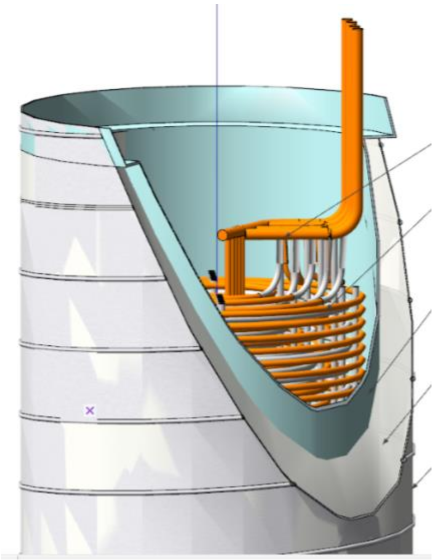
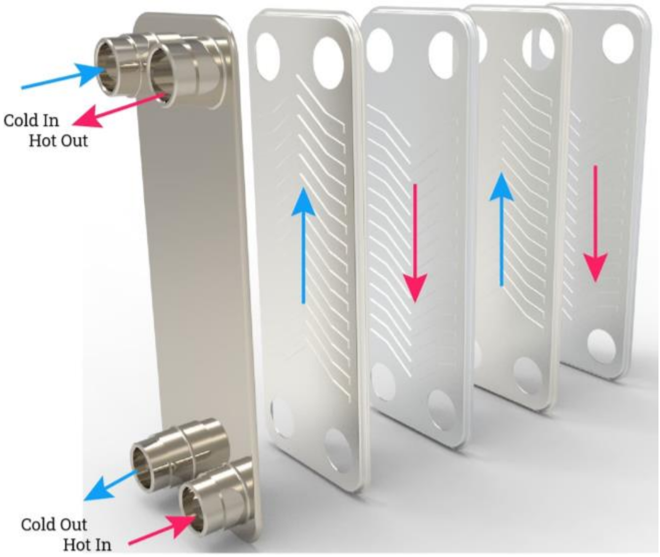
Residential Multi-Function Heat Pump – Heat Exchanger Improvement Project

Final Report

ET22SWE0051





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Executive Summary

Residential heat pump space conditioning and water heating can greatly reduce energy consumption compared to existing electric resistance or natural gas combustion options. Retrofit requirements for electrical service upgrades add cost and installation delays for customers considering heat pumps for space conditioning and/or hot water heating. Between 30 percent and 50 percent of all homes are expected to need electrical service panel upgrades that add cost and cause system installation delays to fully electrify.

Residential multi-function heat pumps (MFHP) use one efficient compressor and outdoor heat exchanger coil to provide space cooling, space heating, and domestic hot water heating. Air-to-air versions of multi-function heat pumps use refrigerants to provide heating and cooling services and have the potential to eliminate the need for electric resistance backup heaters, which reduces the maximum power requirements for full size capacity systems.

Eliminating the need for upgrades to electrical service breaker panel and electrical service reduces cost and speeds up installation times. For retrofits in buildings with existing air conditioning full-size capacity, air-to-air multi-function heat pumps can use existing air conditioning electrical circuits without modification. For buildings without air conditioning, the air-to-air multi-function heat pump is less likely to trigger the need for a service breaker panel or service wire upgrade compared to the typical combination of separate space-conditioning heat pump and standalone heat pump water heater products.

Multi-function Heat Pump Products

A previous technical market characterization by University of California, Davis (UCD) Western Cooling Efficiency Center (WCEC) completed an air-to-air multi-function heat pump product search (Vernon 2022). The Villara AquaThermAire launched commercially in Q1 2023 and is the only air-to-air multi-function heat pump the project team could find for sale in California as of November 2023. Panasonic offers an air-to-air multi-function heat pump product in southern Europe but there is no announced date for offering the product in the U.S. market. At The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Winter Conference Air-Conditioning Heating and Refrigeration (AHR) Expo in February 2023, both LG and Samsung announced plans to offer an air-to-air multi-function heat pump product in the U.S. in 2023.

Water Tank Heat Exchanger Design

In all multi-function heat pump system designs, thermal energy must be exchanged from refrigerant-to-water and then from water-to-water in order to provide the domestic hot water heating service. The design of the heat exchangers has a significant impact on energy efficiency, cost, and the amount of refrigerant required in the system. Heat exchanger design impacts the energy efficiency for water heating through heat transfer resistance and pressure drop. Heat exchanger design impacts cost through materials costs, manufacturing labor costs, and potentially installation costs. Different heat exchanger designs require different amounts of refrigerant, leading to different possible global warming impacts from refrigerant leaks.

The existing multi-function heat pump products use either ambient pressure hot water tank with both a refrigerant-to-water coil and a water-to-water heat exchanger coil immersed inside or use a brazed plate refrigerant-to-water heat exchanger with only the water-to-water heat exchanger coil immersed in a pressurized hot water tank. This project collected specifications and cost data for relevant commercially available heat exchangers, built computer models of the refrigerant-to-water and water-to-water heat exchangers, and completed a techno-economic analysis to recommend improvements that can increase efficiency, reduce cost, and reduce refrigerant greenhouse gas (GHG) impacts.

Results

Finned Tubes

Finned copper tubes can replace the current water-to-water heat exchanger coil design, which uses smooth walled copper tubes. Compared to smooth copper tubes, models built in this project predict finned tubes to enhance heat transfer per linear length of tubing by 4.6 times. The manufacturer claims an enhancement of 5.9 times. The simulation results and manufacturer-specified heat transfer enhancement numbers mean that using finned copper tubes of either 22 percent or 17 percent the length of the current smooth copper tubes will achieve the same hot water heating performance and reduce the amount of copper required and the labor required to assemble. Finned copper tubes can reduce the weight of copper required by either 38 or 51 percent, reducing the influence of copper commodity price fluctuations and reducing the weight of the hot tank for shipping and installation.

The cost of the finned tubes is 5.1 times that of the smooth tubes so for the simulation-predicted 4.6 times enhancement there would be a small materials cost increase, or for the manufacturer-claimed 5.9 times enhancement there would be a small materials cost decrease. We estimate that the labor required to bend the finned tubes into coils, connect to manifolds, and install in the tank will be approximately two hours less than the amount of time it now takes for the much longer smooth tubes. Overall, finned copper tubes of the same heat transfer capacity are predicted to slightly reduce the cost.

Brazed Plate Heat Exchangers

Brazed Plate Heat Exchangers (BPHX) are used in some multi-function heat pump products for the refrigerant-to-water heat exchanger. This study identifies several ways that the BPHX design may be better than an ambient pressure hot water tank with double coil design.

BPHX: COST

Specifications and costs for BPHX from Kaori and SWEP and balance of system pump, pump controller, and connections components show that replacing the current ambient pressure tank smooth copper tube coil refrigerant-to-water heat exchanger can reduce the materials cost by as much as 21 percent. We estimate that the total labor hours for assembling the ambient pressure hot water tank and heat exchangers using the BPHX can be reduced by at least one hour compared to the current design. Depending on packaging of the water pump, site installation time may increase by approximately one hour for a net equal total labor time between the current design and the BPHX design. The cost of pressurized hot water tanks with custom water-to-water heat exchanger coils are strongly dependent on the number of units being manufactured. This project was unable to find publicly available pressurized water tank cost dependence on scale of production, so it is not included in this analysis.

BPHX: REFRIGERANT PRESSURE DROP

The current ambient pressure tank refrigerant-to-water heat exchanger design uses 700 feet of smooth 3/8-inch diameter copper tubing for the refrigerant-to-water heat exchanger. Measurements in a manufacturer lab show a refrigerant pressure drop of 5 psi. This study collected specifications and price quotes for three BPHX models all with refrigerant pressure drop below 1.5 psi. This reduction in refrigerant pressure drop equates to a 30W reduction in compressor power and small increase in efficiency for hot water heating.

BPHX: WATER PUMP POWER CONSUMPTION

The BPHX design uses a small water pump to circulate water through the BPHX and into the tank water-to-water heat exchanger coil. This water pump will consume electrical power whenever the HP is heating the water in the tank. The water pump power consumption is calculated to be 32W.

BPHX: WEIGHT

Depending on which BPHX model is selected, the BPHX and balance of specifications collected for system pump, pump controller, and connections components show a heat exchanger weight reduction of 31 to 78 lbs. compared to the current ambient pressure tank refrigerant-to-water heat exchanger design using 700 feet of smooth 3/8-inch diameter copper tubing.

BPHX: REFRIGERANT CHARGE

The BPHX has a smaller internal volume than the current ambient pressure tank refrigerant-to-water heat exchanger design so it will reduce the amount of refrigerant required. The internal volume of the current ambient pressure tank refrigerant-to-water heat exchanger is 10.5 liters and requires 5.25 lb. of R-410A refrigerant charge. The internal volume of the lowest cost BPHX Kaori K070-98 is 3.1 liters. The BPHX Kaori K070-98 design would reduce refrigerant volume and charge for the hot water tank by a factor of more than three, reducing mass of R-410A refrigerant by approximately 3.7 lbs.

Water-To-Water Heat Exchanger Approach Temperatures

The resistance to heat transfer from refrigerant-to-water and from water-to-water steps leads to a difference in temperature of the two flows, called an approach temperature. Both the ambient pressure tank and the pressurized tank designs use a water-to-water heat exchanger coil immersed in the tank. Resistance to heat transfer in the coil leads to approach temperatures that require the heat pump to move thermal energy to a higher temperature and increase energy consumption.

