BONNEVILLE POWER ADMINISTRATION

Emerging Technologies

Eco2pipe Hydronic Heating System Feasibility Study

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The following report was funded by the Bonneville Power Administration (BPA) to assess emerging technology topics that have the potential to increase energy efficiency. BPA is committed to identify, assess, and develop emerging technologies with significant potential for contributing to efficient use of electric power resources in the Northwest.

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Acronyms

CO_2 . . . . . . Carbon Dioxide
CPVC . . . . . . Chlorinated Polyvinyl Chloride
GWP . . . . . . Global Warming Potential
HFC . . . . . . Hydrofluorocarbon
HFO . . . . . . Hydrofluoroolefins
HPWH . . . . . . Heat Pump Water Heater
HVAC . . . . . . Heating, Ventilating, and Air Conditioning
LEED . . . . . . Leadership in Energy and Environmental Design
PEX . . . . . . Cross-linked Polyethylene
VRF . . . . . . Variable Refrigerant Flow
VRV . . . . . . Variable Refrigerant Volume
WTWHP . . . . . . Water-to-water Heat Pump

Executive Summary

Many building comfort systems capable of providing both heating and cooling for multi-family residential facilities in the Pacific Northwest and California use Variable Refrigerant Flow (VRF) – also known as Variable Refrigerant Volume (VRV) – systems. VRF systems distribute heat around the building through refrigerant piping. Current and upcoming refrigerant phase outs will cause VRF equipment manufacturers to move to next-generation synthetic refrigerants that have lower Global Warming Potential (GWP) but are slightly flammable and require risk mitigation. Refrigerant phase outs will make installation and maintenance of VRF systems more difficult and is prompting developers to consider system designs with hydronic distribution and centralized heat pump equipment.

This report details the Feasibility Analysis for a hydronic-based option that uses air-to-water heat pump technology with a seasonal changeover called Eco2pipe.

The Eco2pipe design will help Bonneville Power Administration meet the energy efficiency goals outlined in its resource plan[1] through energy efficiency, resilience, and cost effectiveness. Future load shift capability and controls will also allow Eco2pipe to be a grid resource.

System: Eco2pipe consists of a 2-pipe hydronic changeover system that supplies either low-temperature heating water (120°F) or chilled water (45°F) to terminal units via a roof-mounted air-to-water heat pump unit. In the simplest case, terminal units are fan coils units, though hydronic distribution allows for many terminal equipment types, including load shift capable radiant slabs.

Current air-to-water heat pump technology uses R410A. However, unlike VRF systems, Eco2pipe allows the heat pump to be easily replaced at end of life without touching the distribution system within the building. This allows systems using R410A to be upgraded to natural refrigerants with higher efficiencies and lower GWP when available.

As air-to-water heat pumps that use natural refrigerant such as CO_2 (R744) and propane (R290) are developed, heating and cooling will become more efficient. This equipment will also allow higher supply and storage water temperatures (greater than 160°F) and may allow sufficient thermal storage to provide significant load shift capability.

Freeze protection is required whenever water piping is installed outside the building in freezing climates and can be provided with glycol or heat trace. If heat trace is used as freeze protection, a backup power supply must be provided to avoid freezing during a power outage.

Performance: With current air-to-water heat pump technologies, Eco2pipe can produce heating water at temperatures up to 149°F at 23°F outside air temperature and up to 131°F at -4°F. With upcoming CO_2 based heat pumps, heating water at temperatures greater than 160°F at outside air temperatures of -15°F may be achievable.

Market Delivery: Currently, Eco2pipe systems require custom engineering for each facility. The engineering effort includes sizing of equipment, equipment selection, and selection of individual system components. All components required for an Eco2pipe system based on R-410a refrigerant are commercially available. Air-to-water heat pumps using natural refrigerants such as CO_2 are expected to become available in the next few years.

The long-term goal for Eco2pipe is to offer a fully specified built-up system market delivery approach. All major system components, including controls, would be procured through a single vendor with full design, installation, and commissioning, maintenance, and warranty support. This market delivery method would reduce procurement and installation costs and would ensure system effectiveness and reliability.

Constructability: The complexity of system installation is expected to be comparable to alternative systems. Use of pre-assembled productized piping risers may reduce system cost and installation time.

Maintenance: The Eco2pipe system requires regular maintenance at the air-to-water heat pump and routine maintenance typical of hydronic systems including strainer blowdowns and water treatment. Unlike VRF maintenance, facilities staff maintaining Eco2pipe systems will not need training to work directly with refrigerant. Due to the localization of refrigerant in the factory-provided heat pump assembly, significantly less refrigerant leakage is expected as compared to other comparable systems.

Background

With summer high temperatures increasing in the Pacific Northwest, more multifamily housing developers are interested in providing space cooling options for their tenants. Over the past decade, Variable Refrigerant Flow (VRF) systems have been widely utilized in multifamily applications for their ability to provide both space heating and cooling at a much lower first cost as opposed to a four-pipe system utilizing gas-fired boilers and chillers.

> ***Eco2pipe is a grid-integrated space conditioning system for use in multifamily buildings intended for nationwide adoption.***

VRF systems have been implemented due to their reduced energy consumption and lower first costs (both as compared to a four-pipe heating/chilled water system). However, with the ongoing phaseout of high Global Warming Potential (GWP) refrigerants and restrictions on the proposed refrigerant replacements due to flammability concerns (especially concerns associated with distributed refrigerant lines within the building envelope), multifamily developers will benefit from solutions other than VRF systems to allow future proofing of their buildings with respect to the refrigerant changes.

Bonneville Power Administration's Emerging Technology Research Team has conceived of a space conditioning system that efficiently and reliably provides heating in the winter months, cooling in the summer months, maintains comfortable temperatures for occupants during shoulder seasons, provides domestic hot water and allows load shift during periods of peak utility demand. This system, which this study asserts is an effective and resilient long-term solution to distributed refrigerant systems, has been named "Eco2pipe."

Market Landscape

The Eco2pipe system concept, though suitable for many applications, is best suited to multifamily residential. In 2021, 48% of the new construction floor area in Seattle, WA was multifamily residential. In BPA service territory, roughly 35 thousand new multifamily residential units are constructed each year. Additionally, the heating system in roughly 25 thousand units is replaced each year. While Eco2pipe is best suited for new construction, it may also be applied in some retrofit applications.

