B O N N E V I L L E   P O W E R   A D M I N I S T R A T I O N

Multi-Family Hot Water Temperature Maintenance Study

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Prepared for
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About the Report

The study described in the following report was conducted under contract to Bonneville Power Administration (BPA) to provide an assessment of different methods to reduce energy loss associated with hot water distribution and temperature maintenance systems in multifamily buildings.

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Acknowledgements

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Abstract

Grow Bainbridge is a recently constructed development of energy efficient housing in the Seattle bedroom community of Bainbridge Island. In several small-multifamily buildings on site, the hot water load is met by a central heat pump system. This project sought to explore two facets of central heat pump domestic hot water heating in multifamily buildings: the optimal strategy for temperature maintenance, and the efficacy of inverter-driven, R-410a based air-to-water heat pumps located in the underground parking structure. Herein we discuss background on central hot water systems, results of the different temperature maintenance strategies, challenges and successes with the R-410a heat pump equipment, and recommendations for future inquiries into efficient water heating in multifamily buildings.

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Executive Summary

Ecotope and Bonneville Power's Emerging Technologies group are actively looking for new and innovative ways to reduce energy use in multifamily buildings. Previous multifamily domestic hot water heating research and demonstrations have helped to identify the large impact that temperature maintenance systems have on overall energy use of hot water systems in multifamily buildings (Heller 2015). The temperature maintenance systems are also known as hot water recirculation loops. This piping circulates water within the building to provide hot water at the point of use with minimal delivery time delay. Prior work has also shown that temperature maintenance for central heat pump water heating equipment can have an even larger impact on system performance than central gas boilers. This study examined two alternative approaches aimed at reducing temperature maintenance loads in buildings served by central heat pump water heating equipment. As an additional goal, the project also examined the viability of inverter-driven R-410a air-to-water-heat pumps for central water heating.

The hot water temperature maintenance pilot study took place on Bainbridge Island, Washington in a new building complex. It examined three distinct system designs in similar, low-rise multifamily buildings. The systems consisted of:

- **Building A – Reference Case**. The reference case with a traditional hot water recirculation system layout.
- **Building B – Heat Trace**. Heat trace tape on the hot water system supply piping maintains temperature in the pipe.
- **Building D – Pipe in Pipe**. A "pipe in pipe" plumbing system. The pipe in pipe system recirculates the hot water with concentric piping.

Conducting the study in nearly identical buildings sought to minimize variation in independent variables between the systems so that the observed differences would be due to the system designs themselves. This strategy worked to varying degrees of success. First, hot water usage at the three buildings was surprisingly different despite having the same number of units. Second, the combination study of temperature maintenance system and the heat pump created an interplay that was not always possible to untangle. Nevertheless, the study generated a number of useful findings in both research areas. In particular, the annual energy used for temperature maintenance across the buildings was relatively close suggesting the optimum water heating strategy relies on the manner in which the temperature maintenance strategy interacts with heat pump operation and system controls.

Table ES-1 provides high-level summary results of the project encompassing nearly a full year of data. A large disparity in occupancy resulted in significantly different water flows at the three nominally similar buildings. This somewhat clouded a direct comparison between the buildings, although many comparisons were revealing regardless. For example, Building B delivered the most hot water with the least amount of energy input to the Altherma. This was due to the Altherma only providing the DHW usage load, whereas the Althermas at sites A and D were tasked with meeting both DHW load and temperature maintenance load.

Further, in interpreting the table, it is useful to know that the Altherma COP in the table was defined as the ratio of total heat added by the Altherma to the electrical input to the Altherma. The System COP in the table was defined as the ratio of total heat added throughout the system to total electrical input to the system. This calculation included the trim tank electric resistance as well as circulation pumps or heat trace as applicable to the different sites. Additionally, for Building A and Building D, maintenance losses were calculated through a measured recirculation flow rate and temperature drop from the supply line to the return line. For Building B the maintenance losses were calculated as the average power consumption of the heat trace.

Table ES-1. Summary Results

	Building A	Building B	Building D[1]
Hot Water Demand (gal / day)	276	511	128
Altherma (kWh / day)	40	33	38
Pump (kWh / day)	5.4	1.5	5.4
Resistance Electric (kWh / day)	6.6	27	-
Total Electric (kWh / day)	52	62	-
Altherma COP	2.7	2.5	2.1
System COP	2.2	1.8	-
Maintenance Losses (kW)	2.1	0.8	1.4

Most generally, the findings suggest an attainable equipment COP between two and three for central domestic hot water heating with this type of equipment, with the pipe-within-a-pipe recirculation strategy leading to maximum energy reduction. This research reiterates the viability of air-to-water heat pumps located in below-grade parking structures in the Puget Sound region for multifamily domestic hot water heating, and points toward the need to identify reliable equipment and designs to specify in such scenarios going forward. Additionally, care should be taken to match equipment with its corresponding, optimal temperature maintenance strategy, which will require a nuanced understanding of how different heat pump designs respond to different approaches for temperature maintenance. Equipment similar to the Daikin Altherma should be paired with a pipe-within-a-pipe recirculation loop to achieve maximum energy reduction, although the savings margin compared to traditional recirculation is small enough that the additional expense may or may not be cost effective for a given project. Single-pass heat pump water heaters should be paired with a heat trace design to bolster heat pump efficiency. Finally, as the distribution load was measured to rank comparable to the DHW load itself, care should be taken to reduce piping losses where wherever possible.

[1] Measurement error on the trim tank power consumption at Building D prevents reporting resistance electric, total electric, and system COP measurements.

1 Introduction

Ecotope and Bonneville Power's Emerging Technologies group are actively looking for new and innovative ways to reduce energy use in multifamily buildings. Previous multifamily domestic hot water heating research and demonstrations have helped to identify the large impact that temperature maintenance systems have on overall energy use of hot water systems in multifamily buildings (Heller 2015). The temperature maintenance systems are also known as hot water recirculation loops. This piping circulates water within the building to provide hot water at the point of use with minimal delivery time delay. Prior work has also shown that temperature maintenance for central heat pump water heating equipment can have an even larger impact on system performance than central gas boilers. This study examined two alternative approaches aimed at reducing temperature maintenance loads in buildings served by central heat pump water heating equipment.

Standard practice for multifamily buildings with central water heating equipment includes a great deal of hot water distribution piping to carry heated water from the central plant to the plumbing fixtures throughout the building. In a mid-sized multifamily building this distribution system will hold hundreds of gallons of water. Without some means to keep the water in the distribution system hot throughout the day the tenants would have to wait a long time to get hot water from the central plant; running many gallons of lukewarm water down the drain. To prevent this, most modern multifamily buildings with central water heating include hot water circulation systems to keep water circulating through the pipes and returning to the central system to be reheated. The loss of energy in the distribution and circulation piping typically represents a large fraction of the overall energy use of a new multifamily building.

1.1 Project Scope

The hot water temperature maintenance pilot study was implemented to compare the overall energy performance of three hot water system designs. The systems serve three similar, low-rise multifamily buildings. The temperature maintenance energy (the energy used to keep hot water at the ready in the pipes between the hot water heater and the fixtures in the apartments) of each system was evaluated to see which, in combination with a heat pump, was most efficient. All systems had similar piping layouts and insulation. The three systems differed in their approaches to hot water maintenance. They consisted of:

- **Building A – Reference Case**. The reference case with a traditional hot water recirculation system layout. The hot water is continuously circulated throughout the building via a pump. This includes a piping layout that sends hot water out to the branch lines and back to the central storage tank.
- **Building B – Heat Trace**. Heat trace tape on the hot water system supply piping maintains temperature in the pipe. The heat trace is electric resistance cable, affixed to the pipe, located underneath the insulation. It operates on a thermostat set to keep the water hot. No return piping to the central storage tank is needed in this configuration.
- **Building D – Pipe in Pipe**. A "pipe in pipe" plumbing system. The pipe in pipe system recirculates the hot water with concentric piping. That is, the hot supply flows through the outside of the pipe and the slightly cooler return water flows back through the inside. The theory is that such a configuration minimizes heat loss by having less surface area through which to loose heat.

Note that the naming convention of buildings A, B, and D derived from site plans rather than an experimental design notation to mask building identity, hence the lack of a strategy "C."

The heating plant for each of the three systems was identical: a Daikin Altherma heat pump. A secondary goal of the study, the project also monitored the efficiency of the heat pumps to see how they differed in response to the recirculation strategy. Results of these measurements are also described in the report.

1.2 Project Location and Buildings Description

The buildings in the study are part of a staged development of small apartment buildings located on Bainbridge Island near Seattle, Washington. Each apartment building is comprised of 12 units (13 in the case of Building D) of two bedroom apartments. The buildings are three stories tall generally with four units per floor. Buildings were equipped with low flow fixtures in accordance with common practice in the Northwest. Likewise, recirculation, where present, operated 24/7 to assure that all units had access to hot water on demand. The buildings all share a common subterranean parking garage where the heat pumps and storage tanks are located. Refer to Figure 1 for a site plan and Figure 2 for exterior views of two of the buildings.