For the current ambient pressure tank design, the cold inlet water goes through the water-to-water heat exchanger; for fast water draws the approach temperatures will be large and can increase heat pump compressor energy consumption. For the pressurized tank designs, the water-to-water heat exchanger coil transfers thermal energy from a primary water loop to the inlet cold water in the tank with significantly lower maximum rate of heat transfer. For this reason, with the same size water-to-water heat exchanger coil the pressurized tank design is predicted to have a compressor energy consumption roughly 4.7 percent, 206W, less than for the ambient pressure tank design. For the hot water consumption measured at the field site being monitored for an ongoing study, the annual energy savings would be 42 kWh.

Recommendations

MFHP hot water heat exchanger designs using a refrigerant-to-water BPHX combined with a pressurized tank containing an immersed water-to-water heat exchanger coil have the potential to save energy and reduce cost compared to the ambient pressure tank double-immersed coil design. The UCD team recommends that a future emerging technology project test both the ambient pressure tank and pressurized tank designs to further inform the path of manufacturer future multi-function heat pump product development.

This project directly prepares for a lab demonstration project to test system performance by informing the decision of whether to test existing or improved heat exchanger designs. This work also informs heat exchanger design selection for future field demonstration(s) and performance verification in disadvantaged community settings and hard-to-reach customer buildings.

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Abbreviations and Acronyms

Acronym	Meaning
AC	Air Conditioner
AHR	Air Conditioning, Heating, and Refrigeration
AHRI	Air Conditioning, Heating, and Refrigeration Institute
AHR	Air Conditioning, Heating, and Refrigeration
AWHP	Air-To-Water Heat Pump
BPHX	Brazed Plate Heat Exchangers
CEC	California Energy Commission
COP	Coefficient of Performance
DAC	Disadvantaged Communities
EE	Energy Efficiency
ET	Emerging Technology
FHR	First Hour Rating
GHG	Greenhouse Gas
GWP	Global Warming Potential
HP	Heat Pump
HPWH	Heat Pump Water Heater
HTR	Hard-to-Reach
HVAC	Heating, Ventilation, and Air Conditioning
IOUs	Investor-Owned Utilities
kWh	Kilowatt-hour
MFHP	Residential Multi-Function Heat Pump

Acronym	Meaning
NEEA	Northwest Energy Efficiency Alliance
R&D	Research and Development
RT	Refrigeration Ton
SCE	Southern California Edison
SDG&E	San Diego Gas & Electric
U.S.	United States
WCEC	UC Davis Western Cooling Efficiency Center

Introduction

Residential heat pump (HP) space conditioning and water heating products are more efficient than existing electric resistance or natural gas combustion options. For retrofit customers considering HP for space conditioning and/or hot water heating, requirements for electrical service upgrades add cost and installation delays for retrofit customers (Sarah Outcault 2021). Around 30 to 50 percent of all homes are expected to need electrical service panel upgrades to fully electrify (Efficiency First California 2020, Merski 2021, Murphy 2022, Zhao 2021, Lindsey 2023). The cost of an electrical service panel upgrade in California is typically around $5,000 but can range from $2,000 to $30,000, potentially a cost-prohibitive additional cost for electrification retrofits (Lindsey 2023, Shoshana Pena 2022).

Residential multi-function heat pumps use one efficient compressor and outdoor heat exchanger coil to provide space cooling, space heating, and domestic hot water heating. These systems offer many energy efficiency (EE) benefits. Air-to-air versions of multi-function heat pumps use refrigerant to provide heating and cooling services and have the potential to eliminate the need for electric resistance backup heaters, reducing the maximum power requirements for full-size capacity systems. For retrofits in buildings with existing air conditioning (AC), this means that full-size capacity air-to-air multi-function heat pumps can use existing AC electrical circuits without modification. Air-to-air multi-function heat pumps will have lower peak power consumption than separate space conditioning and stand-alone heat pump water heater equipment, so they are less likely to trigger the need for a service breaker panel or service wire upgrade.

(Sarah Outcault 2021, Shoshana Pena 2022)This air-to-air multi-function heat pump technology allows a full-capacity HP matching the building heat demand in most California climates to use an existing split-system AC electrical circuit.

Historically, to avoid the need for electrical service panel upgrades heat pumps could be undersized. Under sizing heat pumps is not recommended because they will not be able to meet the peak loads and may use electric resistance strip heaters for auxiliary heating reducing efficiency and increasing energy consumption. Oversizing of single speed heat pump equipment causes short cycling with reduced efficiency and increased energy consumption.

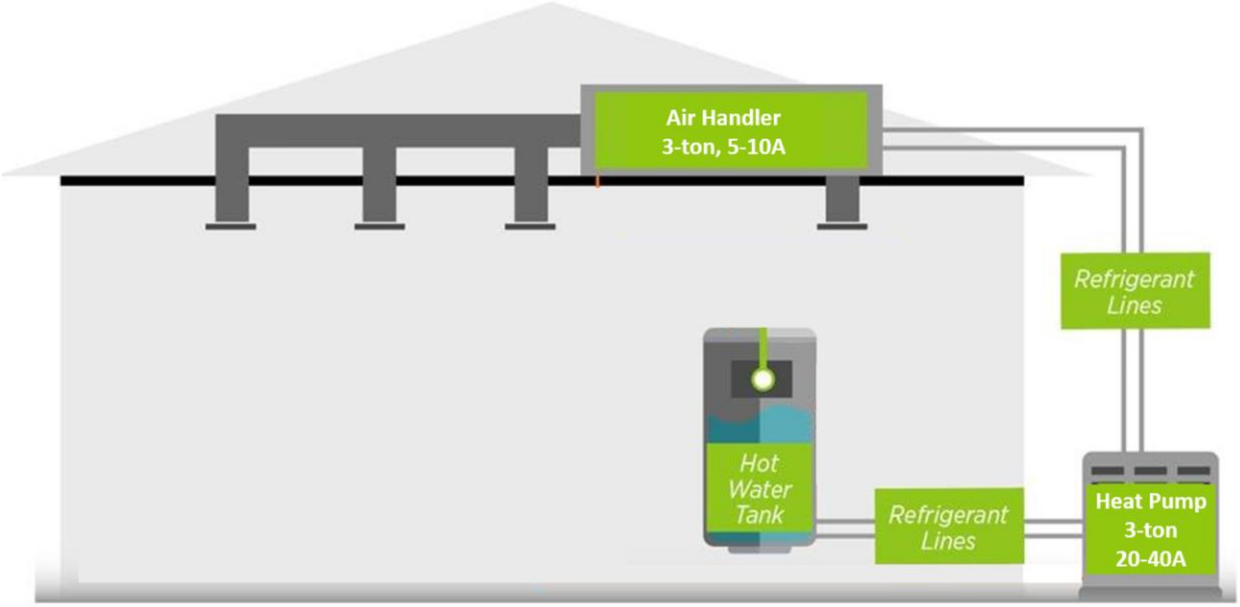

Figure 1. Air-to-air multi-function heat pump system diagram showing the outdoor unit and refrigerant lines serving both the air handler and the indoor hot water tank

Source: Adapted from original image provided by Villara

Disadvantaged communities (DACs) and hard-to-reach (HTR) customers are more likely to live in older, single-family homes and apartment buildings with smaller electrical service panels (30-100A), smaller-gauge building electrical distribution wires, and smaller-capacity utility step down transformers (Lindsey 2023, Shoshana Pena 2022). This means that DAC and HTR customers are more likely to need electrical service upgrades, resulting in more costly projects, and thus experience a larger barrier to electrification. Multi-function heat pumps have the potential to significantly reduce electrification costs and reduce installation times, particularly for such customers.

Multi-function Heat Pump Products

The University of California, Davis (UCD) Western Cooling Efficiency Center (WCEC) completed an air-to-air MFHP product search in 2022 to identify multi-function heat pump products commercially available in the U.S. and globally (Vernon 2022). The Villara AquaThermAire is the only air-to-air multi-function heat pump commercially available in California that the project team was able to find as of November 2023. Panasonic offers an air-to-air multi-function heat pump product in southern Europe but there is no announced date for offering the product in the United States (U.S.) market. In February 2023, both LG and Samsung announced plans to offer a residential air-to-air multi-function heat pump product in the U.S. in 2023 at the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Winter Conference Air Conditioning Heating and Refrigeration (AHR) Expo.

Multi-function Heat Pump System Design

The ambient pressure hot water tank has both a refrigerant-to-water heat exchanger coil and a water-to-water heat exchanger coil immersed inside. This ambient pressure hot water tank design is similar to solar thermal hot water tanks in that municipal water supply flows through a heat exchanger tube and stays separate from the thermal storage water inside the tank. With this design, the hot water tank stays at ambient pressure, does not need to be a pressure vessel, and does not need a pressure relief valve.