Commonly installed systems currently used to meet heating and cooling requirements of this type of facility include four-pipe hydronic, VRF, and ductless split systems. Each of these systems has specific strengths and weaknesses. Another emerging option for multifamily heating and cooling is double-duct packaged terminal heat pumps such as the Olimpia Splendid Maestro Pro[2] and the Innova View 2.0[3], though these systems have not yet been fully vetted using the Technology Innovation Model and there are few installations with which to provide sufficient performance data to compare to other technologies.

Four-pipe hydronic systems provide separate circulation loops for heating and cooling water. Heating is typically provided by gas-fired boilers while cooling is provided by air-cooled or water-cooled chillers. These systems work in all climates, provide both heating and cooling year-round to all tenants, and provide the benefit of centralized equipment (boilers and chillers) which allows ease of maintenance and replacement at end of life. First costs for these systems are high relative to other options due to increased piping and equipment expenses and often result in developers looking to other options. Eco2pipe is a grid-integrated space conditioning system for use in multifamily buildings intended for nationwide adoption.

Ductless split systems are another viable option, and they also allow for year-round heating and cooling to meet the needs of individual tenants. However, as each apartment unit may have multiple indoor and outdoor units with refrigerant piping connecting them, refrigerant phase outs will impact the cost of installation, maintenance, and end of life replacement. Ductless split systems are not the best option for large or high-rise multifamily complexes.

VRF systems have been an effective solution for multifamily buildings that require both heating and cooling. However, these systems allow some occupants to use heating while others use cooling, which is inefficient and can put unnecessary strain on the utility grid.

The use of VRF systems has other drawbacks. Refrigerant is much less efficient at moving heat across distances than water[4]. There is also evidence that greenhouse gas emissions due to refrigerant leakage from VRF may be significant.[5] With upcoming refrigerant phaseouts and increased first costs associated with refrigerant safety, the fact that these systems require extensive piping inside the building envelope results in these systems being less attractive to developers.

System Description

Eco2pipe is a grid-integrated space conditioning system for use in multifamily buildings intended for nationwide adoption.

The system consists of centralized rooftop air source heat pump equipment which produces either heating or chilled water that is distributed to two-pipe fan coil units located in the dwelling units. The entire system transitions between heating and cooling to meet the majority building load (based upon either outside air temperature or average zone heating/cooling loads).

One of the main differences between Eco2pipe and standard two-pipe heating/cooling systems is that a large decoupling tank separates the primary water system (heat pump) from the building distribution to the fan coil units (secondary system). This tank not only acts as a buffer to ensure semi-consistent inlet water temperature to the heat pump, it also can provide thermal storage to allow load shift. The load shift capacity of the system depends on both the temperature of the supply water and the size of the decoupling tank.

Fully specified built-up systems will provide the most cost effective market adoption and energy savings. A fully specified built up system provides all major system components, including controls, through a single vendor with full design, installation, commissioning, maintenance, and warranty support, which reduces system cost and increases reliability.

Other concepts unique to Eco2pipe include pre-assembled productized piping risers inside the building and the ability to implement the system as a combi-system where a single system is used to produce heating water, chilled water, and domestic hot water.

Refrigerant

Currently available air-to-water heat pump technologies use conventional refrigerants such as R410a. R410a has a global warming potential (GWP) of 2088 (as compared to the index CO_2 which has a GWP of 1). This refrigerant allows supply water temperatures of up to 149°F, though R410a units operate more efficiently and reliably at lower supply water temperatures (around 125°F). Refrigerant policy in the United States is moving the industry away from traditional refrigerants. Self-contained HVAC systems using R-410a will no longer be manufactured or imported after January 1, 2025, and other, similar refrigerants are scheduled to be phased out as well.

Natural refrigerants, such as CO_2 (R744) and C_3H_8 (R290), offer non-toxic, low GWP solutions that eliminate the risks of HFC/HFO refrigerants. Manufacturers use R744 widely in the United States though it has several disadvantages[a]. R290 (commonly known as propane) is likely the long-term natural refrigerant solution for air-to-water heat pumps, able to efficiently serve both space and domestic water heating applications. However, while it is available in the rest of the world, UL 60335-2-40 prevents its use in the United States due to flammability, even in outdoor only installations where no refrigerant enters the building envelope.[6] While the Eco2pipe system presented in this study is based around the use of refrigerant R-410a, use of natural refrigerants in the future allows for additional system capabilities such as load shifting and domestic hot water heating.

Like with R290, many transitional refrigerants such as R-32 and R454B are classified as “A2L” for flammability in accordance with ASHRAE Standard 34. This classification introduces additional safety requirements such as routing interior piping in fire-resistant ventilated shafts per section 1109.2.5 of the International Mechanical Code. These additional requirements may adversely affect the first costs of installing some VRF systems making the Eco2pipe concept more cost-competitive as no refrigerant lines are located in occupied spaces.

Potential of refrigerant leakage is minimized with the Eco2pipe system. All refrigerant piping is factory-assembled, charged at the

a As a natural refrigerant, R744 is futureproofed from complex refrigerant policy and operates more efficiently in cold temperatures than available synthetic refrigerants. However, R744 cannot heat high entering water temperatures efficiently which requires systems to use design strategies to drop the temperature of the return water. Additionally, the high pressures at which it operates present manufacturing and maintenance challenges.

factory, and centralized at the roof-mounted heat pump unit. On the contrary, VRF systems have complex refrigerant pipe routing which commonly results in refrigerant leaks that are difficult to isolate.

Purpose

This Feasibility Study examines the Eco2pipe system's ability to provide an energy-efficient and cost-competitive solution to space heating and cooling for multifamily residential projects while also allowing load shift capabilities.

Current Installations

Though there are no known current installations of the Eco2pipe system, a design is in progress for a 90-unit multifamily apartment project located in Seattle, Washington which uses R410A air-to-water heat pumps. The design for this project is anticipated to be completed in late 2024 with construction scheduled to begin in January 2025 and complete in September 2026.

Codes and Certifications

Designs and installations of the Eco2pipe system will need to comply with the following codes for the Pacific Northwest and California.

Codes

ENERGY CODE

- International Energy Conservation Code (IECC) (Includes Idaho and Montana)
- Washington State Energy Code (WSEC)
- Seattle Energy Code (SEC)
- Oregon Energy Efficiency Specialty Code (OEESC)
- Title 24 (in California)

MECHANICAL CODE

- International Mechanical Code (IMC)

PLUMBING CODE

- Uniform Plumbing Code (UPC)
- International Plumbing Code (IPC)

ELECTRICAL CODE

- National Fire Protection Agency (NFPA) 70 – National Electrical Code (NEC)

System Component Assessment

System Component Assessment identifies the equipment needed for a complete system deployment.

