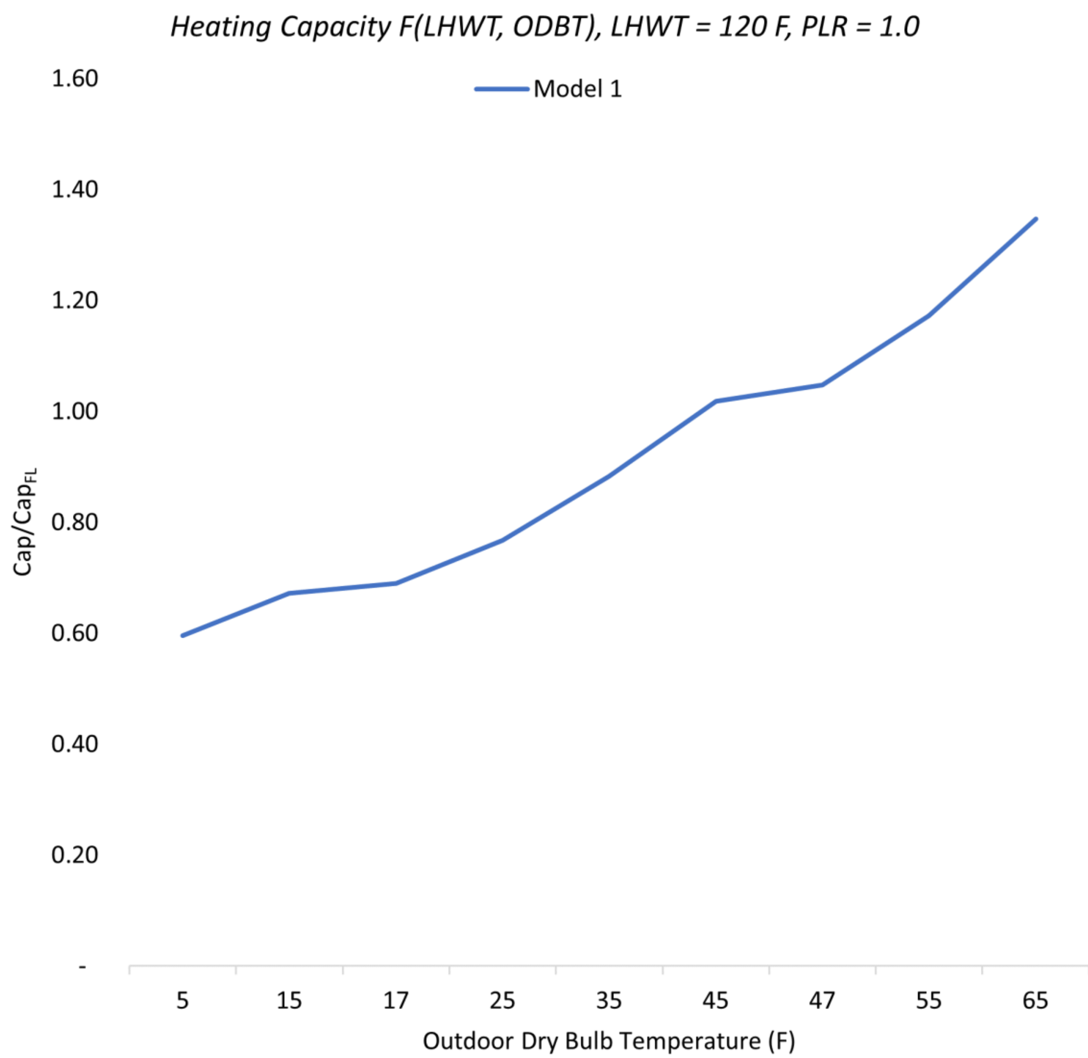

Figure 21: Model 1 heating capacity as function of temperature curve.