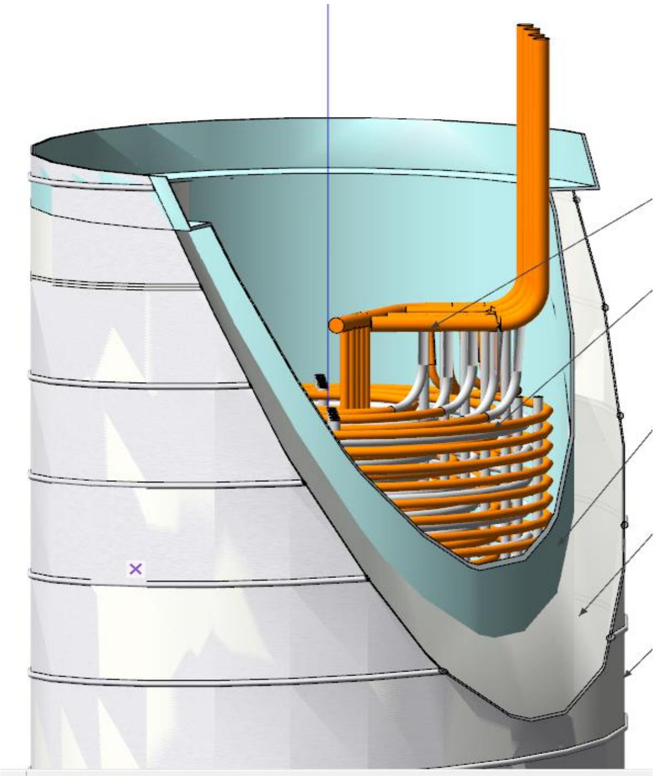

Figure 2. Ambient pressure hot water tank with refrigerant-to-water and water-to-water coiled tube heat exchangers immersed inside the water thermal-energy storage tank

Source: Villara

The pressurized hot water tank design is similar to indirectly heated hot water heaters. In the pressurized tank system design, the refrigerant from the outdoor compressor flows through a refrigerant-to-water brazed plate heat exchanger (BPHX), heating a primary water loop circulated by a water pump to flow through an immersed water-to-water heat exchanger coil in the hot water tank. Municipal water flows into the pressurized tank and is heated by the primary water loop by the immersed water-to-water heat exchanger coil.

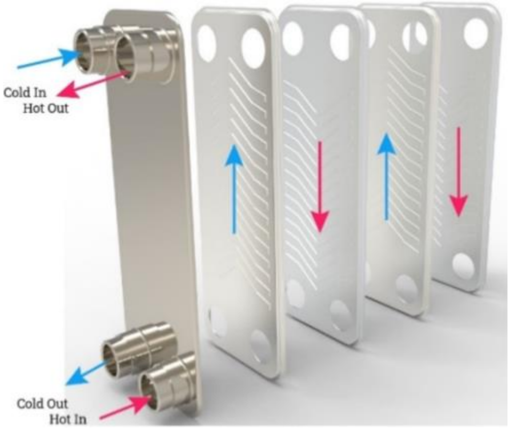

Figure 3. Example plate refrigerant-to-water heat exchanger

Source: IQS Directory

Heat Exchanger Design

In both of these multi-function heat pump system design types, thermal energy must be exchanged from refrigerant-to-water and then from water-to-water in order to provide the domestic hot water heating service. The design of the heat exchangers has a significant impact on energy efficiency, cost, and the amount of refrigerant required in the system. Heat exchanger design impacts the water heating energy efficiency through heat transfer resistance and pressure drop. Heat exchanger design impacts cost through materials costs, manufacturing labor costs, and potentially installation costs. Different heat exchanger designs require different amounts of system refrigerant, leading to different possible global warming impacts from refrigerant leak.

HX Energy Impacts

The resistance to heat transfer from refrigerant-to-water and from water-to-water steps leads to a difference in temperature of the two flows, called an approach temperature. When the heat pump is heating the water, it must move thermal energy from a lower temperature up to the tank temperature plus the approach temperature. In this way heat exchangers with lower effectiveness and larger approach temperatures increase the difference in temperature that the heat pump must overcome (called the heat pump lift) which increases energy consumption. Higher-effectiveness heat exchangers reduce the approach temperature, thereby reducing the lift and reducing the heat pump energy consumption.

Tube coil heat exchanger effectiveness can be improved by using a larger heat transfer area, moving the fluid on one or both sides to achieve forced convection, or by using advanced designs with enhanced surface area. Increasing heat exchanger size to increase area increases cost and can increase the pressure drop and amount of refrigerant required. Moving the fluids on both sides of a heat exchanger would require an additional pump, increasing cost and energy consumption and thus reducing the energy savings. Increasing pressure drop in the refrigerant flow increases the compressor power consumption and, for a primary water loop, increasing pressure drop in the water flow increases pump power consumption. Advanced heat exchanger designs with surface area enhancements have the potential to reduce energy consumption and possibly also reduce costs.

Changing heat exchanger types from simple tube coils to BPHX also requires a water pump to circulate the water through the heat exchanger, adding some equipment cost and reducing the energy savings. BPHX can achieve significantly higher heat transfer effectiveness than tube coil designs in a given volume.

For both multi-function heat pump system design types, there are also options for using lower greenhouse gas (GHG) impact refrigerants. In particular, low- and ultra-low global warming potential (GWP) refrigerants can be flammable, motivating a reduction of the total mass of refrigerant that could leak inside a residential building.

This project identified relevant, commercially available heat exchangers for multi-function heat pump systems, collected specifications and cost data, built computer models of the refrigerant-to-water and water-to-water heat exchangers to assess the current ambient pressure tank design, and completed a technoeconomic analysis to recommend improvements that can increase efficiency, reduce cost, and reduce refrigerant GHG impacts.

This project directly prepares for a future lab demonstration project to test system performance with improved heat exchanger design as well as field demonstration(s) and performance verification(s) in DAC and HTR customer buildings.

Background

Early domestic hot water tank models in scientific literature were developed for solar thermal water heaters of various configurations (Buckles and Klein 1980). Since then, the stratified nature of the temperature profile in the tanks was studied in detail and modeled, with experiments conducted by several research groups (Hariharan, et al. 1991, Hawlader, Bongt and Lee 2007, Hollands and Lightstone 1989, Kleinbach, Beckman and Klein 1993, Rosengarten, Morrison and Behnia 1999). Further studies combined solar thermal water heating with HPs to assist during times of low or no solar irradiation (Comakli, Kaygusuz and Ayhan 1993, Kaygusuz and Ayhan 1999, Sterling and Collins 2012). Carbon dioxide (CO_2) refrigerant HPs were found to be a good fit for domestic hot water and were also combined with space heating for cold climate operation (Brodal and Jackson 2019, Janowitz, et al. 2020, Minetto 2011, Stene 2005, Velasco, et al. 2022). HPs with regular refrigerants used for heating and cooling have also been combined with hot water tanks, where the very hot refrigerant leaving the compressor was used to pre-heat domestic hot water using an additional refrigerant-to-water heat exchanger, called a desuperheater, in an additional pre-heat water tank that then fed to the regular hot water heater (Jia, Lee and Cheng, et al. 2021, Jia and Lee 2015, Modera, Woolley and Grupp 2014). Desuperheater use to heat water leads to lower condenser pressure reducing compressor energy consumption. However, the value of desuperheater energy savings was small compared to the relatively high costs for the desuperheater and pre-heat tank hardware (Heinz, Gritzer and Thür 2022). More recently, standalone integrated heat pump water heaters with heat exchanger tube coils wrapped around the exterior of the hot water tank have been studied (Li and Hrnjak 2018, Shah and Hrnjak 2014, Shen, et al. 2018).

Residential multi-function heat pumps use compressors with capacity greater than two refrigeration tons (RT) for both space conditioning and water heating and would have much larger refrigerant flow than the typical standalone integrated heat pump water heaters with compressor capacities around one-third RT. Searches by the project team did not find any studies analyzing the performance of heat exchangers and tanks for the compressor capacity range of two-to-five RT relevant to residential multi-function heat pumps.

The types of heat exchangers relevant to residential multi-function heat pumps include tube coil (with smooth or enhanced surface area tubes) and BPHX. Smooth tubes are less expensive than enhanced surface area tubes. Smooth tubes have smaller surface area and lower heat exchange effectiveness per volume of heat exchanger than enhanced surface area tubes and brazed plate options. The tradeoffs between cost, surface area, and effectiveness depend on several variables and require modeling to select the best choices.

Improved heat exchanger designs can increase heat exchanger effectiveness and/or reduce heat exchanger size with the following benefits:

- Reduce heat pump energy consumption by reducing approach temperature that reduces HP lift.
- Increasing heat exchanger effectiveness can increase the rate of hot water heating, with the potential to use a smaller tank size to provide the same hot water service, which in turn:
  - Reduces equipment costs
  - Reduces installation costs
  - Allows these products to fit into more buildings while avoiding or reducing the need for physical modification of the tank location
- Increasing the surface area per volume can enable a decrease in the size of the heat exchanger required, thereby reducing:
  - Quantity of refrigerant required
  - Weight of equipment
  - Potential equipment cost

Objectives

This study:

1. Collected technical specifications and cost information for relevant, commercially available heat exchangers.
2. Recommends improvements to heat exchanger designs to further improve efficiency and performance, reduce cost, and support future low GWP refrigerant selection.
3. Recommends improved refrigerant to hot water heat exchanger designs to test in the follow-on lab demonstration emerging technology projects.
4. Recommends improved refrigerant to hot water heat exchanger designs for all manufacturers of MFHPs.
5. Established partnerships with the manufacturer(s) of heat exchanger products to support product improvements.

Methodology & Approach

Heat Exchanger Data

This project collected specifications and cost data for relevant, commercially available heat exchangers through the team's network of heating, ventilation, and air conditioning (HVAC) experts, in-person trade shows, and online searches. To identify other sources for heat exchangers, WCEC worked with HVAC manufacturers including Mitsubishi, Panasonic, Rheem, and Villara.