Figure 1 shows a simple schematic (in heating mode) of the main system components including the roof-mounted air-to-water heat pump(s), primary pumps (fixed or variable speed), secondary pumps (variable speed that control loop differential pressure), decoupling tank, 2-pipe fan coil units (sized for cooling load), and the loop temperature control 3-way valve.

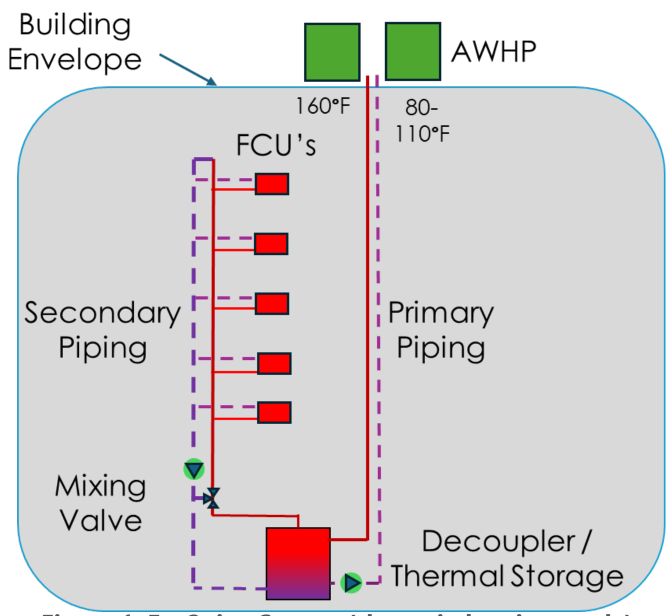

Figure 1. Eco2pipe System (shown in heating mode)

Additional required components include fan coil unit control valves, two 3-way valves to facilitate changeover between heating and cooling, and ancillary components such as valves, expansion tanks, glycol feeders, etc., typical of a hydronic system. Figure 2 shows the system with the two 3-way seasonal changeover valves. Figures 3 and 4 show the configuration of the two 3-way seasonal changeover valves in heating mode and cooling mode, respectively.

With the availability of warmer supply water, the decoupling tank could be sized to accommodate the desired load shift duration.

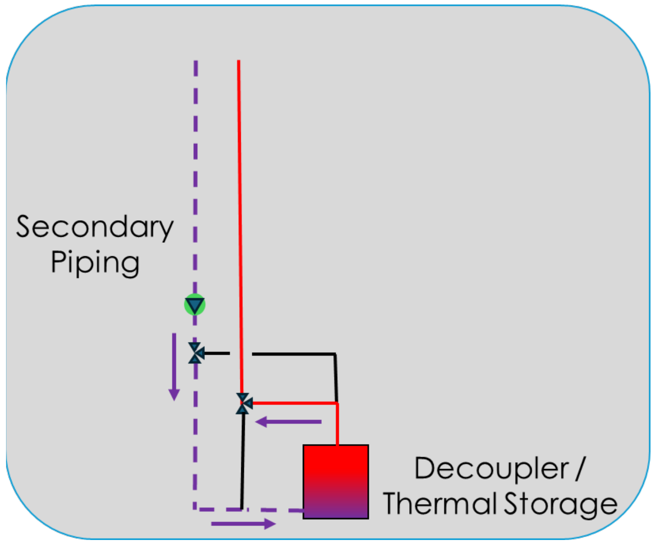

Figure 2. Eco2Pipe system seasonal changeover valves at decoupler

With the availability of warmer supply water, the decoupling tank could be sized to accommodate the desired load shift duration.

Air-to-Water Heat Pump

Currently available technologies for the air-to-water heat pump consist of units that

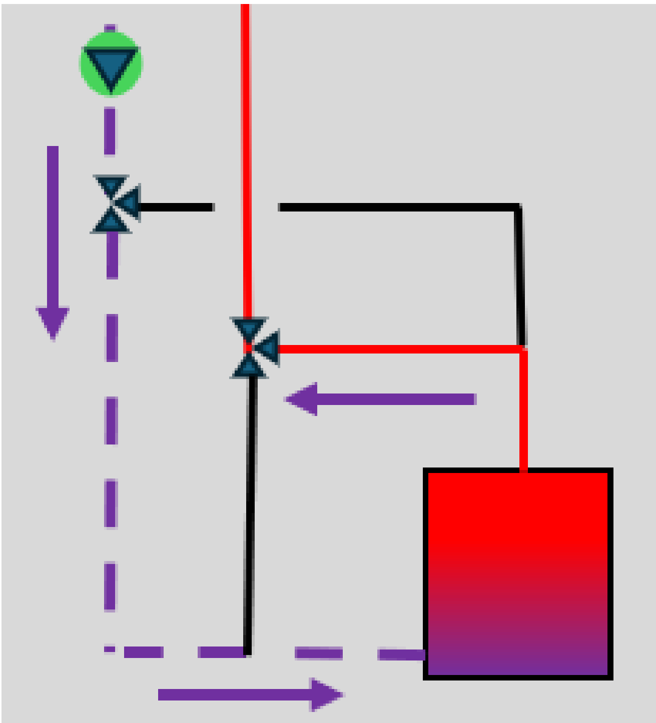

Figure 3. Eco2pipe system seasonal changeover valves (heating mode)