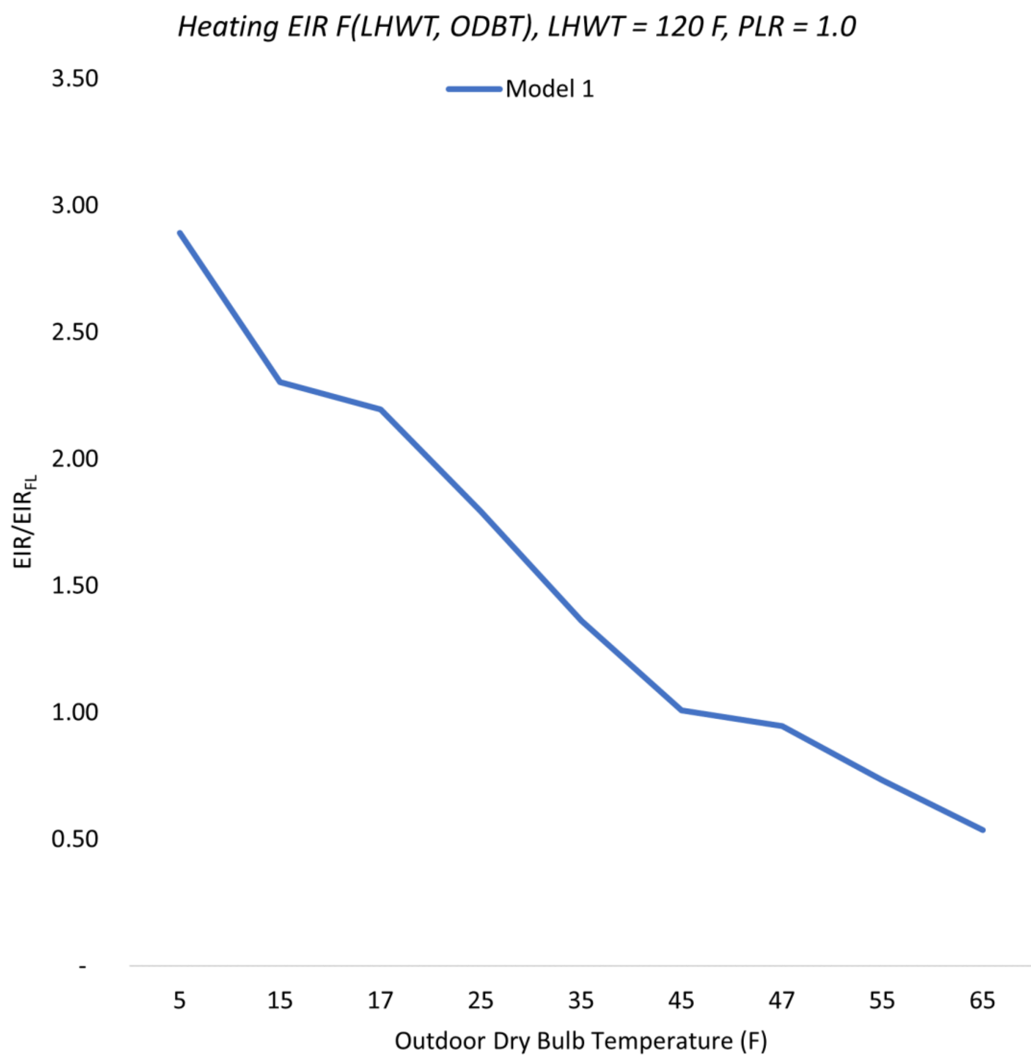

Figure 22: Model 1 electric input to heating output ratio function of temperature curve.