Computer Heat Exchanger Model

This project team identified and reviewed several existing computer models of hot water tanks and heat exchangers.

The team reviewed a finite-difference-based hot water tank and coil model implemented with object-oriented programming in Python developed by UCD Professor Matt Ellis. Consultation with Professor Ellis showed that this model did not have the fidelity for heat exchanger modeling that we were seeking, and the Python implementation introduced limitations that would make the intended project difficult.

The team deeply reviewed a model from the Lawrence Berkeley National Laboratory (LBNL) Modelica Buildings Library containing a refrigerant-to-water BPHX heating process that uses a primary water loop circulated by a water pump and heating a stratified hot water tank with immersed coil tube heat exchanger (Nash, Badithela and Jain 2017)[1]. Modelica is a dynamic simulation tool that can model heat and mass transfer in a broad range of applications. This model has been previously tested and experimentally verified to accurately predict the thermal behavior of the refrigerant-to-water BPHX, primary water loop water-to-water heat exchange, and water tank processes (Kenhove, et al. 2019). Reviewing the model and subcomponent models' documentation and implementation in Modelica

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[1] https://simulationresearch.lbl.gov/modelica/releases/latest/help/Buildings_Fluid_Storage.html

showed a lack of explicit definitions of the equations and assumptions used in the model. This lack of transparent modeling methods was not compatible with the goals of this project.

The project team built a custom model starting from the overall framework methods of the Modelica model in a dynamic simulation software suite called Engineering Equation Solver (EES). This custom model included a stratified hot water tank and immersed coil, as well as a coupled compressor and BPHX model.

Stratified Tank and Coil Model

The stratified hot water tank is heated by a primary loop flow of water passing through the immersed and water-to-water heat exchanger coil. The tank exterior is assumed to be well-insulated since this factor is not important to comparing heat exchanger designs. Figure 4 shows a schematic of the tank. Hot water is supplied to the coil by a primary water loop after exiting from the coil in the tank, is reheated before returning to the tank coil inlet. For system control the tank thermostat temperature sensor is located at a height two-thirds from the bottom of the tank to match typical heat pump water heater designs. Figure 4 shows a schematic of the stratified tank and heat exchanger coil model and visual representation the energy balances on each control volume.

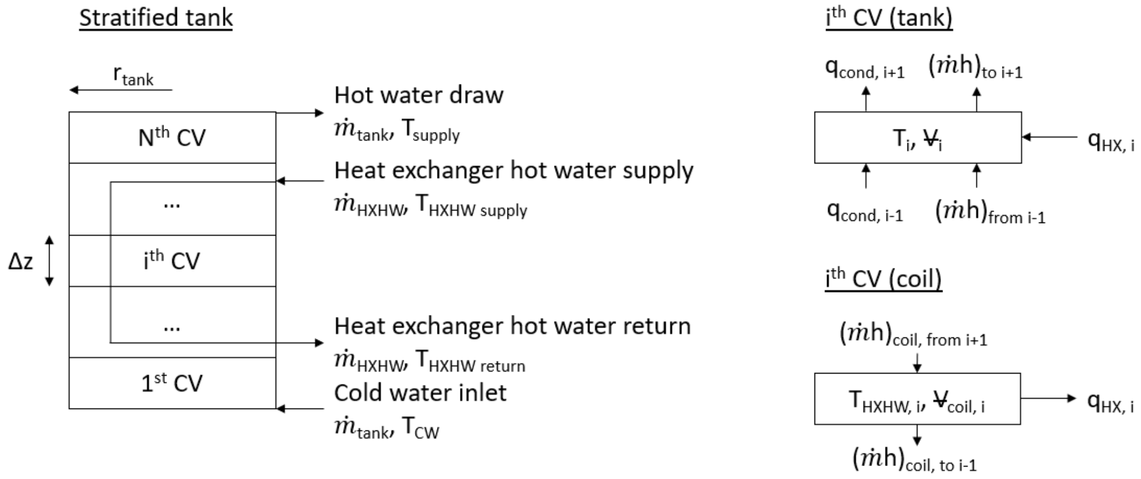

Figure 4 Schematic of tank, as well as energy balances on i^{th} control volumes for tank water and coil water

The stratified tank is divided into control volumes (CVs) as illustrated in Figure 4. Performing an energy balance on the i^{th} tank water CV yields:

$$\frac{dE_{st,i}}{dt} = q_{net,i}, \qquad (1)$$

where the lefthand side is the time rate of change of energy stored in the CV and the righthand side is the net energy transfer across the CV boundaries via heat or mass transfer. The lefthand side of (1) can be rewritten as:

$$\frac{dE_{st,i}}{dt} = \rho_i V_i c_{p,i} \frac{dT_i}{dt}, \qquad (2)$$

where ρ, V, and c_p represent the density, volume, and specific heat of water, respectively. The time rate of change in temperature is approximated as:

$$\frac{dT_i}{dt} \approx \frac{T_{i,j}-T_{i,j-1}}{\Delta t}, \qquad (3)$$

with j representing the time step. The righthand side of (1) can be rewritten as:

$$q_{net,i} = q_{cond,i-1} - q_{cond,i+1} + (\dot{m}h)_{from\ i-1} - (\dot{m}h)_{to\ i+1} + q_{HX,i}. \qquad (4)$$

The conductive heat transfer terms between adjacent tank CVs are given by:

$$q_{cond,i-1} = \frac{k_{water,i}A(T_{i-1}-T_i)}{\Delta z} \qquad (5)$$

$$q_{cond,i+1} = \frac{k_{water,i}A(T_i-T_{i+1})}{\Delta z} \qquad (6)$$

where k_{water} is the thermal conductivity of water, A is the area of the interface between control volumes (πr^2_{tank}). The thermal conductivity is modified as follows to handle the cases where temperatures inversion in the tank occurs (i.e., when lower CVs are at higher temperatures than upper CVs). For the conductive heat transfer term between CVs i-1 and i:

$$k_{water,i} = \begin{cases} k_{water,i} & if\ T_{i-1} < T_i \\ k_{water,i} f|T_i - T_{i-1}| & otherwise \end{cases}, \qquad (7)$$

and for the conductive heat transfer term between CVs i and i+1:

$$k_{water,i} = \begin{cases} k_{water,i} & if\ T_i < T_{i+1} \\ k_{water,i} f|T_i - T_{i+1}| & otherwise \end{cases}, \qquad (8)$$

where f is simply a large number designed to increase the thermal conductivity by several orders of magnitude to account for buoyancy effects [1].

The enthalpy flow terms can be rewritten in terms of specific heats and temperatures as follows (using the average of the adjacent control volume temperatures as the interface temperature):

$$(\dot{m}h)_{from\ i-1} - (\dot{m}h)_{to\ i+1} = \frac{\dot{m}_{tank}c_{p,i}}{2}(T_{i-1} - T_{i+1}) \qquad (9)$$

For tank CVs without the coil, the heat transfer term from the hot water in the coil to the tank is 0. For tank CVs with the coil, the heat transfer is given by:

$$q_{HX,i} = \frac{T_{HXHW,i}-T_i}{dR_{tot,i}}, \qquad (10)$$

where the total thermal resistance is:

$$dR_{tot,i} = dR_{conv\ HX,i} + dR_{cond\ tube,i} + dR_{conv\ tank,i}. \qquad (11)$$

The convective resistance on the coil water side is given by:

$$dR_{conv\ HX,i} = \frac{1}{htc_{HXHW,i}A_{s\ inner,i}}, \qquad (12)$$

where htc_{HXHW} is the convective heat transfer coefficient and $A_{s\ inner}$ is the surface area of the inside of the tube. The conductive resistance of the tube is given by:

$$dR_{cond\ tube,i} = \frac{t_{tube}}{k_{tube}A_{s\ average,i}}, \qquad (13)$$

where t_{tube} is the tube thickness, k_{tube} is the thermal conductivity of the tube, and $A_{s\ average}$ is the average between the tubes outer and inner surface areas.

Both finned and unfinned tubes were considered. For an unfinned tube, the convective resistance on the tank water side is given by:

$$dR_{conv\ tank,i} = \frac{1}{htc_{tank,i}A_{s\ outer,i}}, \qquad (14)$$

where htc_{tank} is the convective heat transfer coefficient and $A_{s\ outer}$ is the surface area of the outside of the tube. For the finned tube, the:

$$dR_{conv\ tank,i} = \frac{1}{\eta_o htc_{tank,i}A_{t,i}}, \qquad (15)$$

where η_o is the overall surface efficiency and A_t is the total external surface area of the tube. η_o is given by:

$$\eta_o = 1 - \frac{NA_f}{A_{t,i}}(1 - \eta_f), \qquad (16)$$

where N is the number of fins and A_f is the area of a fin. η_f is the fin efficiency, calculated using the equations for an annular fin included in Table 3.5 of [2].