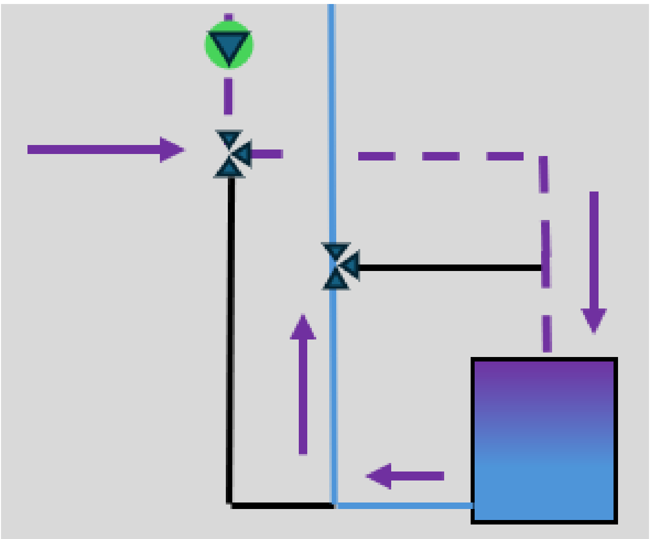

Figure 4. Eco2pipe system seasonal changeover valves (cooling mode)

use conventional refrigerants and allow low supply water temperatures (around 125°F). There are manufacturers currently working on bringing CO_2 heat pumps to market for hydronic heating. This technology allows for warmer supply water temperatures (up to 180°F). Use of propane as a refrigerant will also allow warmer supply temperatures. Propane refrigerant has additional advantages over CO_2 in that it can provide more efficient cooling in higher outdoor air temperatures and more efficient heating with higher return water temperatures. With the availability of warmer supply water, the decoupling tank could be sized to accommodate the desired load shift duration. See section Further Research for discussions regarding feasibility of natural refrigerants for space heating applications.

Pumping Systems

Primary pumps are used to ensure sufficient water flow through the air-to-water heat pump. These pumps could be fixed or variable speed to meet heat pump manufacturer's flow requirements.

Secondary pumps are used to circulate water to the load side of the system (fan coil units). These pumps are controlled based on feedback from a differential pressure sensor located in the system; this control strategy ensures sufficient flow is always available at each fan coil unit.

Decoupling Tank

The primary purpose of the decoupling tank is to ensure there is sufficient volume in the primary system to meet manufacturer's minimum system volume requirements for the heat pump. The secondary purpose is to allow load shift capability. See section *Further Research* for a discussion sizing of load shift capacity.

Control Valves

To control supply water temperature to the fan coil units, a 3-way mixing valve is used. In the case where the air-to-water heat pump used CO_2 technology, this mixing valve allows the 160°F supply water from the heat pump to be mixed down to the low temperature distribution of 100-120°F. Maintaining the secondary system at lower temperatures is vital to allow use of low-cost piping materials such as PEX and CPVC.

In addition to the temperature control mixing valve, a pair of 3-way valves are required on the secondary system at the decoupling tank to allow system changeover between heating and cooling. In heating mode, supply water to the fan coil units is drawn from the highest point of the stratified decoupling tank while return water is directed to the lowest part of the tank. This helps facilitate load shift. In cooling mode, the decoupling tank inlet/ outlet strategy is reversed such that the coldest water is drawn from the bottom of the tank and supplied to the fan coil units while the warmer return water is sent to the highest tank inlet. Without these 3-way valves, proper supply water temperature to the fan coil units cannot be maintained in one of the modes (e.g., in cooling mode, if supply water is drawn from the top of the tank, the water is warmer than the required 45°F due to stratification).

The strategy of productized piping risers reduces installation costs and schedule.

Productized Piping Risers

The strategy of productized piping risers reduces installation costs and schedule. Another innovative feature of the Eco2pipe system is the introduction of productized piping risers. These risers are pre-assembled with supply/return headers located at each apartment unit. They are manufactured of low-cost PEX or CPVC and dropped into place. The strategy of productized piping risers reduces costs associated with site installation and compresses project schedules.

Potential Domestic Hot Water Heating

The current state-of-the-art for domestic water heating in multifamily buildings consists of central heat pump water heater systems. These centralized systems have many benefits such as high system efficiencies and load shift capability and require no equipment in the dwelling units. Adoption of the Eco2pipe concept allows for other high-efficiency options for domestic water heating, including distributed water-to-water heat pumps.

UNITARY WATER-TO-WATER HEAT PUMPS (PROPOSED NEW PRODUCT)

Eco2pipe has the potential to handle domestic water heating loads in addition to space conditioning loads. Water on the return side of the secondary piping is typically between 60°F (in cooling) and 100°F (in heating) which is a suitable range as condensing water for water-to-water heat pumps (WTWHP). The WTWHPs, which are unitary with storage tanks, are piped to/from the secondary return piping with circulation provided by small in-unit pumps.

The benefits of this approach for domestic water heating include:

1. A ~10% total building energy savings due to the removal of the recirculation load. Hot water is typically 25-30% of the total building load and recirculation is typically 30-40% of the hot water load in a multifamily building.[7]

2. Less piping risers are needed, resulting in a lower construction cost. A typical multifamily building has a riser for hot supply, recirculation, and cold water (three total). The WTWHP approach only requires a cold-water riser.

3. WTWHPs absorb heat from the return water, cooling it. In the summer, this “free” cooling reduces the load on the air-to-water heat pumps. In the winter, cooling the return water increases the efficiency of outdoor air-to-water heat pumps.

4. Unlike traditional Unitary Single Family heat pump water heaters (HPWHs) which absorb heat from the air, the WTWHPs used in Eco2pipe would absorb heat from the return water. The fan in traditional HPWHs used to move air across the unit’s evaporator is the noisiest component of the unit. This fan

also absorbs heat from the air and cools the space. The WTWHPs used in Eco2pipe will be quiet (no fans) and do not cool the space in which they are located.

See Figure 5 for a simple diagram showing a dwelling unit using the Eco2pipe system to produce domestic hot water. Note that this packaged water-to-water heat pump with built-in storage and controls does not exist on the market today. However, BPA's Emerging Technologies Research team and partners see enormous value in this approach and hope to partner with manufacturers to prototype and demonstrate the concept.

CENTRALIZED WATER-TO-WATER HEAT PUMP

Like in-unit unitary water-to-water heat pumps, Eco2pipe could alternatively be used to provide condenser water for a centralized water-to-water heat pump system. This centralized system provides domestic hot water to tenants via a traditional supply system with a recirculation line for temperature maintenance.