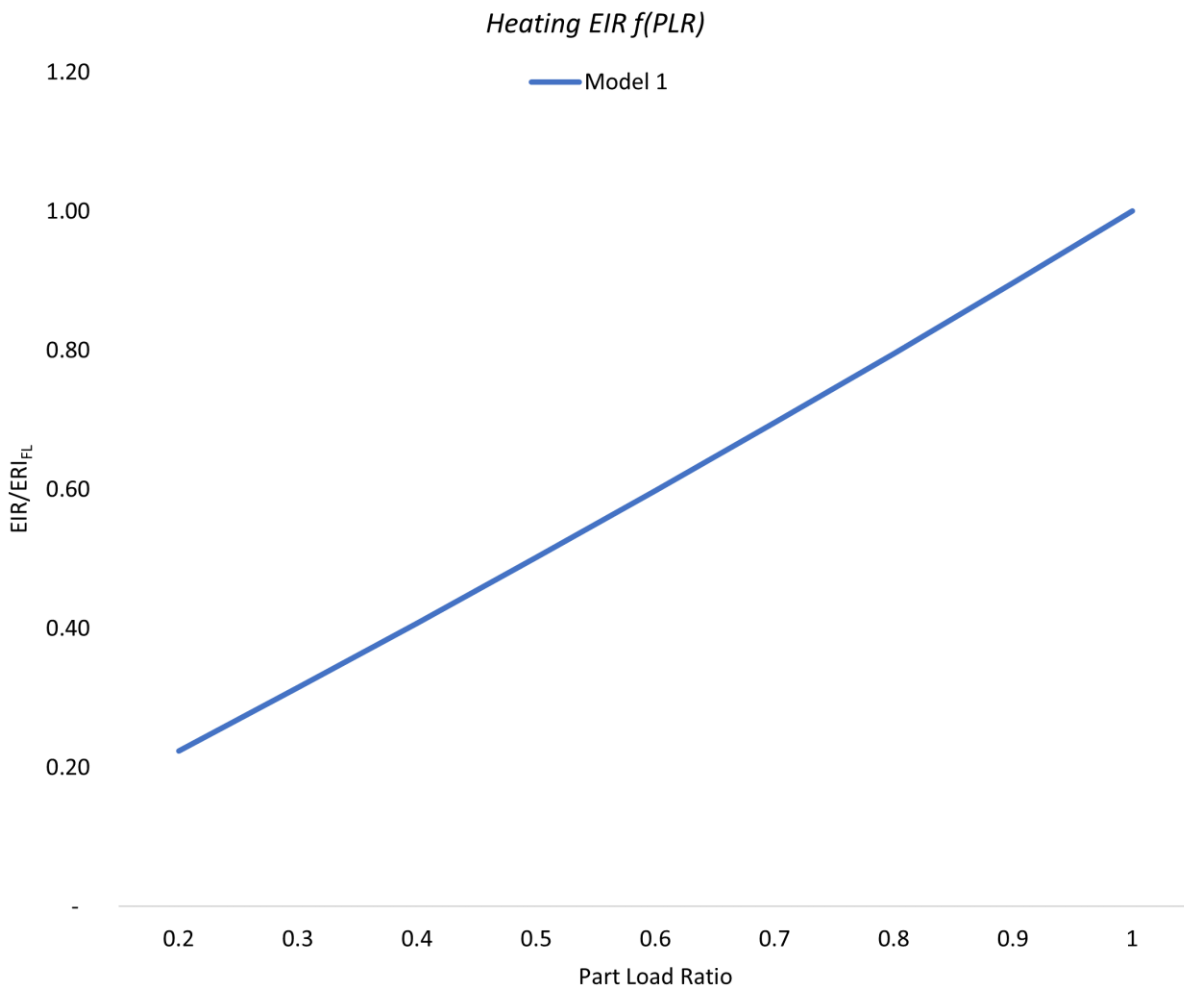

Figure 23: Model 1 electric input to heating output ratio function of part load ratio curve.

Measure 1 Methodology: Two-Pipe Air-To-Water Heat Pump Replacing Gas Boiler in a Water-to-Air Heat Pump System (Full Electrification)Th

The DEER prototype does not have any prototype with WAHP system and boiler or cooling tower. So, in order to model full electrification two-pipe AWHP measure offering, the first step is to start with the ASHRAE901_ApartmentHighRise_STD2022_SanDiego as selected prototype. The baseline is WAHP with a gas boiler and cooling tower. For the measure case, the natural gas boiler will be replaced by two-pipe AWHP. Secondly, after successfully conducing the model runs in EnergyPlus, the team will work with the CPUC ex-ante team to determine if WAHP system needs to be generated for DEER prototype. Then, the team will use the newly created WAHP DEER prototype to generate the EnergyPlus idf (EnergyPlus 22.2) with all the default inputs and replace the natural gas boiler with a two-pipe AWHP (EnergyPlus 24.2). In addition, the team will modify the existing DEER templates to include a two-pipe AWHP module in prototype root files and HVAC templates such as hw.pxt. Therefore, this measure offering actually includes two tasks as listed below. Table 7 listed the building prototypes for energy impacted analysis for the two-pipe AWHP measure offering for existing and new building vintages, as depicted in Table 8. Sixteen climate zones in California will be used for all the measure offering analysis as shown in Table 9.