Performing an energy balance on the i^{th} coil water CV yields:

$$\frac{dE_{st\ coil,i}}{dt} = q_{net\ coil,i}, \qquad (17)$$

where Equations (2) and (3) can be applied to the lefthand side as above for the tank CVs. The righthand side is given by:

$$q_{net\ coil,i} = (\dot{m}h)_{coil,from\ i+1} - (\dot{m}h)_{coil,to\ i-1} + q_{HX,i}. \qquad (18)$$

Note that the coil inlet is higher than the coil outlet, so coil water flows from upper CVs to lower CVs. Rewriting the enthalpy difference in terms of specific heat and temperature yields:

$$q_{net\ coil,i} = \frac{\dot{m}_{HXHW}c_{p\ coil,i}}{2}(T_{HXHW,i+1} - T_{HXHW,i-1}) + q_{HX,i}. \qquad (19)$$

This model was used in two different scenarios. The first scenario used the model to examine the current smooth copper tube coil design and potential for finned tube designs and held the primary water loop coil inlet temperature constant. The second scenario expanded the model to include a BPHX and simple compressor model with components sized to match the 4-RT capacity of the outdoor unit compressor. This BPHX and compressor reheat the primary loop water from the coil outlet temperature back to a coil inlet temperature.

Compressor and BPHX Model

Starting with AHRI rating test results for a single speed Carrier split-system heat pump for space conditioning, the project team calculated the compressor refrigerant mass flow rate and isentropic efficiency. This compressor mass flow rate and isentropic efficiency were held constant to predict the compressor behavior for hot water heating showing a capacity of 13.9 kW and compressor electrical power of 4.5kW. These compressor model results aligned well with the field test data for this equipment modified to provide water heating.

A simple brazed plate refrigerant to water heat exchanger model was created to simulate the water conditions when the BPHX is connected to the water tank and coil model. The refrigerant side of the brazed plate is held constant to provide a heat duty of 13.9kW with constant refrigerant inlet and outlet conditions. The water side of the BPHE is modeled with physics equations. An epsilon NTU method is used to calculate the heat transfer to the water. The brazed plate model operated in conjunction with the water tank model and a pump. Given the inputs of the mass flow rate (based on pump speed) and inlet water temperature (based on tank stored water temperatures), the model would calculate the heat transfer coefficient of water and subsequently output the water outlet temperature. The water outlet temperature is used as input for the primary loop entering hot water temperature to the tank water-to-water heat exchanger coil.

The simulations of the pressurized tank BPHX system combined the above equations for the tank and immersed coil model with the compressor and BPHX models to calculate the tank temperatures and domestic hot water supply temperatures to be predicted in different operating scenarios.

Water Heating Efficiency Prediction

HEAT EXCHANGER APPROACH TEMPERATURE

The impact of the heat exchanger designs on water heating efficiency was predicted using empirical system-level heat pump models to calculate the heat pump coefficient of performance (COP) at the different temperature lifts associated with each of the different heat exchanger options. The UC Davis Western Cooling Efficiency Center (WCEC) has completed a PG&E-funded emerging technologies project field testing an early 2022 production ready prototype of the Villara AquaThermAire Multi-function Heat Pump. Continuing field data collection for this early 2022 production ready prototype by the WCEC funded by the California Energy Commission – California Flex Hub program is collecting additional field energy performance data. Field data collected over the past year for hot water heating show a dependence of the efficiency of water heating on the average tank temperature measured by three sensors spaced vertically though the tank, Figure 5. Lower effectiveness heat exchangers lead to a higher approach temperature, effectively increasing the heating temperature that the heat pump needs to supply and reducing the HP efficiency. The coefficient of performance (COP) versus average tank temperature data can be used to roughly estimate the energy consumption impact from these higher approach temperatures. These estimates are relatively rough due to variability in the field data, imperfect correlation of the average tank temperature and the effective tank temperature impact of heat exchanger approach temperature, and application across multiple heat exchangers in the system. These predictions are directional and need to be verified by laboratory tests for high confidence in the magnitude.

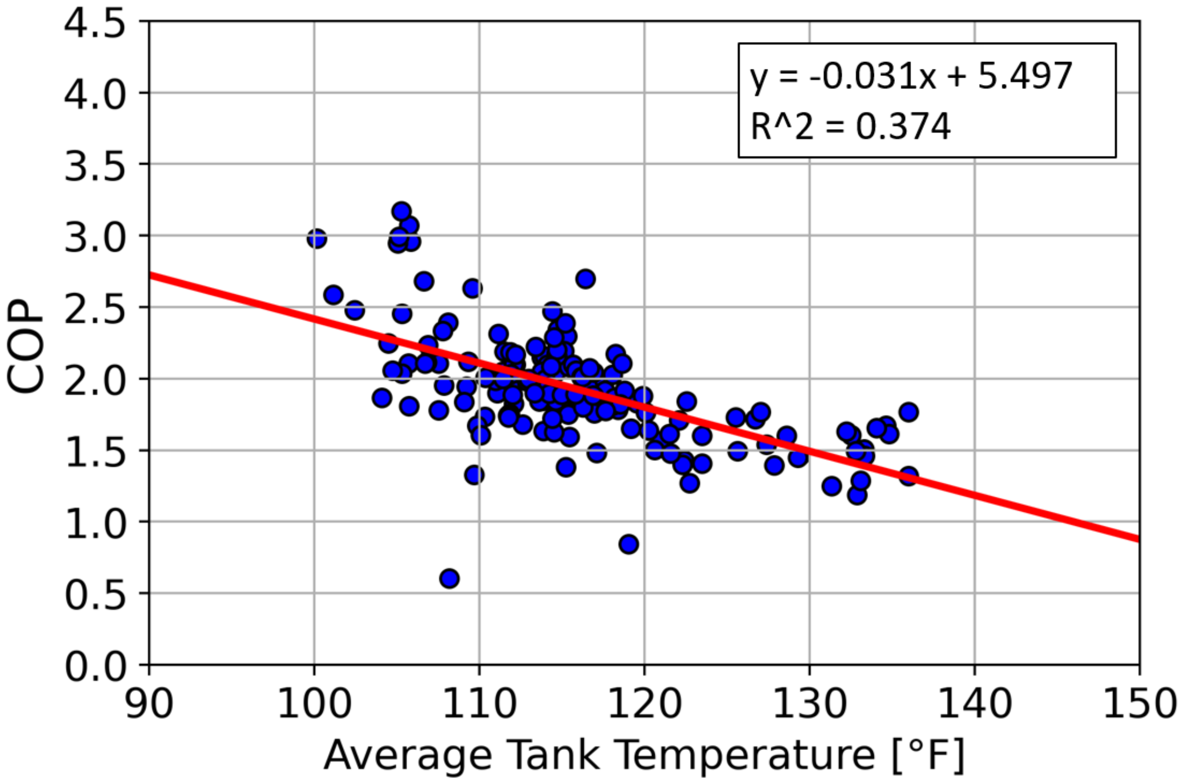

Figure 5 Field test data of the Villara AquaThermAire for water heating cycles, COP versus average tank temperature

Source: UC Davis WCEC

HEAT EXCHANGER REFRIGERANT PRESSURE DROP

Refrigerant flowing through the refrigerant-to-water heat exchanger experiences pressure drop that depends on the heat exchanger design as well as what fraction of the length the refrigerant is in superheated vapor, saturated vapor and liquid mix, and subcooled liquid states. Manufacturer lab tests of the pressure drop in the current ambient pressure hot water tank refrigerant-to-water heat exchanger and manufacturer specifications for the BPHX are used to quantify the pressure drop in typical operating conditions.

The compressor model described above was used to assess the impact of refrigerant pressure drop in the different refrigerant-to-water heat exchanger options.

HEAT EXCHANGER WATER PRESSURE DROP

The EES model also predicts water flow pressure drop through the tube coils or BPHX and the associated pumping power required. The model uses Reynolds number correlations to determine the friction factor and associated pressure drop per length of water passage. The flow power required for pumping water through the coil or BPHX is given by:

$$P_{flow} = \Delta P Q, \qquad (20)$$

where ΔP is the pressure drop in the water and Q is the volumetric flow rate of the water. To find pump power consumption this flow power is divided by an assumed pump total efficiency of 50 percent.

Findings

Heat Exchanger Cost and Specifications

The team collected information on available products through internet searches, academic literature searches, and in-person interactions at the ASHRAE Winter Conference AHR Expo in February 2023 with contacts at suppliers including Weiland, Energy Transfer, SWEP, Kaori, and A.O. Smith-Lochinvar. The project team worked closely with the manufacturer of the ambient pressure hot water tank to understand the materials and labor costs for producing the current ambient pressure hot tank with both refrigerant-to-water and water-to-water heat exchanger coils.

Enhanced Surface Area Tubes

Enhanced surface area tubes can improve heat exchanger effectiveness per length of tube compared to the smooth tubes used in the current hot water tank refrigerant-to-water and water-to-water heat exchanger coils.

Wieland is the largest manufacturer of enhanced surface tubes with production facilities in Germany, Figure 6 and Figure 7. Energy Transfer is a U.S.-based manufacturer of enhanced surface tubes, Figure 8. Both manufacturers of enhanced surface area tubes, Weiland and Energy Transfer, recommended externally finned copper tubes with medium fin height for this application. Medium finned tubes also have excellent bending properties and processability.

Figure 6. Weiland finned tubes

Source: https://www.wieland.com/en/products/finned-tubes

Figure 7. Wieland smooth coil versus finned tube coil for the equivalent heat transfer performance

Source: https://www.wieland.com/en/products/finned-tubes

Discussions with Weiland identified two good options for the finned tube specifications that are produced regularly and therefore are not cost prohibitive and available in sufficient quantities. Costs were estimated with an annual purchase of enough material to build 100 hot water tanks per year and include all shipping costs, tariffs, and taxes, Table 1.