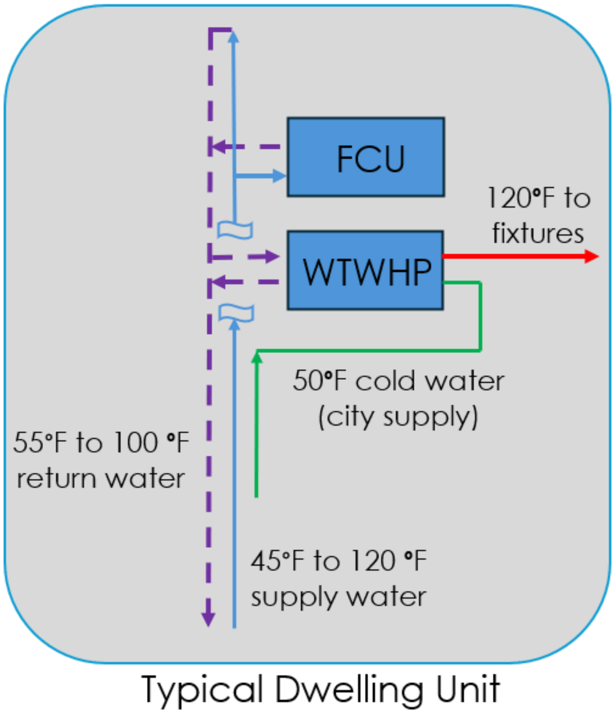

Figure 5. Diagram of dwelling unit piping with water-to-water heat pump

The benefits of this centralized system, when coupled with Eco2pipe, are:

1. WTWHPs absorb heat from the return water, cooling it. In the summer, this "free" cooling reduces the load on the air-to-water heat pumps. In the winter, cooling the return water increases the efficiency of outdoor air-to-water heat pumps.

2. The condenser water is tempered by the Eco2pipe system, so no air-to-water heat pumps are required to produce domestic hot water. Since the water-to-water heat pump is located inside the building envelope, the need for freeze protection on this system is eliminated.

3. Centralized heat pump water systems typically employ large storage tanks. These tanks can be used as "thermal batteries" allowing load shifting of the domestic water heating load.

See Figure 6 for a simple diagram showing a centralized domestic WTWHP system using the Eco2pipe system to provide source condenser water. Note that the domestic hot water electronic mixing valve has been omitted for clarity.

Control System

Controls for the Eco2pipe system are simple and effective. Central plant and dwelling unit controls are broken out and described below. Distributed controls, built into the major components of the central plant, are used in combination with a single central plant controller to ensure space conditioning supply and return water are provided to the units. The central plant controls may vary depending

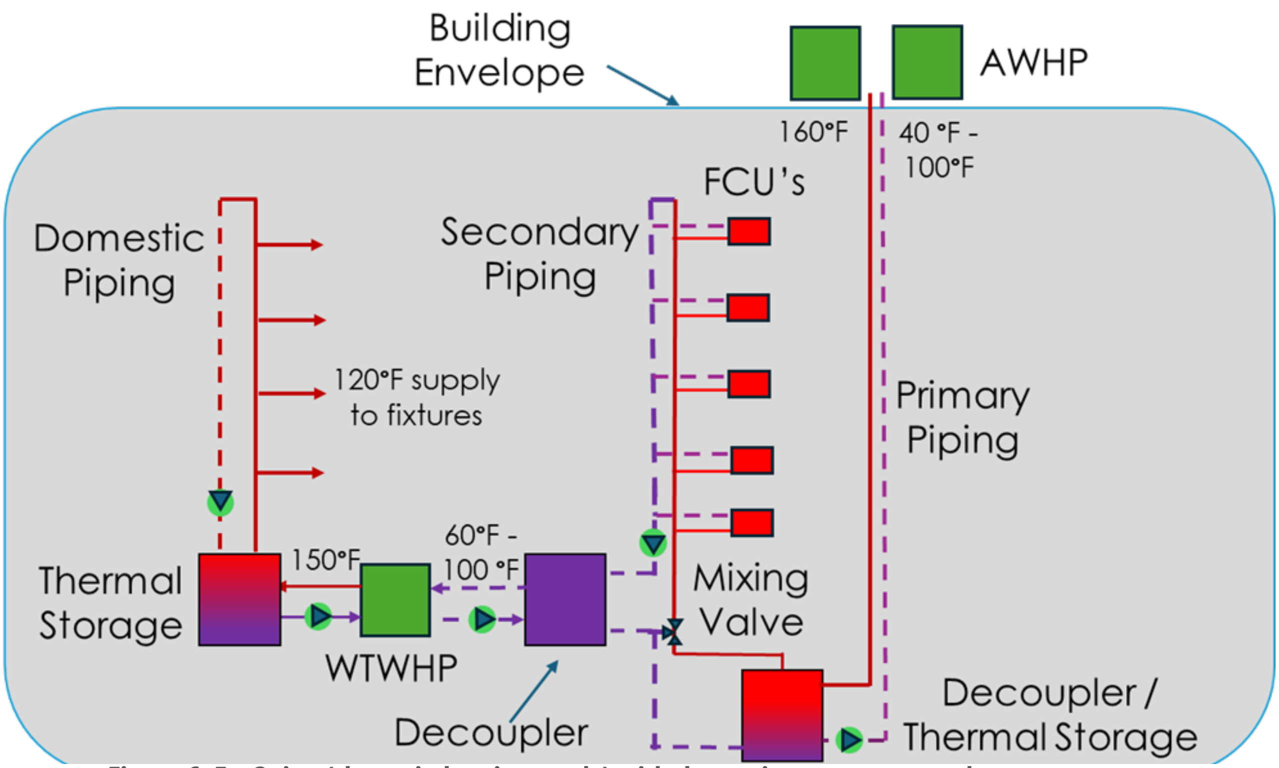

Figure 6. Eco2pipe (shown in heating mode) with domestic water-to-water heat pump

on what specific equipment is used, but a common approach may include:

- Secondary pumps are set to differential pressure control. As control valves within the terminal units open to allow for heating and cooling, the pumps increase speed to meet the demand. Central plant controller may be used to stage multiple pumps in parallel.
- Mixing valve internal controls target setpoint set by central plant controller. Central plant controller adjusts setpoint temperature with outdoor air reset and seasonal changeover.
- Primary pumps are set to differential pressure control. As AWHPs open internal control valves to heat or cool water from the decoupling tank, primary pumps increase speed to meet demand. Central plant controller may be used to stage multiple pumps in parallel.
- Central plant controller turns AWHPs ON/OFF based on temperature sensors located in the decoupling tank(s).
- Central plant controller used to determine when seasonal changeover occurs through energy use monitoring, outdoor air temperature, and weather forecast.

Dwelling unit control is local and decoupled from the air-to-water heat pump system. Temperature control for dwelling units is provided via a stand-alone thermostat that modulates the 2-way control valve at the fan coil unit.