- Create WAHP measure offering
- Create two-pipe AWHP measure offering

Table 7: Prototype Buildings Used for Energy Impact Analysis for Two-Pipe Air-To-Water Heat Pumps

Building Type	Building Type Code	Modeled
Nursing Home	Nrs	Yes
Hotel	Htl	Yes
Office – Small	OfS	Yes

Table 8: DEER Prototype Building Vintage

VINTAGE ERA	VINTAGE	VINTAGE CODE	MODELED
Existing (Ex)	1975	Before 1978	Yes
	1985	1987 – 1992	
	1996	1993 – 2001	
	2003	2002 – 2005	
	2007	2006 – 2009	
	2011	2010 – 2013	
	2015	2014 – 2016	
	2017	2017 – 2019	
	2020	2019 – 2022	
	2023	2023 – 2024	
New (New)	2025	New Construction	Yes

Table 9: Climate Zones

Climate Zone	Climate Zone Description	Modeled
1	Arcata Area (CZ01)	Yes
2	Santa Rosa Area (CZ02)	Yes
3	Oakland Area (CZ03)	Yes
4	Sunnyvale Area (CZ04)	Yes
5	Santa Maria Area (CZ05)	Yes
6	Los Angeles Area (CZ06)	Yes
7	San Diego Area (CZ07)	Yes
8	El Toro Area (CZ08)	Yes
9	Pasadena Area (CZ09)	Yes
10	San Bernardino Area (CZ10)	Yes
11	Red Bluff Area (CZ11)	Yes
12	Sacramento Area (CZ12)	Yes
13	Fresno Area (CZ13)	Yes
14	China Lake Area (CZ14)	Yes
15	Blythe Area (CZ15)	Yes
16	Mount Shasta Area (CZ16)	Yes

Measure 2 Methodology: Four-Pipe Air-To-Water Heat Pump With Heat Recovery Replacing Air-Cooled Chiller (partial electrification)

EnergyPlus development team recently implemented “Heat-Recovery” field in EnergyPlus 24.2 for HeatPumpPlantLoopEIR object including "Heat-Recovery Inlet Node Name," "Heat-Recovery Outlet

Node Name," and "Heat-Recovery Reference Flow Rate" fields and new optional "Heat-Recovery Capacity Modifier Function of Temperature Curve Name," "Heat-Recovery Electric Input to Output Ratio Modifier Function of Temperature Curve Name" fields.

While the DEER prototype currently uses EnergyPlus 22.2 as a simulation engine, this version of EnergyPlus has limited input for AWHP objects and cannot specifically simulate four-pipe AWHP with a heat-recovery capability, as shown below. Therefore, the team will use EnergyPlus 24.2 as a simulation tool for all AWHP and HRC modeling work. The team needs to further discuss and collaborate with the CPUC ex-ante software development team on upgrading the EnergyPlus simulation engine to EnergyPlus 24.2 in the future. Table 10 lists the building prototypes for energy impacted analysis for four-pipe AWHP with heat-recovery measure offering in 16 climate zones.

HeatPump:PlantLoop:EIR:Heating Object Modeling Input in EnergyPlus 22.2

- Load side inlet node name
- Load side outlet node name
- Condenser type
- Source side inlet node name
- Source side outlet node name
- Companion heat pump name
- Load side reference flow rate {m3/s}
- Source side reference flow rate {m3/s}
- Reference capacity {w}
- Reference coefficient of performance {w/w}
- Sizing factor
- Capacity modifier function of temperature curve name
- Electric input to output ratio modifier function of temperature curve name
- Electric input to output ratio modifier function of part load ratio curve name