Figure 1. The Grove at Grow. Site Plan.

Figure 2. Building Exteriors

Table 1 provides a quick summary of the building configurations

Table 1. Building Configuration Overview

Building	Experiment ID	Hot Water Distribution System	Number Units	Occupants
The Salal	Building A	Traditional Recirculation	12	18
The Juniper	Building B	Heat Trace w/out Recirculation	12	30
The Tsuga	Building D	Pipe in Pipe Recirculation	13	?? <30

1.3 Background Research

Previous work by Ecotope and others has motivated this project. The following section presents an overview of the importance of hot water heating in multifamily buildings.

1.3.1 Multifamily Building Water Heating Energy Use

The Commercial Building Energy Consumption Survey (CBECS) from 2009 reports that domestic water heating accounts for 26% of energy end use in multifamily buildings in the western region of the United States. All buildings with five or more units are included in the estimates, including a range of water heating systems and building eras.

Recent research of energy use in a sample of ten new construction Seattle buildings indicates that domestic water heating likewise accounts for about 25% of the energy use of a typical Seattle apartment building (Heller 2009). The median energy use intensity observed for the buildings was 39 $kBtu/ft^2$ per year meaning site energy used for water heating was 10 $kBtu/ft^2$ per year alone. While heating and cooling loads vary significantly by climate, domestic water heating loads are driven by fixture flow rates and occupant behavior. Therefore, we expect hot water needs to be similar across the Pacific Northwest if fixtures and occupant behaviors are comparable.

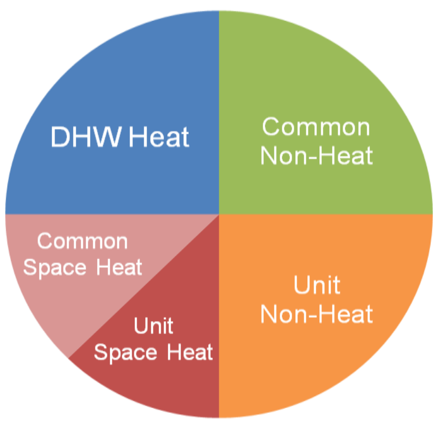
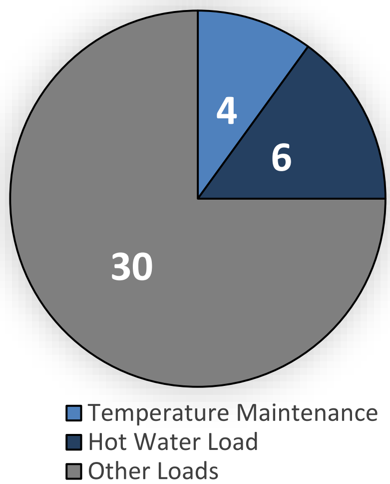


Figure 3. Energy End Use Breakdown for new Multifamily Buildings in Seattle (Heller 2009)

Previous research to support the adoption of reverse cycle chillers (RCC otherwise known as air-source heat pumps) in larger multifamily apartments involved estimation of the efficiency of the systems as a whole (Heller 2015). Results indicated that while the heat pump equipment functioned reasonably well, the overall performance of the system was not as high as expected. These observations revealed that temperature maintenance losses from traditional recirculation systems were greater than current assumptions of 20%. The systems monitored at two new construction midrise apartment buildings (92 and 118 units, respectively) indicated maintenance losses of approximately 40% of the water heating load. This is equivalent to 10% of all the energy used on site. Figure 4 illustrations the proportion of the energy used and, in the left infrared photo, shows a typical source of heat loss: an uninsulated valve on the distribution piping.



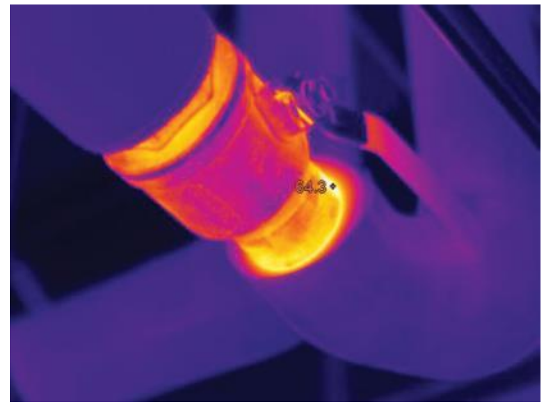


Figure 4. Temperature Maintenance Energy Use (Btu/ft^2/yr) And Typical Heat Loss Source

1.4 Central Systems and the Necessity of Hot Water Temperature Maintenance

Clearly, temperature maintenance of hot water is a large inefficiency in multifamily buildings. The observation poses the obvious questions: why it is done in buildings and is it even necessary?

In smaller multifamily buildings, the most common domestic water heating method is placing tanks, generally electric resistance, in each unit. This does away with the need for circulation loops by placing the hot water source close to the fixtures. The Residential Building Stock Assessment found about 90% of existing Northwest low-rise apartments have tanks in the units, the remaining 10% are served by central systems (Ecotope 2013). In existing mid-rise and high-rise buildings, 10% and 50%, respectively, are served with central systems (Ecotope 2013). However, in the past decade of its own *new* construction projects, Ecotope has observed nearly all buildings using central systems. Central water heating is desirable by architects and developers to maximize the leasable space of a unit by moving the water heating out of the apartment. Central water heating equipment also centralizes the maintenance associated with this equipment and avoids potential water damage from leaking hot water heaters distributed throughout the building.

As alluded to previously, building occupants do not tolerate long wait times for hot water to be delivered to their fixtures. A typical unit could be located 100 feet of pipe away from the hot water storage tank mostly connected by a 1”-2” diameter pipe. Most of the time, hot water is not in active use and that is when the water cools off in the pipes. To get hot water to reach the fixture, it can then take many gallons and minutes of cold to warm flow which ends up down the drain. Research by LBNL suggests 15 seconds is a tolerable wait time for hot water delivery. Accidental experiments conducted at buildings designed by Ecotope suggest that not having hot water circulating and available at all times generates serious occupant complaints.

1.4.1 Water demand curves data

As part of the previous RCC research, hot water withdrawals from apartment central water heating systems were monitored. With a large number of apartments, and residents bathing and washing on differing schedules, water withdrawals happened throughout the day and night (see Figure 5). This meant that there were few if any periods when turning off the circulation pump would not result in delays in delivery of hot water. Even in the 2-4am hours, there were very few times when someone in the building wasn’t using water every hour. This constant use means there is no opportunity to allow the temperature in pipes to drop. The result is a need for temperature maintenance twenty-four hours per day.