Performance Assessment

The Performance Assessment confirms the systems will have adequate performance to

gain acceptance from designers and users.
Architecture

The two main system components to consider with respect to the building architecture are the central air-to-water heat pump, and the decoupling / storage tanks.

Installation location of the central air-to-water heat pump unit impacts the site's architectural design and acoustics. The generally accepted practice is to install the central heat pump unit on a rooftop. When installed in a visible location, the architect may want to provide a screen wall to obscure it from view. As with the locating of any equipment, architects will need to coordinate with the mechanical or plumbing engineer to identify an appropriate location.

The decoupling / storage tanks, which can total more than 1,000 gallons of capacity, can require a significant amount of space, so attention should be paid both to allowances for adequate floor space and ceiling-height. These tanks can typically be installed in a basement or garage (though freeze protection concerns should be considered if located in an unconditioned space). If installed indoors, tank size should be limited to allow for removal through doorways; multiple smaller tanks installed in parallel can be used in lieu of a single large tank to allow for tank removal/replacement as appropriate.

Space Requirements

One of the major benefits of the Eco2pipe system is the concept of prefabricated productized pipe risers. These risers can be manufactured in-shop and shipped to the site for quick and simple installation. These risers could also allow location of fan coil units in a back-to-back configuration minimizing floor space requirements.

A large laydown space, typically on a rooftop, is required for the central air-to-water heat pump. Unit dimensions vary by make and model and are provided in the respective manufacturer's literature. In addition to laydown space, additional clearances on each side and above the unit (for maintenance access and unit airflow) should be provided as required by the specific manufacturer.
In addition to clearances, units should be designed in a way that allows for future removal and replacement when equipment reaches end-of-life.

For discussions on placement of the decoupling / storage tank(s), see discussion in the section on *Architecture*.

Acoustics

The central air-to-water heat pump is the main source of sound on the exterior of the building. Sound pressure levels from the heat pump depend on the make and model. As an example, for the Aermec NRK-0700 (with nominal heating capacity of 593 kBtu/h), sound pressure levels at 10 meters are 59.9 dBA. Many heat pump manufacturers offer sound attenuators to reduce sound pressure levels. An acoustic screen wall at the roof can also provide a sound dampening effect.
The main source of sound in the dwelling units is the two-pipe fan coil units. Again, sound pressure levels from this equipment depend on the make and model. For example, the Polar Air SWC-04-V-AECM produces 33 dBA at minimum fan speed. For designers looking for quieter solutions, other hydronic options, such as finned-tube radiators, radiant ceiling panels, and in-floor radiant heating, produce nearly no noise.
Allowable sound power levels at property lines vary by jurisdiction. A project acoustician should be consulted during the equipment

selection process.

Climate

With regards to ambient air conditions, the Eco2pipe system, using air-to-water heat pumps on the market, is suitable in areas dry bulb temperatures are between -4.0°F and 118°F, respectively. As manufacturers adopt other refrigerant technologies such as CO_2 and Propane, adoption into colder climates will become possible. See section Further Research for a discussion regarding potential benefits of natural refrigerant technologies.

Like all heat pump systems, capacity decreases with outdoor air temperature. This fact must be considered when selecting and sizing equipment in cold climates. Installation of a back-up electric boiler is one strategy to hedge against colder-than-expected temperatures and provides system redundancy. This topic is discussed under *Engineering, Mechanical.*

Engineering

Engineering performance is broken into structural, mechanical, electrical, and plumbing performance.

Structural

The two main weight considerations for system installation are associated with the air-to-water heat pump and the decoupling tank.

Depending on system capacity, air-to-water heat pump weight loads can vary from nearly 1,000 pounds up to several thousand pounds. Care should be taken to include the weight added when the system is filled with water/glycol. The installed unit may require vibration isolation depending on the installation location and facility vibration requirements. Like other major mechanical components, the unit must be securely bolted to prevent it from falling in seismic or wind events.
The weight of the decoupling tank also varies with system configuration. For a 1,000-gallon tank, weight (when filled) can easily be more than 12,000 pounds.
Structural engineers should be notified early in the design process regarding proposed locations for the heat pump and decoupling tank(s) so they can plan accordingly.

Mechanical

PIPING

Piping for the system includes the primary system (serves heat pump) and secondary system (serves building load).

Piping for the primary system should be designed to accommodate high temperatures (up to 180°F). Suitable pipe materials include iron and copper.

Secondary system piping can be designed to accommodate lower temperatures (below 125°F) and could materials such as PEX or CPVC. Two-way control valves are required for temperature control at each fan coil unit. Balancing valves would also be required at each fan coil unit, though use of a reverse-return piping configuration at each riser may eliminate the need for some balancing valves.

While the system can be installed in any elevation of building, care should be taken when considering installation in high rise buildings. Pipe pressure ratings should be selected carefully, and engineering direction should be given with respect to system charge pressure.

In cold climates, use of glycol may be necessary for freeze protection. Though the primary and secondary systems are decoupled, there is water exchange between the two systems resulting in 100% of the system requiring glycol. Note that domestic hot water is a separate system, and glycol is never used in domestic hot water.

INSULATION

The 2-pipe piping configuration means that both primary and secondary piping loops are exposed to both heating water and chilled water (~45°F). To prevent condensation issues, all primary/secondary piping should be insulated and provided with vapor barrier per local codes. Consideration should also be given to insulation of condensate drain piping in humid climates.

CAPACITY

Designers should size heat pump capacity based on building design, climate, and need for redundancy. Defrost derate should also be considered.

Performance maps associated with specific heat pumps should be reviewed to ensure system capacity meets load at design outdoor air temperatures.

REDUNDANCY

A certain amount of redundancy is built into the Eco2pipe system as the air-to-water heat pumps can be provided with multiple modules, each with their own refrigeration circuit. System designers should consider sizing the system such that full design capacity can be met with one module down for maintenance.

Redundancy in the pumping systems should also be considered. Use of multiple pumps in a lead/standby configuration is a typical strategy to protect against failure of a single pump.

ELECTRIC RESISTANCE SUPPLEMENTAL HEATING

The dwelling unit electric resistance heaters, installed primarily to minimize comfort issues during shoulder seasons (~60 – 70°F ambient temperatures), provide a second layer of redundancy. These heaters provide some space heating capacity in the case of a major failure of either the air-to-water heat pump or associated primary/secondary piping systems, though the heaters are not intended to carry the entire building load.