HeatPump:PlantLoop:EIR:Heating Object Modeling Input in EnergyPlus 24.2

- Load side inlet node name
- Load side outlet node name
- Condenser type
- Source side inlet node name
- Source side outlet node name
- Heat-recovery inlet node name
- Heat-recovery outlet node name
- Companion heat pump name
- Load side reference flow rate {m3/s}
- Source side reference flow rate {m3/s}
- Heat-recovery reference flow rate
- Reference capacity {w}

- Reference coefficient of performance {w/w}
- Sizing factor
- Capacity modifier function of temperature curve name
- Electric input to output ratio modifier function of temperature curve name
- Electric input to output ratio modifier function of part load ratio curve name
- Heating-to-cooling capacity sizing ratio
- Heat pump sizing method
- Control type
- Flow mode
- Minimum part load ratio
- Minimum source inlet temperature {c}
- Maximum source inlet temperature {c}
- Minimum supply water temperature curve name
- Maximum supply water temperature curve name
- Dry outdoor correction factor curve name
- Maximum outdoor dry bulb temperature for defrost operation
- Heat pump defrost control
- Heat pump defrost time period fraction
- Defrost energy input ratio function of temperature curve name
- Timed empirical defrost frequency curve name
- Timed empirical defrost heat load penalty curve name
- Timed empirical defrost heat input energy fraction curve name

Table 10: Prototype Buildings Used for Energy Impact Analysis for Four-Pipe Air-To-Water Heat Pumps and Water-To-Water Heat–Recovery Chiller

Building Type	Building Type Code	Modeled
Community College	ECC	Yes
Secondary School	Ese	Yes
University	Eun	Yes
Hospital	Hsp	Yes
Nursing Home	Nrs	Yes
Hotel	Htl	Yes
Manufacturing Biotech	MBT	Yes
Office – Large	OfL	Yes
Office – Small	OfS	Yes
Retail - Multistory Large	Rt3	Yes

Measure 3 Methodology: Water-To-Water Heat-Recovery Chiller Replacing Water-Cooled Chiller (partial electrification)

As addressed in the EnergyPlus Engineering reference manual, a water-to-water heat pump could be connected to a cold and hot plant loop to move energy from one plant to another. This is a form of heat recovery that is used to meet small plant loads in one plant loop (e.g., heating) while the other plant loop is active (e.g., cooling). The activation of a heat-recovery heat pump in this manner will reduce the active cooling plant load while meeting the heating plant load, which improves the overall plant efficiency. In EnergyPlus the plants are separate and therefore the load side of one coil is connected to one loop (e.g., cooling), while the source side is connected to the other loop (e.g., heating). The corresponding coil would be connected in the opposite fashion, where the load side is connected to the other loop (e.g., heating) while the source side is connected to the original loop (e.g., cooling). Given the constraints of a single mixer and splitter for a given plant loop, this connection can be challenging. One possible connection option is to connect one coil's load side to the plant inlet branch, while the source side is connected to the other plant's demand side outlet branch. Only one coil is operating at a time, while the idle coil operates as a pass-through unit.

As listed below, (PlantEquipmentOperation:ChillerHeaterChangeover) object can provide capabilities to control multiple plant loops using just one operation scheme. This operation scheme is intended for commercial building applications with hydronic heating and cooling systems served by heat pumps. While most plant controls in EnergyPlus provide control over operation of a single plant loop, some applications require heating and cooling plants to be controlled together. Heat pump type plant equipment systems can provide heating or cooling or both. Individual air source plant heat pumps can only operate in cooling or heating at a given time. However, in EnergyPlus, the plant modeling approach currently dictates that the heating loops and cooling loops are separate, and equipment is connected to one or the other for the entire simulation. Therefore, a plant heat pump is modeled with two companion machines that represent a single real machine. The heating side companion is connected to the heating loop and the cooling side companion is connected to the cooling loop. (PlantEquipmentOperation:ChillerHeaterChangeover) provides supervisory control over both the heating and cooling systems, so that switching the operation between heating and cooling can be coordinated and take into consideration the loads on the building and plant systems. In addition to a main set of one or more heat pumps, this operation scheme controls auxiliary boilers and a special water to water heat pump that is dedicated to moving heat between the returns of cooling and heating distribution systems. The control decisions involve turning heat pump equipment on and off, calculating and applying setpoint temperatures, and calculating and applying load distributions for back up boilers. Control decisions are based on inputs to the (PlantEquipmentOperation:ChillerHeaterChangeover), outdoor air temperatures, current building loads, and current loads on plant loops. The same prototypes will be used for WWHRC measure offering, as shown in Table 10.