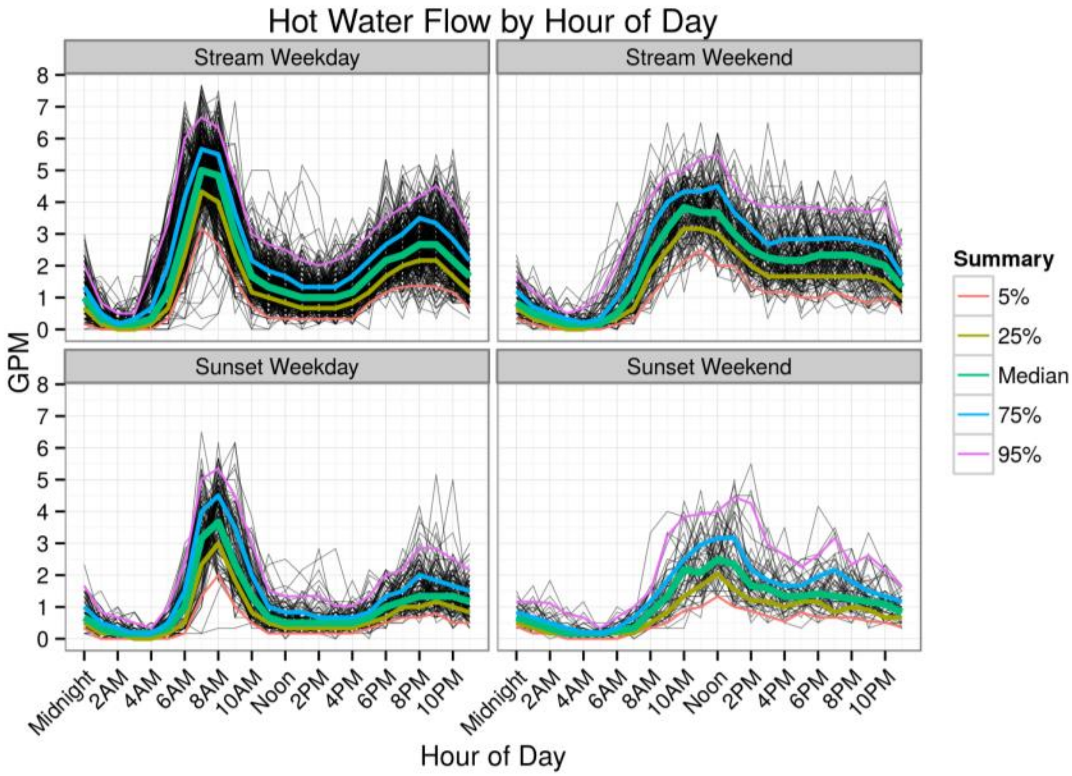


Figure 5. Hourly Hot Water Use in two ~100 Unit Multifamily Buildings

1.4.2 Heat Pump Opportunities

Central water heating offers an opportunity to use heat pump technology in the place of resistance heating. One way to reduce the non-temperature maintenance water heating energy use is to employ heat pumps. Integrated, hybrid heat pump water heaters (HPWHs) are currently available on the market which offer considerable energy reduction to resistance heating (Ecotope 2015). The integrated design of those HPWHs makes them challenging for multifamily installations. They exhaust cold air and create localized noise which is acceptable in houses with space to isolate the HPWH but apartments are too space-constrained for this to be reliably practical. Centralizing the entire heating plant to the garage, however, enables the use of heat pumps. The equipment can benefit from moderating influence of earth and concrete on the air temperature and run the entire year. This concept was the genesis of the RCC systems and is continued with this project.

2 Equipment, Measurement, and Experimental Design

The experimental design called for three identical heat plants installed in three similar buildings each with a different temperature maintenance strategy. The design sought to minimize differences between installations where the differences were not an integral part of the systems being compared. However, real world conditions do not allow for identical operation of all the systems, as apartments have different occupancies and occupants have differing water use patterns. A further confounding factor, discussed later, is the fact that the heat pumps themselves operate at different efficiencies when heating different water temperatures. The three different maintenance strategies inherently have different water temperatures for the heat pumps to heat. Where possible the effects of this were isolated by multiple measurement points.

2.1 Heat Plant

The heat plant for all the buildings was comprised of multiple components with the heat source provided by a Daikin Altherma heat pump in the monobloc configuration. It has a variable capacity inverter-driven compressor, uses R-410a refrigerant, and has a nominal output capacity of 47,800 Btu/hr (4 tons or 14kW) at 45F ambient air temperature. Additional design engineering was required to build out the full heating plant. The additional components include:

- Hot water storage tanks. Two, 200 gallon tanks. Rheem Model ST200A.
- Aquastat for storage tanks. Honeywell L series.
- Flat plate heat exchanger. Flat Plate Model FG10X20-40.
- Storage tanks to heat exchanger circulating pump. Taco Model 008-IFC.
- Switching relay. Taco Model SR-501.
- Trim/Backup electric resistance water heater. Rheem Model E85-15G.
- Building circulation pump (Buildings A & D). Taco Model 0014.

The Altherma is piped in isolation on one side of the heat exchanger. It has its own pump which can circulate water from the heat pump, through the heat exchanger and back. On the other side of the heat exchanger are the storage tanks and a pump. The switching relay is designated the master control point. When the aquastat in the storage tank drops below setpoint, it sends a call to the switching relay which, in turn activates the Altherma and the Taco pump on the storage tank side of the exchanger simultaneously. The Altherma then provides hot water to the heat exchanger on one side and the flow of water on the other extracts heat to warm the tanks. The hot water from the storage tank is piped first through the trim tank before it is sent to the building. The trim tank has a 15kW resistance element. It was originally planned to raise the water temperature from 120F to 130F but subsequent optimizations lowered the setpoint so the trim tank runs less. As a bonus, the tank also acts as a backup to the Altherma system. Finally, the building circulation pump is set to run constantly.

The heat pump compressors were installed in open mechanical bays in the parking garages. Figure 6 shows the Altherma heat pumps in the center. Other mini-split heat pumps for apartment space heating can be seen mounted to the walls. When used for summertime cooling, these units dump heat to the garage which can be harvested by the water heating system. Storage tanks were located behind the heat pumps, in the unconditioned space of the garage. The tanks were not insulated over code required levels. Figure 7 shows the hot water tanks on the right and the back of the Altherma unit on the left.

Figure 6. Altherma Monobloc Heat Pumps in Parking Garage

Figure 7. Hot Water Storage Tanks and Heat Pump

2.2 Pipe Insulation

The water distribution pipes were insulated in excess of 2012 Washington State Energy Code requirements. In the parking garage, all exposed piping was insulated with two inches of pipe wrap. Contractors used best practices as pictured in Figure 8. The pipe hangers were installed outside the insulation to prevent conductive thermal bridging.

Figure 8. Pipe Insulated without Thermal Bridging

The hot water risers were installed in wall cavities which were themselves insulated (Figure 9). The pipes ran through the middle of a double 2x4 wall and the cavity was dense packed with insulation resulting in R-11 encasing the pipes. Once in the units (the final leg of the piping), and hence beyond the purview of the circulation loop, the pipes were uninsulated.

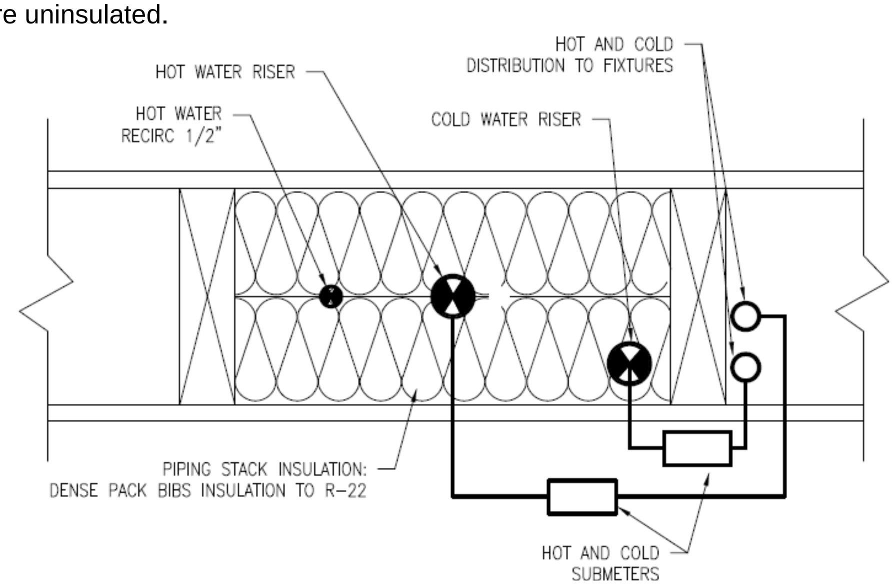


Figure 9. Typical Cavity Insulation Detail

Overall, even for the traditional, baseline recirculation system the strategy was to deploy high levels of insulation to reduce heat loss. The idea with the traditional system was to demonstrate best practices and then compare the other systems to it as opposed to just code minimum or worse practices.

2.3 Hot Water Temperature Maintenance Strategies

2.3.1 Traditional Recirculation

The traditional recirculation system uses a pump to move water in a loop from the central storage tank, past branch pipes for every unit, and back to the central tank. The branch pipes are not continuously flushed with hot water but are short enough that they quickly empty of cool water when occupants open fixtures. Once water is heated, it losses heat constantly until it leaves the building (well, it keeps cooling off to surrounding temperatures then too). Heat losses occur in the storage tank and more acutely in the circulation system. Heat loss is simply a function of insulation and surface area. The more circulation pipe, the more heat loss. Typically, water may be supplied to the loop at 125F and pump flow rates set so the water returns ten degrees cooler. Figure 10 illustrates a traditional system lay out.