FREEZE PROTECTION

Freeze protection is required for the primary piping system in cold climates since that system penetrates the building envelope to reach the rooftop air-to-water heat pump, potentially exposing this piping to freezing temperatures.

Two methods of freeze protection are suggested. The first method consists of using a glycol solution as the working fluid in the system. The percentage of glycol would be provided as required to ensure the freeze point of the solution is appropriate. The second method is to install heat trace on all water piping located outside the building envelope. These two freeze methods could be used concurrently as well for redundancy if appropriate. It should be noted that glycol is the preferred method of freeze protection as it protects the system in case of a power outage where heat trace does not.

DEFROST

In cool, humid conditions, the heat pump may require periodic defrost to prevent ice buildup on the condensing unit / gas cooler during heating mode. This defrost mechanism is typically accommodated via a system internal to the heat pump and the physical mechanism for defrost varies by manufacturer. In the case of a reverse refrigerant cycle as defrost, consideration should be given to the effect of the temperature at the decoupling tank (the defrost cycle may adversely affect tank stratification).

Owners want a product that is affordable to install, performs consistently, requires little maintenance, meets green building targets, and reduces energy costs.

SHOULDER SEASON CONTROL STRATEGIES

To minimize comfort issues during shoulder seasons including operable windows and trim electric resistance unit heaters in the overall building design should be considered. Including operable windows allows cooling during shoulder seasons on units that are West facing. Trim electric resistance heating may provide a small amount of heat in North facing units during shoulder seasons.

Electrical

Depending on system capacity, most heat pump units require 460-Volt, 3-phase power connections. Step-up transformers may be needed in buildings with 208-Volt distribution, which is common in multifamily buildings.

In addition to heat pump power requirements, electrical connections for auxiliary equipment such as heat trace, pumps, and the building control system are required.

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Plumbing

POTENTIAL DOMESTIC WATER HEATING

As discussed in the System Component Assessment section, one of the most exciting features of the Eco2pipe system is its ability to generate domestic hot water while simultaneously providing space temperature control. Whereas typical multi-family systems incorporate centralized domestic hot water plants with supply and recirculation lines running to each dwelling unit, the system associated with Eco2pipe eliminates the need for these two piping runs. With Eco2pipe, the only piping at the dwelling units is the secondary system supply and return and a cold domestic water pipe (three pipes total).

CONDENSATE

As with any terminal equipment that provides cooling in conditions where the supply air may reach the dew point, condensate drains must be installed on each fan coil connected to the secondary piping system. This condensate is typically routed to the nearest sanitary drain, upstream of the associated p-trap (to prevent sewer gases from becoming entrained in the supply airstream). Condensation is also a consideration at the heat pump. Condensate should be routed to sanitary drains in accordance with local building codes and freeze protection such as heat trace should be considered in cold climates. When heat trace is used as freeze protection on water piping, a backup power system much be provided. However, on condensate lines backup power is not required because condensate is not produced when during a power outage.

Owners

Owners want a product that is affordable to install, performs consistently, requires little maintenance, meets green building targets, and reduces energy costs. When designed and maintained correctly, Eco2pipe allows building owners to meet all these objectives. In key markets such as California, time-of-use and real-time pricing are starting to drive utility charges. The addition of air-to-water heat pumps that can provide high supply water temperatures (~160°F) will allow the Eco2pipe system to shift electricity usage to periods with lower energy costs. The allowable duration of the load shift depends on supply water temperature and the size of the decoupling / storage tanks. This ability to shift load and operate on a customizable schedule maximizes value for customers and reduces the simple payback period for system installation.

End Users

The primary need of the end users is the ability to maintain a comfortable climate within their dwelling units. The Eco2pipe system is unique in that it only allows mechanical cooling or heating at any given time; it does not allow for some units to be in cooling while others are in heating (as a traditional four-pipe system would). This fact may cause concern for some building owners for fear the system may result in increased comfort complaints.

The two keys to minimizing comfort complaints with the Eco2pipe system are 1) properly determining the correct time for system changeover between heating and cooling and 2) providing tenants with supplementary means to manipulate their climate (i.e., incorporation of operable windows to allow free cooling when Eco2pipe is in heating and installation of electric resistance heaters to allow heating when Eco2pipe is in cooling). Additional controls can be implemented to ensure no simultaneous heating and cooling takes place within a single dwelling unit. Examples of this controls strategy are:

- Lockout of the fan coil unit when a window is proven to be open via a position switch
- Lockout of the electric resistance heaters when the Eco2pipe system is in cooling.

Cost and Constructability Assessment

The Cost and Construction Assessment describes benefits and challenges associated with system installation and operation. It also compares these factors to those associated with available alternatives.

System Benefits

This section lists the benefits of the Eco2pipe system as compared to other solutions:

- Hydronic systems are a known technology (simple 2-pipe technology has been around for over 100 years in the form of hot water radiators).

- No refrigerant is located within the building envelope (as compared to both VRF and split-systems). This fact eliminates the need for vented, fire-rated shafts and refrigerant leak detection.

- Centralized refrigerant piping yields less potential for refrigerant leakage (as compared to the potentially hundreds of required site-installed connections of both VRF and split-systems).

- Moving heat throughout the building via water is more efficient than moving heat via refrigerant.

- Centralized compressors vs. distributed compressors (in the case of split-systems) result in fewer points of failure.

- Individual components can be replaced at end-of-life while leaving the remaining system components in operation. With VRF systems and split-system heat pumps, there are no retrofit options; the entire system must be replaced at its end of life.

- System is not dependent upon a specific refrigerant. As current refrigerants such as R410a are phased out, air-to-water heat pumps could potentially be retrofitted to use new refrigerants. Alternatively, only the heat pump unit could be replaced with one using new refrigerants; the remaining system components could be left in place.

- Simple controls: Outside of the factory heat pump controls, the remaining controlled parts of the system consist only of valves and pumps. There is nothing proprietary about these system components and maintenance does not require manufacturer-specific training.

- Reduced piping material costs. Only primary system piping is copper/iron pipe; the secondary system and domestic piping can be CPVC or PEX piping. Systems that use distributed refrigerant piping require expensive all copper piping due to the higher pressures.

- Productized risers yield simplified site installation.

- Potential to heat/preheat domestic hot water.

- Longer life span: Though the life span of the air-to-water heat pump may be 20 to 25 years, the distribution system (piping, valves, and fan coil units) can easily provide more than 50 years of service. As a comparison, the expected lifespan of VRF systems is approximately 15 years after which the entire system, including distribution piping, must be replaced.