Table 1 Medium Height Finned Copper Tube Costs

Finned Tube Model Number	Cost per length ($/ft)	Manufacturer claimed heat transfer enhancement relative to 3/8" smooth copper tubing
D-1135.12100-00	$ 3.84	5.9
DW-1135.12100-16	$ 3.84	5.9

Figure 8. Energy Transfer, DuraFin finned tubes

Source: https://durafintube.com/wp-content/uploads/2022/01/Energy-Transfer-Product-Catalog.pdf

After many requests, Energy Transfer was unable to provide price quotes in time for this project.

Brazed Plate Heat Exchangers

For refrigerant-to-water heat exchangers, BPHXs can offer high heat transfer effectiveness for reduced approach temperature, compact size, and reduced weight. The project team worked with the three leading BPHX manufacturers, SWEP, Kaori, and Alfa Laval to identify designs appropriate for this application with a 14kW heat transfer duty matching the 4-RT heat pump compressor capacity. All three manufacturers use sophisticated asymmetric channel designs to achieve high heat transfer effectiveness and low pressure drop in a compact space, Figure 9 and Figure 10. Price quotes were requested for annual purchase quantities of 100 units to build 100 hot water tanks per year, Table 2.

Table 2 BPHX Cost and Specifications

Manufacturer	Model	Cost	Dry Weight (lb)	Manufacturer Refrigerant Pressure Drop (psi)	Manufacturer Water Pressure Drop (psi)	UCD Estimated Refrigerant Charge R-410A (lb)
SWEP	Q3 B26Hx16	$367.00	7.86	1.45	0.31	0.14
Kaori	K070-98	$172.70	31.9		0.044	1.56
Kaori	K095-38	$195.40	23.3		0.20	0.86
Alfa Laval	CB65	TBD	TBD	0.55		TBD

Figure 9. BPHX from SWEP

Source: https://www.swepusa.com/

Figure 10. Kaori double wall BPHX in comparison to regular BPHX

Source: http://kaori.com.tw/

BPHX Balance of System Components

BPHX designs require a water pump to move water through the primary loop and pump controller. A range of retail water pump options are available ranging from $134 to $261 with a representative controller $87, all quoted at the 150 units per year purchase volume. The total for the lowest cost option is $229 including the pump, controller, shipping, and taxes. These pump options are likely more expensive than what would be selected for the final manufacturing design. To connect the water pump to the water tank requires small lengths of tubing and fittings with relatively low costs in the range of $15.

Indirectly Heated Hot Water Tanks

Multiple manufacturers offer indirectly heated hot water tanks with an integrated tube coil heat exchanger. These products have traditionally been used with solar thermal hot water systems or natural gas fired boilers. The project team collected price quotes from A.O. Smith – Lochinvar and Hydro Solar. A Lochinvar 50-gallon pressurized hydronic buffer tank with no heat exchanger coils was quoted at $1935 per tank. Hydro Solar quoted pressurized buffer tanks with bulk pricing of $561 for 26-gallon, $937 for 52-gallon, and $1052 for 79-gallon tanks without any heat exchanger coils. These indirectly heated hot water tanks often use large diameter water-to-water heat exchanger coils better suited to combustion boiler indirect heating and not a good fit for heat pump application. The cost of pressurized hot water tanks with custom water-to-water heat exchanger coils is strongly dependent on the number of units being manufactured. This project was unable to find publicly available pressurized water tank cost dependence on scale of production, so it is not included in this analysis.

Heat Exchanger Simulation Results

This project team built a custom EES computer model of the hot water tank, immersed coil and BPHX options, coupled with a compressor. The models were used to:

- Identify length of finned tubes for equivalent heat transfer rate
- Predict the approach temperature for different water-to-water heat exchanger options
- Predict refrigerant compression power and water pumping power requirements

Finned Tube Results

Finned copper tubes can replace the current ambient pressure hot water tank water-to-water heat exchanger coil design using 500 feet of smooth walled copper tubes. The custom computer model simulations of finned copper tubes, with the specifications of the Weiland D-1135.12100-00, predict a 4.6 times enhancement in heat transfer per linear length of tubing compared to smooth copper tubes. This means that using finned copper tubes of 108 feet length, 22 percent the 500 feet length of the current smooth copper tubes, will achieve the same hot water heating performance. The manufacturer predicts a heat transfer enhancement of 5.9 times based on their lab tests and modelling. The 5.9 times heat transfer enhancement would require 85 feet of finned tube to match the heat transfer performance of the current 500 feet smooth copper tubes.

The Weiland D-1135.12100-00 medium height finned copper tubes have almost double the weight of copper per linear length compared to the smooth copper tubes. Using the 4.6 times heat transfer enhancement predicted by the model developed in this project results in a reduction of the total weight of copper required by 38 percent, 27 lbs. Using the manufacturer claimed 5.9 times heat transfer enhancement would reduce the weight of copper by 51 percent, 37 lbs. Reducing the amount of copper required reduces the influence of copper commodity price fluctuations and reduces the weight of the hot tank for shipping and installation.

The cost of the finned copper tubes is 5.12 times that of the smooth tubes per length. Using the model estimated heat transfer enhancement of 4.6 results in an 11 percent heat exchanger materials cost increase of $39. Using the model estimated heat transfer enhancement of 5.9 results in a 13 percent heat exchanger materials cost decrease of $49.

We estimate that the labor required to bend the finned tubes into coils, connect lengths of finned tubes, and install in the tank will be approximately two hours less than the amount of time it now takes for the much longer smooth tubes. The total combined materials and labor cost of building the hot water tank water-to-water heat exchanger using the model predicted 4.6 times heat transfer enhancement is very close between a smooth tube and finned tube design with a small cost savings likely. The total combined materials and labor cost using the manufacturer claimed 5.9 times heat transfer enhancement would reduce the cost by more than $100.

BPHX Results

A BPHX can replace the current ambient pressure tank refrigerant-to-water heat exchanger coil design using 700 feet of smooth walled copper tubes. The cost of pressurized hot water tanks with custom water-to-water heat exchanger coils are strongly dependent on the number of units being manufactured. This project was unable to find publicly available pressurized water tank cost dependence on scale of production, so it is not included in this analysis and the cost results for each of the other components are given separately.

BPHX WEIGHT

The current ambient pressure hot water tank refrigerant-to-water heat exchanger coil design using 700 feet of smooth walled copper tubes weights 102 lbs. The BPHX design specifications appropriate for this application had a 14 kW or larger thermal power rating with weights ranging from 8 to 35 lbs. The BPHX designs require a water circulation pump, pump controller, short lengths of tubing, and fittings. Rough estimates for the weight of these balance of system components are 17 lbs. The total weight of the BPHX and balance of system components ranges from 24 to 52 lbs., for a refrigerant-to-water heat exchanger weight reduction of 31 to 78 lbs.

BPHX COST

The tubing material cost for the current ambient pressure tank refrigerant-to-water heat exchanger with 700 feet of 3/8” smooth walled copper tubes is $525. The BPHX price quotes range from $173 to $367. The BPHX balance of system components (water circulation pump, pump controller, tubing, and fittings) are estimated to cost $244 with costs coming down with increasing number of units produced. The total BPHX and balance of system costs would range from $417 to $611. For the lowest cost BPHX this would be a cost savings of 21 percent for $108 reduction.

BPHX WATER CIRCULATING PUMP POWER

The BPHX requires a small water pump to circulate water through the BPHX and then either into the tank or through the water-to-water heat exchanger coil whenever the HP is heating the water. The flow power through the current ambient pressure hot water tank water-to-water heat exchanger coil with three parallel paths and a total of 500ft length of tubing is calculated to be 14W for the 2.5 gallon per minute primary loop flow rate used in the model. With an assumed total pump efficiency of 50 percent this would give a pump power consumption of 28W when running. The BPHX designs have many parallel paths so that the water pressure drop is very small, the tubes connecting to the tank will be less than 10 feet total length, so the total pumping power is predicted to be less than 32W.

Water heating cycles only occur for a relatively small amount of time each day, particularly when heating with a high-capacity heat pump in the multi-function heat pump system. With short run times the total energy consumption of the water pump will not be very large. For example, in the AquaThermAire field test site single family home with three occupants the average daily runtime in water heating mode was 34 minutes, mean power draw during water heating cycles was 4360 W, mean daily energy use was 2.47 kWh. A 28W pump power over 34 minutes per day adds up to 5.8 kWh per year for pump energy consumption which is 0.6 percent of the total water heating energy consumption.

BPHX: REFRIGERANT CHARGE

The BPHX has a much smaller internal volume than the ambient pressure hot water tank refrigerant-to-water coil, so the BPHX requires less refrigerant. The internal volume of the ambient pressure hot water tank refrigerant-to-water coil with 700 feet smooth copper 3/8” tube is 10.5 liters. This large internal volume of the existing refrigerant to water heat exchanger requires 5.25 lbs. of R-410A refrigerant charge. The internal volume of the lowest cost BPHX Kaori K070-98 is 3.1 liters. The BPHX Kaori K070-98 design would reduce refrigerant volume and charge for the hot water tank by a factor of more than three, reducing mass of refrigerant required by approximately 3.7 lbs. for R-410A.

Typical refrigerant charge for space conditioning heat pumps is roughly three lbs.-per-ton capacity with some variation depending on the type of refrigerant used and different system designs. Using the three lb.-per-RT capacity benchmark, a 4-RT heat pump system would have a refrigerant charge of 12 lbs.