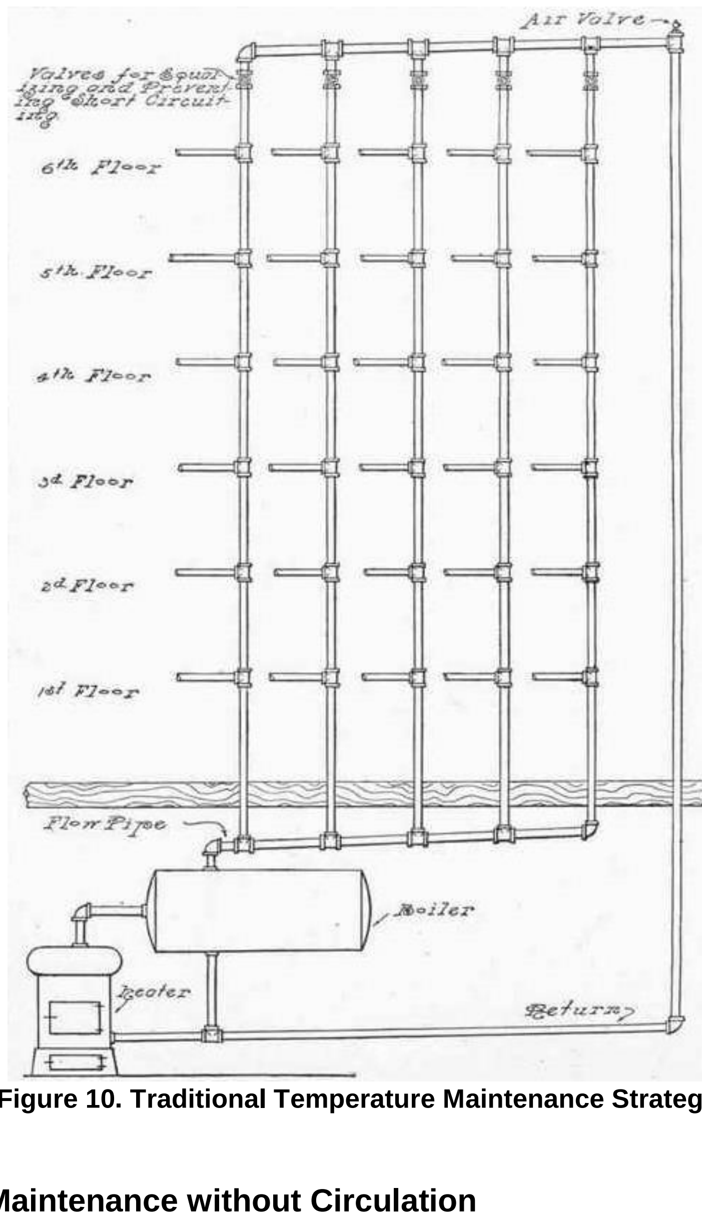


Figure 10. Traditional Temperature Maintenance Strategy

2.3.2 Temperature Maintenance without Circulation

As an alternate to circulation, electric resistance heat trace cable, or tape, can be employed to keep the standing water in the distribution pipes hot. This is the same technology that is used frequently to keep water pipes from freezing in unheated locations. Figure 11 demonstrates how heat trace is installed on the water pipe between the pipe and the pipe insulation. A thermostatic controller is set to maintain the desired temperature in the piping. For good heat transfer, conductive piping should be used with the heat trace. Heat trace systems have a limited lifespan and will potentially need replacement within the life of the building. For this reason the heat trace should be placed in areas that can be easily accessed to allow for future replacement.

A heat trace system realizes savings in materials as no return system or circulation pumps are needed. Pumping energy use is also eliminated. In contrast with traditional recirculation or the pipe in pipe system, where an efficient heat pump system can reheat returning water, electric resistance heating from the heat trace makes up the distribution heat losses in the piping. Still, with no return needed, the distribution pipe distance is effectively cut in half. This, in turn, reduces the heat loss by a factor of two. Compared to a traditional circulation system, this doubles the efficiency.

Heat trace also offers an added benefit to some heat pump systems. Heat pump water heaters are most efficient when they heat the coldest water; this is especially true for single pass R-134a and CO_2 refrigerant systems. With heat trace, no water recirculates to the storage tanks. Typical return water temperatures could be 110-115F which, by heat pump standards, are hot. Heating 115F water to 125F water typically occurs at a low efficiency. The heat trace skips this problem entirely and allows the heat pump to heat only the coldest incoming water.

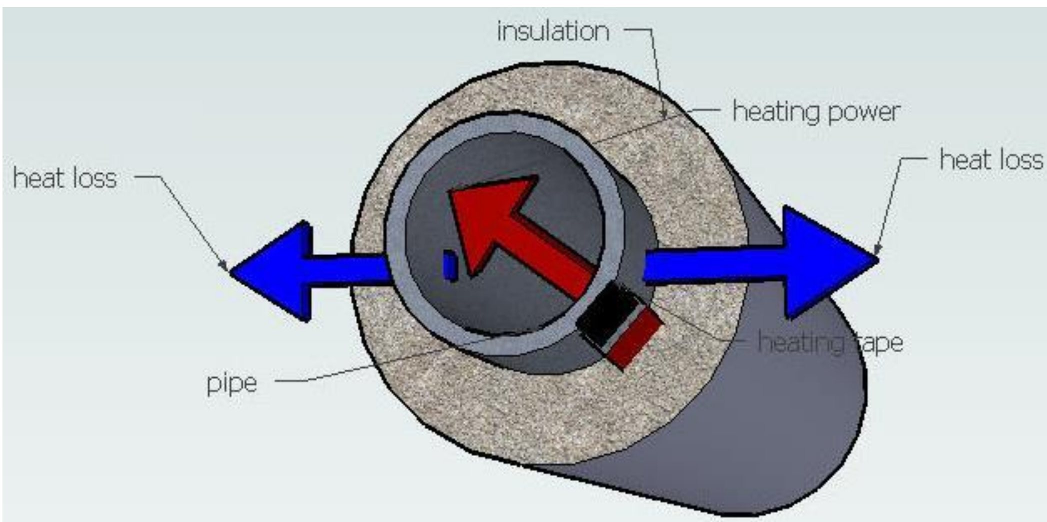


Figure 11. Temperature Maintenance With Heat Trace

2.3.3 Temperature Maintenance with Pipe in Pipe

To reduce the losses from recirculation, distribution alternatives such as the pipe in pipe system have been designed. The plumbing design is similar to traditional hot water circulation, except that the return piping is located inside of the supply riser. Figure 12 illustrates the configuration. Two concentric pipes are used. Water is supplied on the exterior and returned through the interior. In effect, this design insulates the return water from the surrounding building (it would actually heat it slightly). Overall, this reduces the heat loss rate of the distribution system although it does not cut it in half because larger diameter pipe is needed for this system. Pipe surface area, and heat loss, increases proportional to the natural log of the radius. So, the pipe run is half but surface area is more than half. Still, it is a significant reduction in area.

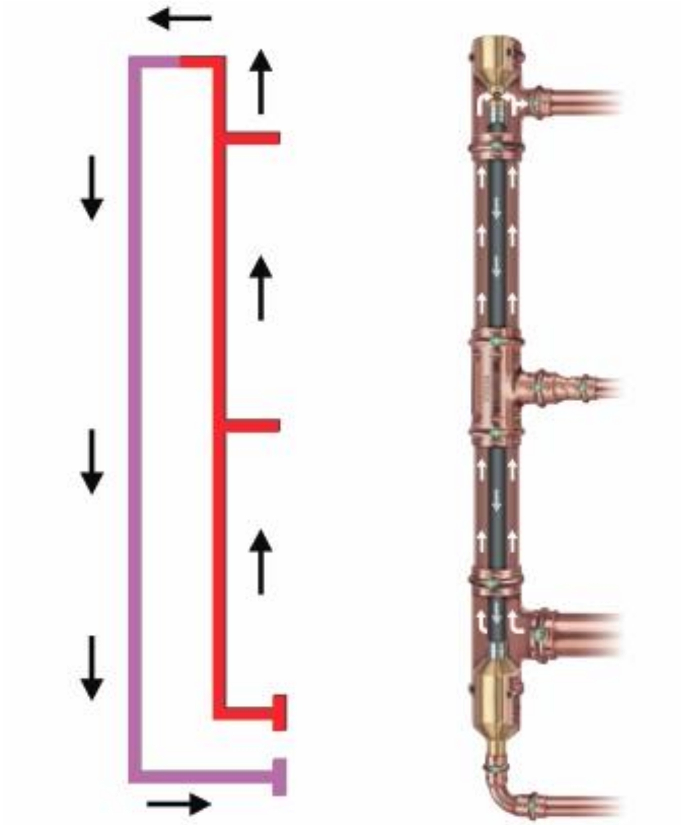


Figure 12. Pipe in a Pipe Temperature Maintenance System at right. Conventional at left.

2.3.4 Temperature Maintenance Strategies Heat Loss Rate Compared

Table 2 presents the hot water piping distribution system characteristics for the buildings. The information is for the pipe between the heating plant (after it leaves the trim tank) and the individual unit branches. These are the physical characteristics that change with each temperature maintenance strategy. The values are calculated from building drawings – the length and diameter of pipe, its location, and the amount of insulation. The estimated heating load is based on an approximate 65 degree F temperature differential from the water to the surroundings. This is an average temperature value given that some pipe runs are in the garage and other are internal to the building. The estimates exclude any thermal bridging due to exposed valves or other fittings and are therefore a low estimate.

As can be seen, the heat trace system cuts the pipe length in half. The heat loss rate isn't quite cut in half because there are different amounts of insulation along the distribution system. To note, the pipe length at building D is presented as the same as A but 150 feet of it is the return pipe contained within the supply pipe so it has a negligible heat loss rate. Further, there is some pipe length where it is not feasible to use the pipe in pipe design which accounts for some additional heat loss.