(PlantEquipmentOperation:ChillerHeaterChangeover) Object Modeling Input in EnergyPlus 24.2

- Primary cooling plant setpoint temperature
- Secondary distribution cooling plant setpoint temperature
- Primary heating plant setpoint at outdoor high temperature
- Outdoor high temperature
- Primary heating plant setpoint at outdoor low temperature
- Outdoor low temperature
- Secondary distribution heating plant setpoint temperature
- Zone load polling zonelist name
- Cooling only load plant equipment operation cooling load name
- Heating only load plant equipment operation heating load name
- Simultaneous cooling and heating plant equipment operation cooling load name
- Simultaneous cooling and heating plant equipment operation heating load name
- Dedicated chilled water return recovery heatpump name
- Dedicated hot water return recovery heatpump name

Conclusions

This research provides a summary of AWHP/HRC technologies, case studies and evidence of successful projects in the field, preliminary research into modeling strategies for this equipment in EnergyPlus, and a preliminary list of high priority offerings for inclusion in a measure package. Based on extensive research and socialization efforts, the team is confident that the three initial offerings, being proposed as part of Phase 1, will provide appropriate deemed offerings in the commercial hydronic fuel substitution space that can enable cost-effective and high-volume program throughput.

The team has engaged with market actors (including manufacturers, mechanical designers, and distributors) throughout this research effort. It has presented the initial measure list to the Cal TF measure screening committee in September 2024 and gathered initial IOU feedback, which has been valuable in developing the final prioritized three initial offerings, as presented in this report. The team has also outlined some potential future measure offering opportunities (e.g., offerings that leverage thermal energy storage and wastewater heat recovery), for additional research and inclusion in future deemed measure development efforts.

Currently, the project team believes that one measure package is appropriate. However, the project team also acknowledges that California measure packages are designed to evolve, and further work following the conclusion of this project may shed light on the need for additional measure packages (e.g., splitting the two-pipe AWHP and HR equipment into separate measure packages, adding a separate measure package for wastewater heat recovery).

There are several next steps that will be undertaken in the next stage of development efforts, expected to commence early in 2025. The team plan to initiate further discussions with the market to narrow down on program rules and requirements, collect base case and measure case cost information, and better understand how to ensure that heat recovery equipment is prioritized as the first stage of heating in the system controls so that the anticipated reduction in boiler runtime hours is realized.

A non-critical but beneficial next step within the EnergyPlus DEER modeling task would be to collect additional manufacturer performance data and generate additional performance curves for AWHPs. This data will help refine the understanding of AWHP efficiency and performance characteristics.

Next Steps

In summary, for the measure package modeling task, the next steps are as follows:

- **Phase I, Short-Term:** Integrate the AWHP, WAHP, and WWHRC technologies into the DEER prototypes environment. Currently, the DEER prototypes lack an AWHP model, so this integration is crucial for ensuring accurate assessments and program design.
- **Phase II, Medium-Term:** Evaluate and implement the WAHP, AWHP, and WWHRC models within the DEER prototype, ensuring that it aligns with existing data and performance metrics. This will involve testing and validation to confirm the model's accuracy and reliability. Conduct the necessary parametric simulations to generate the impacts for a measure package.
- **Phase III, Long-Term (i.e., activities that could occur after version 1 of the measure package is finalized):** Consider further data collection and development of modeling approaches for HRCs. This will involve researching and gathering performance data for HRCs and developing robust modeling techniques to accurately reflect their efficiency and operational characteristics. This step will help expand the scope of energy efficiency measures and improve program effectiveness. From there, the project team will consider implementing a follow-up project.

The project team has engaged SDG&E for feedback at key stages of the project's development. A subsequent project is planned to begin measure package development under SDG&E's guidance, led by the same team.

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