The current ambient pressure hot water tank refrigerant-to-water heat exchanger design uses 700 feet of smooth 3/8-inch diameter copper tubing requiring 5.25 lbs. of R-410A refrigerant. This means that the current ambient pressure hot water tank design would require approximately four lbs. of additional refrigerant.

Approach Temperature Impacts

For the current ambient pressure hot water tank hot water tank design, city cold inlet water enters the tank water-to-water heat exchanger coil at close to the ground temperature and is heated to the coil exit temperature. In winter the minimum cold inlet water temperatures reach 58°F (14.4 °C) in Davis, California (Hoeschele and Weitzel 2013). Domestic hot water draw flow rates can range from around one gallon per minute for faucets to around two gallons per minute for showers, and three to seven gallons per minute for filling a bathtub. Simultaneous draws from more than one fixture can lead to even higher flow rates. At high water draw flow rates the thermal power requirement to heat the water from cold inlet to hot water supply temperatures can be very large, Figure 11.

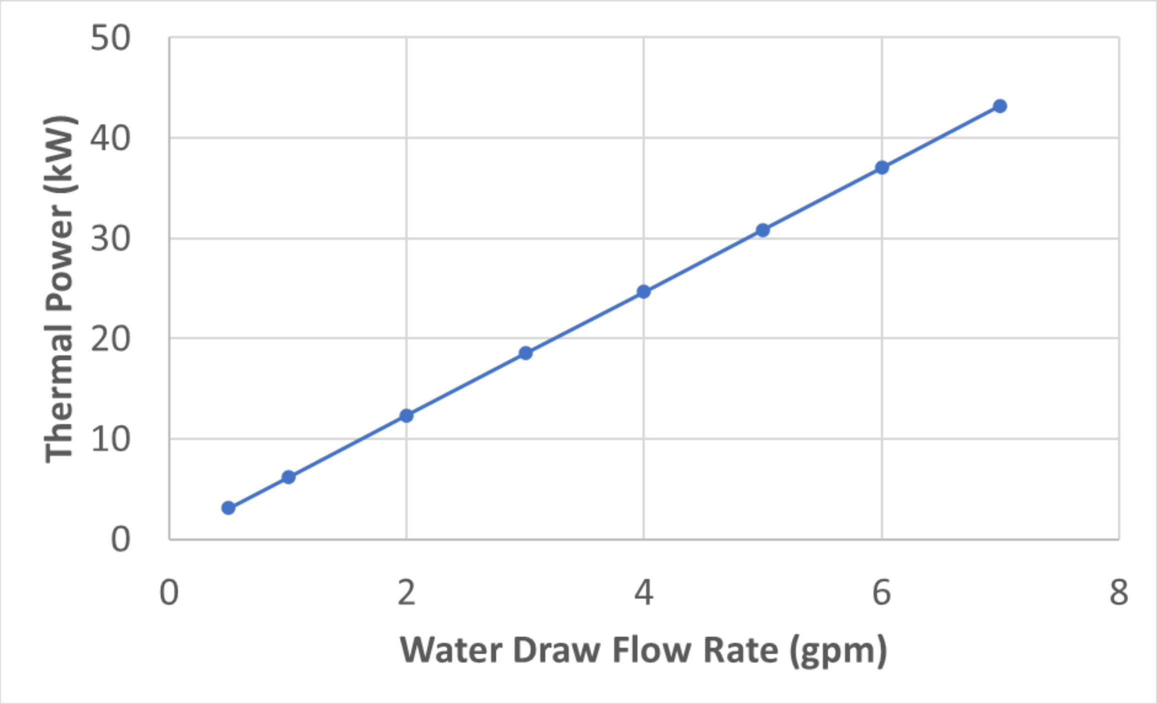

Figure 11 Water heating thermal power (kW) for different water draw flow rates, cold water inlet 58°F (14.4 °C), water supply 100°F (37.8 °C).

These large thermal power requirements with high water draw flow rates lead to either a very large water-to-water heat exchanger, adding cost, or to large approach temperatures, increasing energy consumption. Water-to-water heat exchangers of moderate size and large approach temperatures would require the heat pump to heat the water tank to a higher temperature to produce hot enough water leading to increased energy consumption.

The computer model developed in this project estimates that the approach temperature for the current ambient pressure tank water-to-water heat exchanger coil, the difference between the supply domestic hot water leaving the coil and the tank water temperature at that location. For a five gpm water draw flow rate, with an entering temperature of 58 °F (14.4 °C), and approach temperature of 12 °F (6.7 °C) is predicted when reheating the tank from 110 °F to 120 °F in typical heating cycles. Based on COP versus tank temperature data collected in the field test of the Villara AquaThermAire prototype, increasing the effective average tank temperature due to an approach temperature of 12 °F (6.7 °C) is predicted to result in an increase in compressor power consumption of roughly 11.8 percent which is 518W, based on the measured COP versus tank temperature field test data.

For the BPHX with primary water loop and pressurized tank design, the maximum thermal power for water heating is the rate of thermal energy that the heat pump can provide. With the 4-RT rated HP in the AquaThermAire system the maximum thermal power is approximately 14 kW. This smaller thermal power can be achieved by a smaller water-to-water heat exchanger design with similar or smaller approach temperatures compared to the domestic hot water heating coil in the ambient pressure tank design. For the BPHX supplying the primary water loop, the computer model estimates that the approach temperature for the water-to-water heat exchanger coil, the difference between the primary hot water loop temperature at the entrance of the tank water-to-water heat exchanger coil and the tank water temperature at that location, averages 7.5°F (4.8°C) when reheating the tank from 110 °F to 120 °F in typical heating cycles. Based on COP versus tank temperature data collected in the field test of the Villara AquaThermAire prototype, increasing the effective average tank temperature due to an approach temperature of 7.5 °F (4.8 °C) is predicted to result in an increase in compressor power consumption of roughly 7.1 percent, which is a 312W penalty.

Switching from the current ambient pressure tank to the pressurized tank BPHX design using the same water-to-water heat exchanger coil in both, the smaller heat transfer rate for the pressurized tank design would reduce the approach temperature by 4.6 °F (2.5 °C) with an average power consumption savings of 4.7 percent for 206W. For the Villara AquaThermAire multi-function heat pump field site hot water heating energy consumption of 2.47kWh per day this approach temperature reduction energy savings is equivalent to 42kWh per year.

These approach temperature impacts only consider the water-to-water heat exchanger. The resistance to heat transfer in the refrigerant-to-water heat exchanger results in additional efficiency penalties. Quantification of the impacts from the refrigerant-to-water heat exchangers would require full dynamic modelling of the compressor or laboratory testing which is beyond the scope of this project. Qualitatively, engineering judgement suggests that the BPHX can achieve similar or smaller compressor power penalties than a coil-based design for a similar refrigerant-to-water heat exchanger cost.

Refrigerant Pressure Drop Impacts

The compressor model described above was used to predict the impact of refrigerant pressure drop in the different refrigerant-to-water heat exchanger options. The current ambient pressure tank refrigerant-to-water heat exchanger design uses 700 feet of smooth 3/8-inch diameter copper tubing. Measurements in a manufacturer lab show a refrigerant pressure drop of five psi (34kPa) for a 4-RT outdoor unit refrigerant flow. This study collected specifications and price quotes for three BPHX models all with refrigerant pressure drop below 1.5psi (10kPa). The lowest pressure drop BPHX has a manufacturer estimated refrigerant pressure drop of 0.5psi (3.5 kPa). The compressor model predicts that this reduction in refrigerant pressure drop from 5 psi (34kPa) to 0.5psi (3.5 kPa) would lead to a 30W reduction in compressor power.

Future Low GWP Refrigerants

California requirements for low GWP refrigerants starting in 2026 will lead to use of slightly flammable A2L refrigerants such as R32. For these slightly flammable refrigerants, it is important to keep the total mass of refrigerant that can leak into an enclosed space to a minimum. Because hot water tanks are likely to be installed in closets or other relatively small unventilated spaces refrigerant-to-water heat exchangers with smaller refrigerant volume and smaller refrigerant charge are preferred. The BPHX system designs can significantly reduce refrigerant volume with safety benefits for future A2L refrigerants. There is an R32 air-to-air multi-function heat pump sold in Europe that uses a BPHX design.

Technology Risks

Over time, as cold inlet water flows through the ambient pressure tank design water-to-water heat exchanger tubes it is heated and water mineral deposit scaling is likely. This water mineral deposit scaling has the potential to reduce flow through the ambient pressure tank water-to water heat exchanger tubes. This potential scaling issue poses a risk and may require regular maintenance for the ambient pressure tank design. For the pressurized tank with primary water loop water-to-water heat exchanger coil, any scale would form on the outside of the tubes. This is similar to many natural gas storage tank water heaters and standalone heat pump water heater currently in use. While scale can reduce heat transfer rates in both hot water tank heat exchanger designs, for the pressurized tank the hot water would continue to flow with low domestic hot water pressure drop.

In pressurized tank designs using finned tubes for water-to-water heat exchange, the primary water loop will also face a water mineral scaling issue. Further research on the heat transfer impacts of scale buildup on finned tubes will be needed to evaluate whether they are more sensitive or less sensitive to scaling than smooth tubes.