Table 2. Hot Water Distribution System Heat Loss

Building	Strategy	Pipe Length (Feet)	Pipe Heat Loss Rate (Btu/Hr-F)	Estimated Heat Load (Btu/Hr)	(Watts)
A	Traditional Recirculation	349	47	3040	890
B	Heat Trace	177	28	1830	540
D	Pipe in Pipe	349	29	1920	560

2.4 Measurement System

Ecotope deployed a measurement system at each building to sufficiently characterize both the heat pump performance and the temperature maintenance systems. This included direct heat output measurements at the heat pumps and power inputs to calculate a coefficient of performance. Data loggers were deployed with a number of individual sensors. All data were logged at 1-minute intervals and transmitted daily, via a cellular modem to an Ecotope server. Data were subsequently processed and monitored over the course of the project. The measurement points include:

- Water Flow
    - Total building hot water use
    - Altherma heat pump water loop flow rate
    - Recirculation loop flow rate (for Buildings A and D only)
- Energy Use
    - Heat pump true power
    - Backup electric tank true power
    - Storage tank to heat exchanger pump power
    - Heat trace power (Building B only)
- Temperatures
    - Garage air temperature
    - Incoming cold water temperature
    - Domestic hot water supply temperature (water temperature supplying the circulation loop or heading to the heat trace)
    - Recirculation water return temperature (Buildings A and D only)
    - Temperature split across the heat exchanger on the storage tank side (2 measurements)
    - Water temperature supplied to trim/backup tank

3 Findings

The high level findings of hot water demand, system energy use, system efficiency, and relevant water temperatures are displayed in Table 3. The estimates provided in the table encompass nearly a full year of data, and could reasonably be interpreted as annual averages. A large disparity in occupancy resulted in significantly different water flows at the three nominally similar buildings. This somewhat clouded a direct comparison between the buildings, although many comparisons were revealing regardless.

Table 3. Building Measurement Summary

	Building A	Building B	Building D
Hot Water Demand (gal / day)	276	511	128
Altherma (kWh / day)	40	33	38
Pump (kWh / day)	5.4	1.5	5.4
Resistance Electric (kWh / day)	6.6	27	-
Total Electric (kWh / day)	52	62	-
Altherma COP	2.7	2.5	2.1
System COP	2.2	1.8	-
Maintenance Losses (kW)	2.1	0.8	1.4
HX Inlet Temp (F)	120	99	120
HX Outlet Temp (F)	125	113	125
Water to Trim Tank Temp (F)	125	117	122
Delivered Water Temp (F)	125	123	124

Hot Water Demand and Total Energy -
Building B delivered the most hot water with the least amount of energy input to the Altherma. This was due to the Altherma only providing the DHW usage load, whereas the Althermas at sites A and D were tasked with meeting both DHW load and temperature maintenance load.

Coefficient of Performance (COP) -
The Altherma COP in the table was defined as the ratio of total heat added by the Altherma to the electrical input to the Altherma. The System COP in the table was defined as the ratio of total heat added throughout the system to total electrical input to the system. This calculation included the trim tank electric resistance as well as circulation pumps or heat trace as applicable to the different sites. Resistance electric, total electric, and equipment COP measurements were not provided for Building D due to measurement error on the trim tank power consumption. The trim tank energy at D is likely more similar to A than anything else but this remains unverified.

Maintenance Losses -
For Building A and Building D, maintenance losses were calculated through a measured recirculation flow rate and temperature drop from the supply line to the return line. For Building B the maintenance losses were calculated as the average power consumption of the heat trace.

Operational Differences -
The summary table also demonstrates the operational differences between a recirculation-based temperature maintenance system and the heat trace. Building A shows the pattern most cleanly: the constant presence of an approximately four GPM recirculation loop flushed the tank with warm water at all times. The Altherma, then, consistently saw 120F inlet water to the heat exchanger, and applied a five degree temperature lift. As the storage tanks remained well-mixed, this temperature was delivered to the trim tank and, of a sufficiently usable temperature, delivered to fixtures with little additional trim tank heat. In contrast, with no recirculation loop at the heat trace site B, temperature stratification in the tank was allowed to develop, with colder water sent to the heat exchanger. One consequence of this was that the water to the trim tank lagged behind an acceptable threshold for deliverable hot water, and thus the Building B Altherma was frequently supplemented by trim tank electric resistance to finish heating the DHW to an acceptably high temperature. It is not clear if this was an unavoidable consequence of the heat trace design or something that could have been addressed with an alternate control

scheme. Building D, also with a recirculation loop, showed a similar pattern to Building A, although with slightly lower temperatures at the trim tank.

3.1 Measured Annual Energy Use

Figure 13 visualizes the energy use findings of DHW load, recirculation load, and the energy input expended to meet the recirculation load. This figure makes plain the large discrepancy in hot water demand, which confounded the ideal comparison between sites. As expected, the traditional recirculation scheme resulted in the highest temperature maintenance load. Somewhat surprising was how much higher the pipe-within-a-pipe load was than the heat trace load. We had expected them to be closer. The chart shows that, in the case of sites A and D with recirculation loops, the maintenance load was larger yet met with heat pump COP. At site B, the maintenance load was smaller but met with an electric resistance COP of 1. Despite the varying magnitudes of temperature maintenance load, the estimated energy use spent meeting the load turned out remarkably similar. We estimate annual energy use for temperature maintenance as 7800, 7000, and 6600 kWh per year respectively for Building A, B, and D. (The estimate for Building D reflects equipment problems encountered at that site, and under ideal system operation the pipe-within-a-pipe energy use for temperature maintenance could be as low as 5600 kWh per year.) The relative closeness of these numbers suggests that the optimal strategy may also rely crucially on the manner in which the temperature maintenance strategy interacts with heat pump operation and system controls. This will be discussed further in the report.

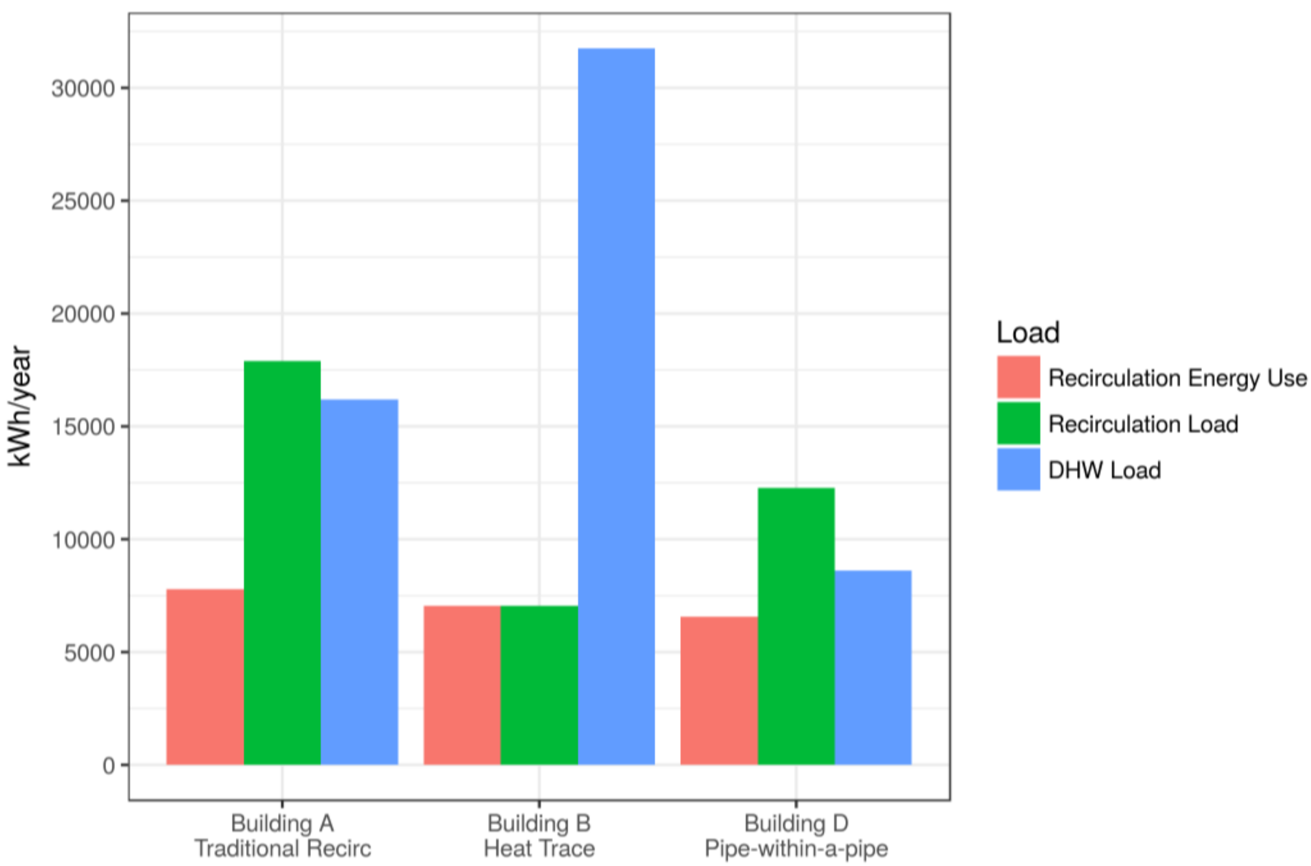


Figure 13. Measured Annual Energy Use

3.2 Hot Water Use and Patterns

3.2.1 Daily Hot Water Demand

The total hot water flow meters showed significant variation in hot water use between the three buildings, despite having similar unit counts. As the fixtures and appliances were also identical across the buildings, these differences were then driven by occupant count and demographics. Occupant counts were provided by property management. Building B had the greatest number of occupants concomitant with the largest water demand. We were unable to ascertain an accurate count at D – it was suggested that some of the occupants at D may have been snowbirds, occupying the space only during summertime. The data monitoring of this project spanned the fall, winter, and spring, so this would have appeared functionally as vacant units. We do know that the Building D occupancy was lower than B. Information from the property manager further suggested that Building B was predominantly occupied by families, while Buildings A and D were more likely to have working professionals and retirees who typically use less hot water than families. The occupant count was as follows:

- Building A – 18
- Building B – 30
- Building D – less than 30

Figure 14 shows the daily hot water demand over 7 months of the study. The expected shape is to have a peak in February and a trough in July/August corresponding to the coldest and hottest inlet cold water temperatures. That did not reveal itself in these buildings potentially due to irregular occupancy (snow birds) or the buildings not being completely leased for the period graphed.

Hot water use is an important factor in determining the heat pump efficiency and the amount of energy spent on temperature maintenance. Greater overall hot water use should improve both – a higher heat pump COP and lower maintenance energy requirements. The fact that total water usage differed by a factor of three between buildings confounded some of the subsequent performance comparisons in ways that are not quantifiable. We simply have no way to answer the question: what if the occupants of Building B had used 100 gallons per day instead of 500? How would that have affected the operation of the variable speed heat pump system with heat trace temperature maintenance? The qualitative aspects of the differences described previously, however, should be kept in mind when interpreting the findings.

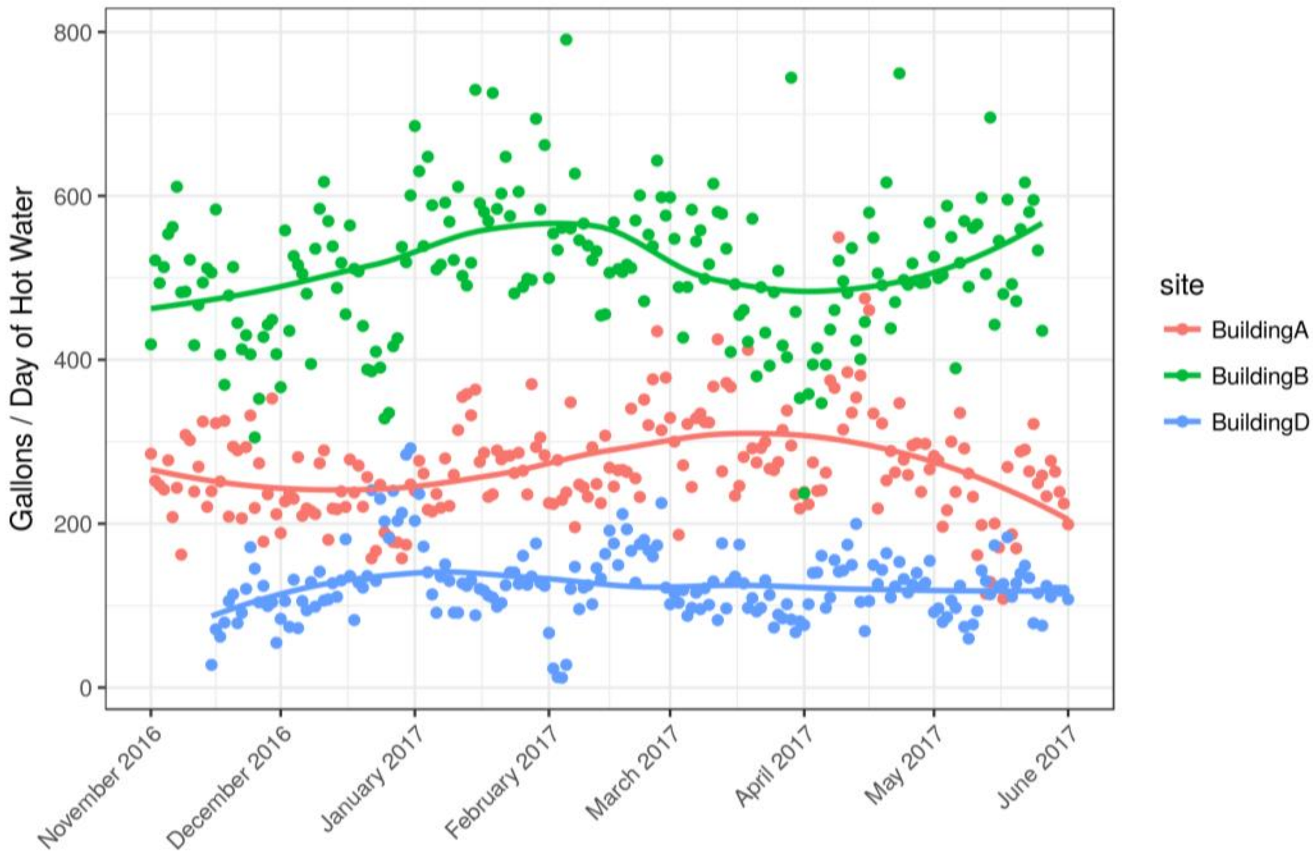


Figure 14. Daily Hot Water Demand

3.2.2 Hot Water Time of Use

Figure 15 displays the chance of no hot water being used in a building for a given hour of the day. The data were based on Buildings A and B from this project and two larger mid-rise buildings recently constructed and monitored in Seattle (the pilot buildings for the RCC project). The graph highlights the need for constant temperature maintenance – that is to say, continuously operating circulation pumps or heat trace. The graphs can be interpreted as follows: between 1am and 4am there was a 2/3 chance that no one in the Grow buildings would have needed hot water during that hour. Those sound like pretty high odds but, examined another way, it means that every one out of three nights, someone wanted hot water at 3am. This is simply too frequent to turn the temperature maintenance off and not provide hot water in a timely fashion. Surprisingly, this usage requirement was in a building as small as twelve units. For larger buildings, like the two mid-rise cases, the no-usage window was narrower and peaked at only a ¼ chance. The hot water demand monitoring at these buildings suggested limited potential for opportunistically disabling the temperature maintenance system.

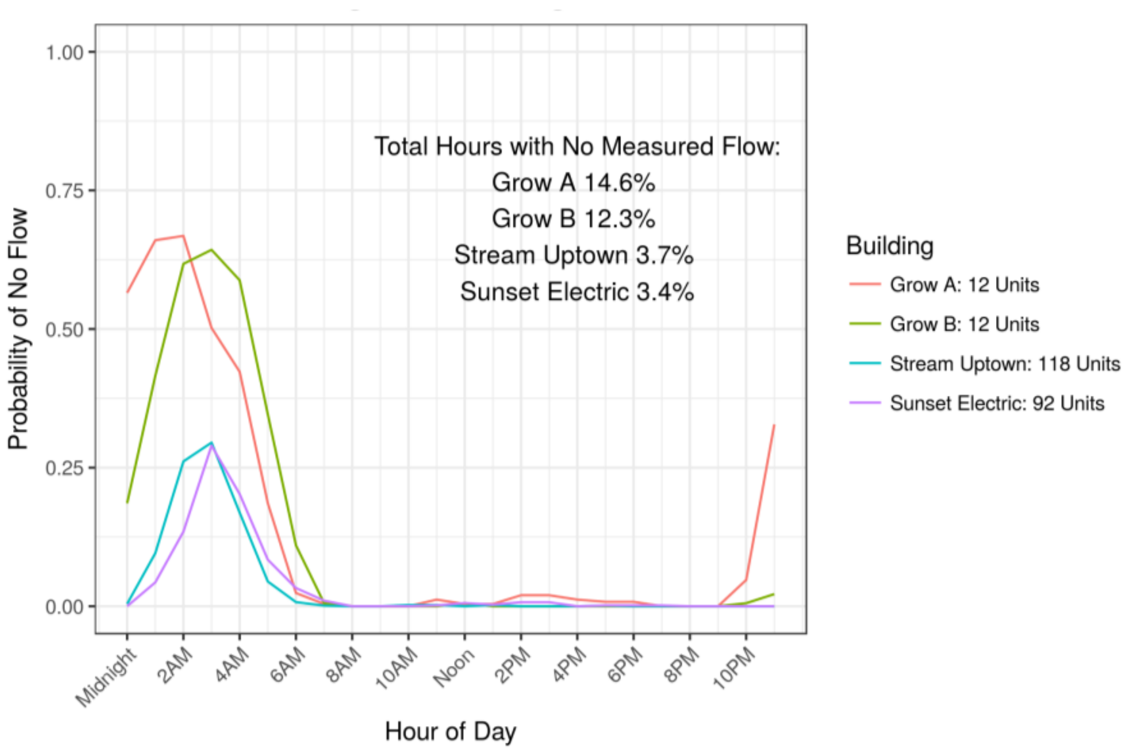


Figure 15. Chance of No Hot Water Use

Additional graphs of hot water use patterns are located in Appendix A: Supplemental Graphs.