- Verification of system efficiency: Measurement of Coefficient of Performance (COP) of the Eco2pipe system is simple and straightforward and requires only a flow meter and two temperature sensors on the primary pumping system. For VRF systems, verification of installed system performance is extremely difficult since it is hard to quantify the useful heat being produced by these systems.

System Challenges

This section lists the challenges associated with the Eco2pipe system as compared to other solutions:

- Seasonal changeover does not allow for true simultaneous heating and cooling.

- Weight, floor space, and physical installation concerns associated with large decoupling tanks.

- Hydronic systems require freeze protection in cold climates.

- For early installs, since it is a built-up system, detailed commissioning will be required. However, as future installations trend towards fully specified built up systems provided by a single vendor, less intensive commissioning processes will be required as the systems we be more "plug and play."

First Cost Comparison to Available Alternatives

Based on recent cost estimates for a 90-unit apartment complex located in Seattle, Washington, the installation cost of an Eco2pipe system is expected to be on par with a traditional VRF system (less than 10% cost premium). With upcoming International Mechanical Code requirements for fire-rated ventilated shafts for distributed refrigerant piping, the cost of VRF system installation is expected to increase by as much as $1,000 per dwelling unit in the Seattle area.

Maintenance Cost Comparison to Available Alternatives

Specific maintenance cost data associated with Eco2pipe systems as compared to alternative systems is not available to include as part of this feasibility analysis. However, discussions with HVAC service contractors located in the Pacific Northwest show that systems that use distributed refrigerants can have a much higher cost of ownership as compared to hydronic systems.

> ***...the installation cost of an Eco2pipe system is expected to be on par with a traditional VRF system (less than 10% cost premium).***

Some maintenance costs unique to VRF systems are:

- Biannual data collection from condensing units

- Condensing unit issues due to poor quality installation of field piping

- Maintenance personnel require specialized manufacturer-specific training

- Failed parts must be replaced with those from the same manufacturer

- Systems associated with multifamily installations can experience premature failures due to lack of maintenance on the indoor fan coil units

- Failures of small components (e.g., valves) can result in the need to replace larger components (e.g., branch controllers)

It should be noted that costs associated with recharging systems with distributed refrigerant piping (VRF and split-system heat pump units) are not insignificant. A 2020 study performed by PAE Engineers[8] estimates annual refrigerant leakage rates for VRF and split-system heat pumps between 4% (low estimate) and 9% (high estimate) as compared to rates between 2% and 4%, respectively, for air-to-water heat pumps used in hydronic systems. The higher leakage rates of distributed refrigerant systems, in addition to the higher refrigerant charges used in these systems, results in substantial annual expenditures and greenhouse gas emissions to recharge these systems.

Availability

All system components required for an Eco2pipe system are currently available on the market.

Though currently not available, air-to-water heat pumps using natural refrigerants such as CO_2 are in development and should be available in the coming years.

Construction Schedule

Expected construction schedule for a building that implements Eco2pipe is not expected to require any additional time as compared to buildings that use other heating/cooling technologies. In fact, due to the lower number of components to be installed (as compared to VRF and split-systems) and the use of productized risers in the secondary system, construction duration for the system may be less as compared to alternative systems.

Retrofit Feasibility

The Eco2pipe system can be implemented in existing buildings where low-temperature supply water (~120F) is required (such as a multifamily building with low-temperature finned tube radiators). However, in most retrofit applications cooling would not be allowed due to condensation concerns due to the nature of the seasonal changeover. Retrofits of existing systems with terminal equipment requiring high-temperature water (~160°F) could be possible with the adoption of natural refrigerants at the air-to-water heat pump.

Retrofits of existing systems with terminal equipment requiring high-temperature water (160°F) could be made possible with the adoption of natural refrigerants at the air-to-water heat pump.

Maintenance Assessment

Maintenance assessment is broken into two sections: Customer Service and Maintenance. Customer service assesses the ability of the manufacturer to aid Northwest customers. Maintenance addresses upkeep requirements performed by the owner to ensure system longevity.

Customer Service

Most components associated with the Eco2pipe system are "off the shelf" except for the air-to-water heat pump and the building controls system. Accessibility of customer service for these components varies depending on system/equipment selection and location.

For the heat pump, many options are available to designers in the Pacific Northwest. Two manufacturers with large distribution networks in North America are Multistack (based in Wisconsin) and Aermec (based in Ontario, Canada); these manufacturers are particularly well represented in the Pacific Northwest. Representatives from both manufacturers are well trained regarding proper application and design, system startup, and commissioning, including maintenance and troubleshooting. Products from other heat pump manufacturers should also be considered, based on location.

The building controls system for use with the system is not proprietary and should be selected based on previous experience, system cost, and strength of local support.

Maintenance

Due to the relative simplicity of the Eco2pipe system, most maintenance staff should be able to understand the system characteristics and maintenance requirements with little instruction. Routine maintenance includes seasonal maintenance on heat pump, periodic pump maintenance, periodic review of glycol and water treatment, regular blowdowns of system strainers, and regular filter changes at air handling equipment.

Implementation of performance monitoring and fault detection and diagnostic capabilities of the chosen building control system can help maintenance teams minimize issues by allowing predictive maintenance and quick issue response.

Conclusions, Recommendations, and Future Research

Eco2pipe can help Bonneville Power Administration and its utility customers reduce energy demand in the region, provide grid resilience, and lessen greenhouse gas emissions. By transmitting heat around the building using water instead of refrigerant, Eco2pipe minimizes refrigerant leakage, facilitates load shifting, and allows the distribution system within the building to remain untouched when primary heating and cooling equipment is replaced. Eco2pipe is a resilient system for building owners, and it provides benefits to the electric grid. Ideally a demonstration project can be provided during either 2024 or 2025 to prove the concept.

This research into the feasibility of Eco2pipe has raised many opportunities for further research. These topics include:

1. Feasibility of CO_2 for use as refrigerant in air-to-water heat pumps for space heating.
2. Feasibility of Propane for use as refrigerant in air-to-water heat pumps for space heating.
3. Load shift capability of the Eco2pipe system.
4. Load shift capability of thermal slabs and other building structural elements.
5. Feasibility of small water-to-water heat pumps for hot water heating at the dwelling unit level.
6. Feasibility of using space conditioning return water as source water for a centralized water-to-water heat pump to provide domestic hot water.

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