Stakeholder Feedback

The team has engaged with relevant stakeholders as part of the original project idea development, part of the CalNEXT proposal scoring process, and through ongoing collaboration during the project.

Manufacturers

The most direct stakeholders are the HVAC manufacturers who offer—or will soon offer—air-to-air residential multi-function heat pumps, including Villara, Panasonic, LG, and Samsung. HVAC manufacturers are stakeholders of this project as a source of information about existing heat exchanger designs, alternative designs, and heat exchanger component manufacturers. HVAC manufacturers are also direct stakeholders as recipients of the project recommendations for improved heat exchanger designs for MFHPs to improve water heating capacity, increase energy savings, enable reduced GHG emissions, and potentially reduce equipment costs. The team engages Villara regularly and Villara has helped solicit cost information from heat exchanger component suppliers. The team also has regular conversations with Panasonic, and they are interested in the results of the project. The team plans to test the Villara AquaThermAire single speed multi-function heat pump and the Panasonic variable speed multi-function heat pump in UCD WCEC environmental chamber laboratory. The team maintains good communication with Mitsubishi, and they too are interested in the project results. The team also contacted LG and Samsung at the ASHRAE Winter Conference AHR Expo in February 2023 and continues to attempt to connect with their engineering and product management staff.

Other direct stakeholders are heat exchanger component manufacturers and indirectly heated hot water tank manufacturers. These manufacturers provide information about the technical specifications of their currently available components, the cost of these components, as well as being potential suppliers of components for multi-function heat pump manufacturers. The team communicated with technical sales and engineering staff at multiple component manufacturers including Weiland, Energy Transfer, SWEP, Kaori, Alfa Lava, and A.O. Smith – Lochinvar.

CalNEXT Team

Key stakeholders for this project are the target audience of the team(s) that will evaluate the energy performance of the new multi-function heat pump technology category, including UCD WCEC and potentially other CalNEXT partners such as Energy Solutions, TRC, Alternative Energy Systems Consulting, Inc. (AESC), and Vermont Energy Investment Corporation (VEIC). Energy Solutions, TRC, AESC, and VEIC have provided feedback on this project from the idea stage and throughout development of the project plan.

Investor-Owned Utilities

Investor-owned utilities (IOUs) are key stakeholders for development and adoption of new multi-function heat pump efficiency measures for energy efficiency programs. The team has and will continue to engage with IOU representatives to share information about residential MFHP and to learn how this new class of heat pump products can enable efficiency program designs to overcome heat pump adoption barriers.

The UCD team will continue to engage with the stakeholders identified above, including HVAC manufacturers, heat exchanger component manufacturers, the teams likely to perform next step lab testing and follow on measure development for the technology—including WCEC—other CalNEXT team members, and IOU staff to maximize the impact of this project. Table 3 lists the stakeholders the team has engaged during this project, specifically and more broadly around the new class of air-to-air multi-function heat pump products.

Table 3. Stakeholder Engagement

Organization Type	Organization	Contacts
HVAC Manufacturer	Villara	President Product Development
HVAC Manufacturer	Mitsubishi	Director Residential Product Management—METUS
HVAC Manufacturer	Panasonic	Liaison with UCD
Heat Exchanger Component Manufacturer	Weiland	Applications Engineer for Air Conditioning & Refrigeration, Process Technology
Heat Exchanger Component Manufacturer	Energy Transfer	Technical Sales Specialist
Heat Exchanger Component Manufacturer	SWEP	Business Development Manager
Heat Exchanger Component Manufacturer	Kaori	Sales Representative
Heat Exchanger Component Manufacturer	Alfa Laval	Sales
Heat Exchanger Component Manufacturer	A.O. Smith – Lochinvar	Director Corporate Technology
Heat Exchanger Modelling Experts	UCD	Faculty Director WCEC, Professor Mechanical Engineering Professor, Chemical Engineering WCEC Co-Director of Engineering WCEC Associate Engineer Graduate Student Researcher
Heat Exchanger Modelling Experts	LBNL	Senior Scientific Engineering Associate
Heat Exchanger Modelling Experts	Harvey Mud College	Professor Mechanical Engineering

Organization Type	Organization	Contacts
IOU	SCE	Project Manager
IOU	SDG&E	Project Manager Emerging Technologies Project Manager Tech Innovation Strategies & Programs Manager Energy Efficiency and R&D Project Manager
CalNEXT Partners	TRC	Senior Director, Research and Technology Commercialization Vice President, Research and Technology Commercialization
CalNEXT Partners	AESC	Director
CalNEXT Partners	Energy Solutions	Senior Project Manager Senior Staff Engineer
CalNEXT Partners	The Ortiz Group	Pilot Lead Project Leader
CalNEXT Partners	VEIC	Principal Engineer, Simulation Modeling Senior Consultant
California ET	CalTF	Principal Engineer
ET Researchers	Energy 350	President
Other State ET Coordinator	Northwest Energy Efficiency Alliance	Senior Product Manager Senior Manager
Product Developer and Installer	Harvest Thermal	Chief Technology Officer

Stakeholder Feedback

During review of the project plan, the team received feedback from several parties. One piece of feedback asked for clarification on whether the heat exchanger design recommendations would be relevant to all MFHP manufacturers. The results of this heat exchanger improvement project—and the models developed—will both directly inform the next steps for manufacturing scale up for existing MFHP products and will also be relevant to inform future designs and manufacturing decisions for other manufacturers.

As part of the CalNEXT proposal scoring process, the team also received feedback from CalNEXT partner The Ortiz Group that residential multi-function heat pumps have the potential to provide value to DAC and HTR populations by reducing the barriers to electrification these groups often encounter.

A Southern California Edison (SCE) project manager reviewed both the pre-draft and draft plan for this project and inquired how this project was different than SWEPP-2022-0045 - Tech Evaluation of Air-to-Water Heat Pumps, which is evaluating air-to-water heat pump systems built from several separately purchased parts with custom design to size water heating for each building. The primary difference is that this multi-function heat pump heat exchanger improvement project is focused on improving heat exchanger design for refrigerant based (air-to-air) MFHP products. Air-to-air multi-function heat pump products use refrigerant to move thermal energy, which is expected to be less expensive and more efficient than air-to-water heat pumps which use water to move thermal energy.

Retrofit air-to-air multi-function heat pumps—the focus of this project—are expected to have a lower installed cost than air-to-water based multi-function heat pump systems because:

- The air-to-air multi-function heat pump systems soon to be commercialized are standardized products with all parts fully integrated by the manufacturer and do not require custom design, whereas air-to-water heat pump based MFHP systems are built up from several separately purchased parts that require design customization to determine the size of the water pump(s), piping size, and valve selection.
- Air-to-air multi-function heat pumps are more similar to the most common split-system AC units that HVAC contractors are intimately familiar with and are often the existing HVAC system type in many residential buildings.
- Refrigerant based direct expansion coils are less expensive than hydronic coil air.
- Air-to-water heat pumps (AWHP) require a water pump, which adds cost and consumes more energy.
- AWHP installations often require HVAC and plumbing trades coordination and likely require electrical upgrades as well bringing a third trade group and more complicated coordination.

Additionally, air-to-air multi-function heat pumps are expected to have higher efficiency than AWHP based multi-function heat pump systems because:

- Air-to-water heat pump systems require an additional heat transfer step, from refrigerant-to-water and then to air or domestic hot water, so the heat pump will consume more energy to raise or lower the temperature more to deliver the same end-use service.
- Air-to-water heat pumps that heat hot water during the space cooling season need to switch back and forth between supplying cold water to the air handler and hot water to the water tank so that the HP will consume more energy heating cold water and cooling hot water whenever it switches modes.

The SCE project manager also asked if there are any overlaps between this air-to-air multi-function heat pumps heat exchanger improvement project and the VEIC led SWEPP-2022-0045 – Tech Evaluation of Air-to-Water Heat Pumps project related to market intel, design, and technoeconomic analysis. The UCD project team is in close communication with the VEIC team. The VEIC study is focused on air-to-water multi-function heat pumps and is using a Harvest Thermal system that requires an entire second heat pump outdoor unit to provide space cooling. The project team expects that the Harvest Thermal system will likely be cost prohibitive for installations that require space cooling because it uses two separate heat pump outdoor units and has significantly more complex installation and controls than the systems considered in this study.

Recommendations

Multi-function heat pump hot water heat exchanger designs using a refrigerant-to-water BPHX combined with a pressurized tank containing an immersed water-to-water heat exchanger coil using finned tubes have the potential to increase efficiency and reduce costs compared to the ambient pressure tank double immersed coil design. The UCD team recommends that a future emerging technology projects test both the ambient pressure tank and pressurized tank designs.

Next Steps

The project team's next steps include:

- Recommend improved refrigerant-to-hot-water heat exchanger designs for all manufacturers of multi-function heat pumps
- Solicit MFHP manufacturers for equipment with improved heat exchanger design for inclusion in the follow-on lab demonstration emerging technology projects
- Future lab demonstration projects will measure residential multi-function heat pump equipment efficiency and capacity across a range of outdoor conditions to build performance curves
- Future technology transfer efforts will engage with IOU and California Technical Forum to use the multi-function heat pump performance curves to develop energy savings estimates for a new MFHP deemed measure
- Future technology transfer efforts will engage with the California Energy Commission staff responsible for CBECC-Com to allow use of the multi-function heat pump performance curves for code compliance
- A future multi-function heat pump market study project can investigate barriers to adoption and estimate a potential timeline for adoption

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