3.3 Temperature Maintenance Loads

Hot water maintenance losses averaged 2.1kW at Building A and ranged from 1.5 kW in the summer to 2.5 kW in the winter. Figure 16 depicts the seasonal trend and the maintenance loads at all the buildings. The energy use is clearly correlated with garage and outdoor air temperature. Building B, with heat trace, showed a persistent 0.8kW load with, perhaps a mild upward trend in the colder months. At Building D, a 1.4kW load, there is no obvious seasonal effect. Some seasonality is to be expected, as the garage temperature varied with season and all systems contained piping in the parking garage. With 120F delivered water temperature, 40F wintertime garage air temperature, and 70F summertime garage temperature, one would expect the losses occurring in the garage to increase by 60% with the remaining losses mostly unchanged. Oddly, the overall maintenance losses at A increased by 60% between summer and winter, which seems erroneously high. Further, it is not clear why the other buildings showed no seasonality. The discrepancy could be due to incorrect temperature measurements or differences in water temperature delivered to the taps. It is possible that the water temperature delivered to apartment fixtures varied seasonally, although within a narrow enough range to obviate occupant complaints. Even under suspicion of the measured maintenance losses, though, the three systems at least ranked in the correct order, with traditional recirculation showing the highest losses, heat traces the lowest, and pipe-within-a-pipe intermediate.

Also note that the interval in late 2016 where the maintenance losses at D dropped to 1.1 kW occurred due to an equipment malfunction that dropped the delivered water temperature approximately 4F compared to normal.

Figure 16. Temperature Maintenance Load

3.4 Heat Pump Performance

The expected seasonal trend of heat pump performance is revealed in Figure 17. All the heat pump "outdoor" units are located in the subterranean parking garage. Those for Buildings A and B are deep within the garage while Building D's heat pump is close to the garage entrance. This proximity creates more direct, unmoderated air exchange with the outside. Monitoring of air temperatures at the system intake indicated that temperatures were both lower and more variable for Building D's system during the study. Still, that doesn't explain the consistently 0.5 COP point lower value. In the summer months, one would expect its COP to be higher because it would be exposed to warmer air. Monitoring in July, August, and September may reveal as much. A major source for the lower COP, asynchronous component operation, is explained in section 3.5.1

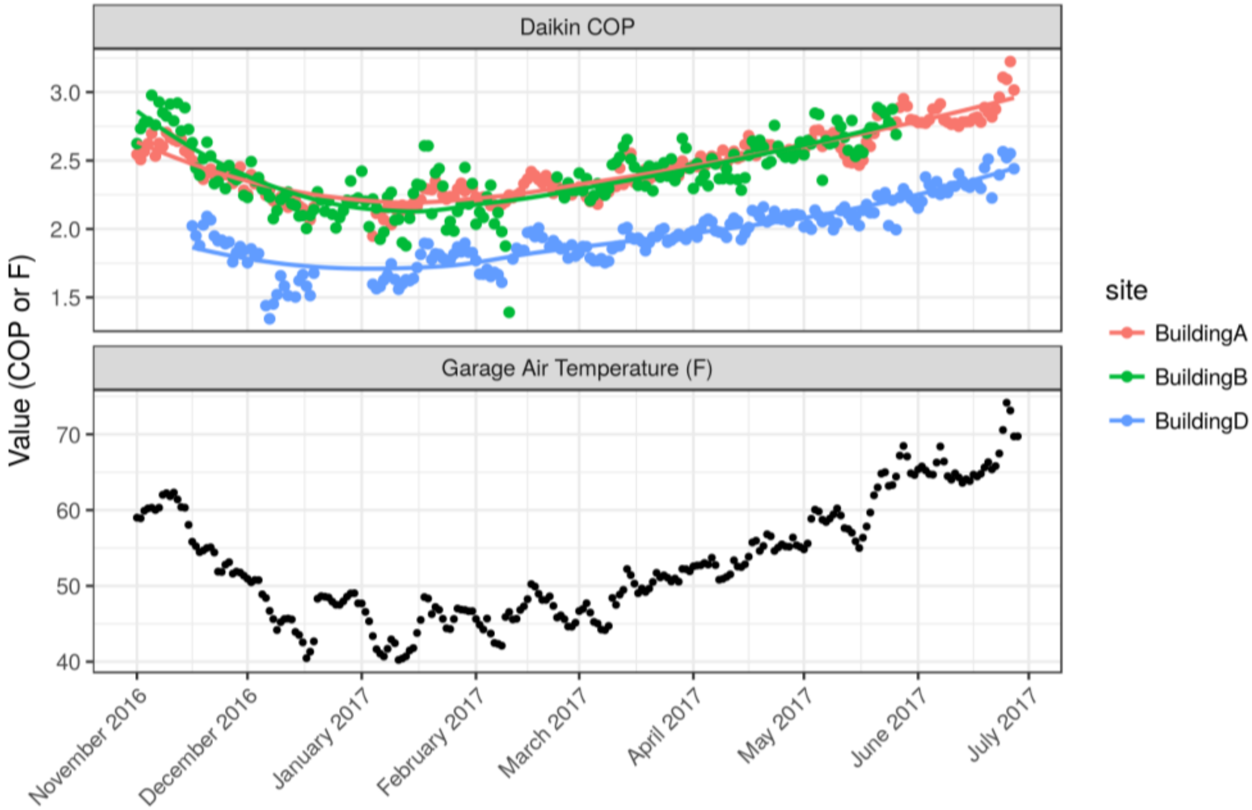


Figure 17. Daily Heat Pump COP and Garage Air Temperature

It is also useful to know the equipment COP as a direct function of the source air temperature which, in this case, is the garage air. Figure 18 plots average daily COP for Altherma A against average daily garage air temperature. The data are remarkably linear.

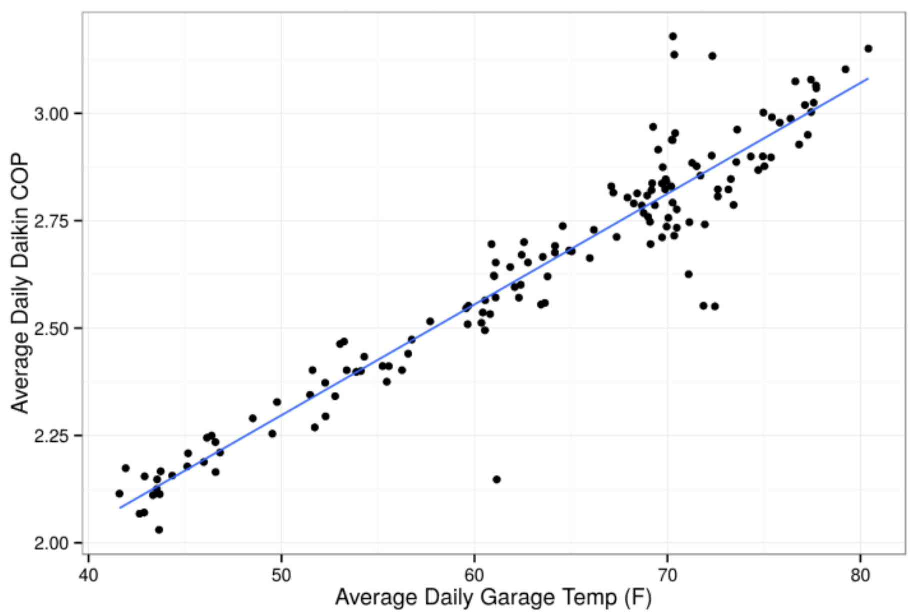


Figure 18. Building A Altherma COP vs Garage Temperature

3.5 Equipment and Control Difficulties

As with piloting any new design concept, Ecotope encountered difficulties with both the equipment and controls. Project staff used the data from the measurement system to diagnose and, in many cases, fix operational problems. The most acute difficulties are discussed here.

3.5.1 Synchronizing Operation

The heat pumps in buildings A and B performed consistently after start up, with similar equipment COPs in response to temperatures of source air. Communication interaction failures between the aquastat, switching relay, and Altherma unit occurred in all the installations. Ecotope made numerous site visits, including some with a Daikin assigned Altherma expert, to adjust settings throughout the system. Figure 19 shows ideal operation, after optimization efforts at Building B. The Daikin Altherma and the heat exchanger loop flow in lockstep as directed by the switching relay. The figure also shows extended runtimes in the morning extremely typical of the hot water use patterns in these buildings.

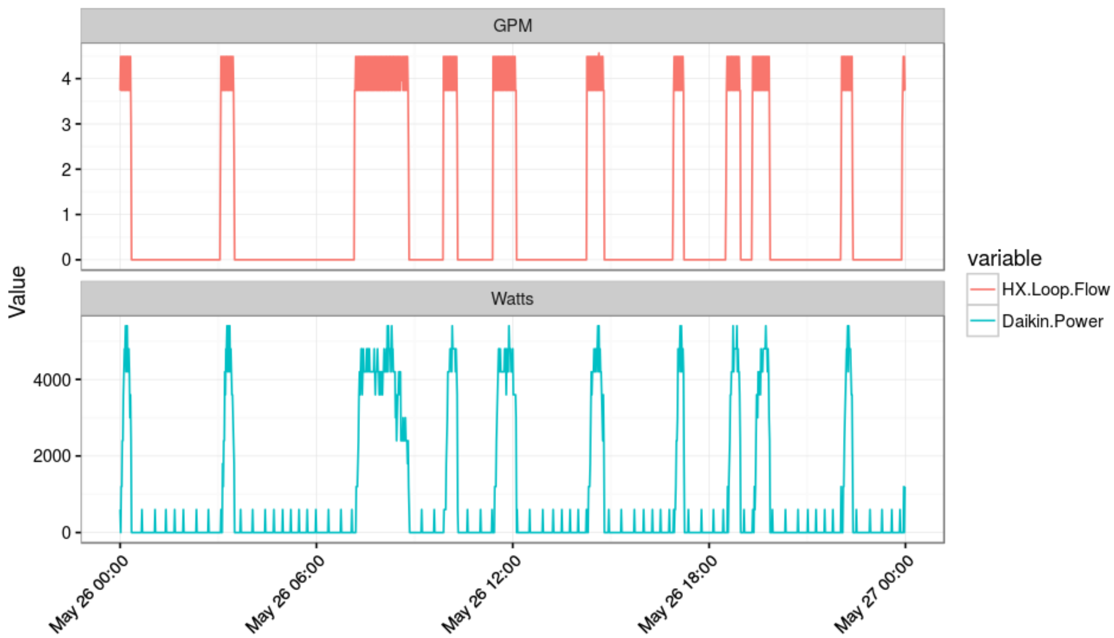


Figure 19. Ideal, Synchronized Operation at Building B

In contrast, the system at Building D experienced ongoing difficulty in interactions between the Altherma operation and heat exchanger loop pump operation. Ideally, they run in sync but this was never achieved in the project. Figure 20 shows the problematic operation where the Altherma is on when it doesn't need to be. This resulted in hot water looping repeatedly through the heat exchanger on the Altherma side without the heat then being moved on to the storage tanks. The behavior reduced the efficiency of the system, employing the heat exchanger to work on water which was not in need of input heat. Repeated attempts to synchronize the behavior of the Altherma with the water pump were not successful. Strategies used to solve the same problems at Buildings A and B did not work at D. Likely, the issue is within the control logic of the Altherma and the inability of the switching relay to override it.

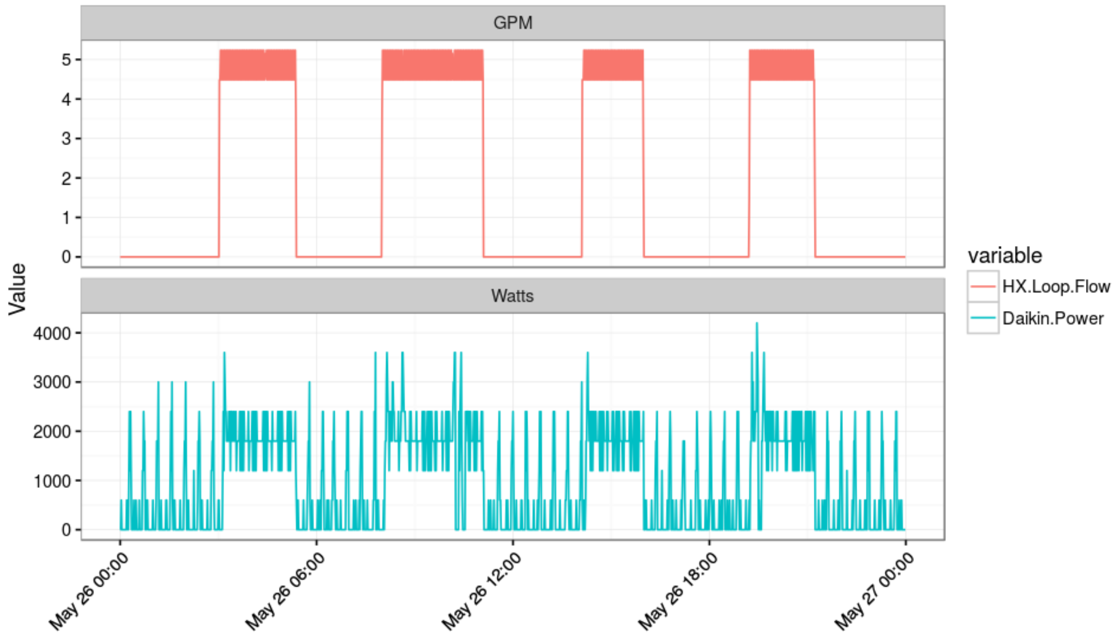


Figure 20. Problematic, Asynchronous Operation at Building D

3.5.2 Power Surges

Bainbridge Island suffered from occasional power supply irregularities over the winter months, which interfered with the function of the heat pumps. The power supply was disrupted mainly as the result of several severe wind storms. The associated surges and voltage changes caused the Althermas to shut off. This appeared as some manner of protection but they would not automatically turn on again later. Instead, the systems would require a manual reset after each power outage event. In the interim, the only hot water being delivered to the building was created by the trim tanks (or heat trace) which, at 15kW was adequate for a full backup for the days in question. Power conditioning equipment, or uninterruptable power supplies, may provide a buffer for this kind of problem. As it is, this remains an ongoing concern. To continue to operate at heat pump efficiencies site staff need to be aware of power surges and then verify heat pump operation. It is not clear if this problem applies only to the Daikin Altherma, or would reappear with similar inverter-driven, R-410a, air-to-water heat pumps.

3.6 Variable Speed Heat Pumps

An interesting finding in this study is related to the variable speed nature of the Daikin Altherma heat pump. Driven by an inverter, the Altherma possess the ability to change compressor speed as deemed advantageous or necessary by the onboard controls. This appears to have delivered surprising consequences for the heat pump operation when comparing temperature maintenance strategies.

Some background: typically, heat pump efficiency declines with increasing water temperatures. This is actually intuitive. If the task is to move heat from, say, 50F garage air into a water tank (the “heat sink”), this job will be easier when trying to move heat into 50F water than 120F water. As the heat pump works against a larger temperature difference between the source temperature and the sink temperature, the efficiency of the cycle drops. This finding necessarily holds for a constant speed system, although variable speed systems are more complicated.

One of the biggest surprises from this research project was that we had anticipated the heat trace temperature maintenance strategy to yield a higher Altherma COP. Because the absence of a recirculation loop would allow temperature stratification to develop in the tank, the inlet water temperature to the heat exchanger – the heat sink temperature relevant to the Altherma vapor-compression cycle – should have been lower, and as such yielded higher thermodynamic efficiency. While the inlet water temperature was indeed lower, the heat pump efficiency was not higher. Refer back to Table 3 and Figure 17. In fact, data collected in 2011 under a project for the Northwest Energy Efficiency Alliance (NEEA) on a single-family-sized, variable-speed, R-410a Daikin heat pump water heater suggested an efficiency gain of approximately one COP point when comparing 100F inlet water to 120F inlet water. While not exactly the same equipment, the comparison is useful. Specifically, the lab testing indicated, with 67F air temperature, a COP of 2.9 when heating 120F water and 3.9 when heating 100F water. We would have expected, then, a roughly one point increase in Daikin COP at Building B, but instead saw no increase at all.

While not a conclusive result, we suspect that the lack of an efficiency boost at the heat trace site may have derived from the variable speed logic of the Altherma in this particular design. See Figure 21. While the Altthermas at Buildings A and D – working constantly against 120F water from the well-mixed tanks – ran almost exclusively around the minimum input power of 2kW, the Building B unit regularly ramped up to as much as 5kW in response to colder water temperatures. It may have been that the Altherma responded to cooler water temperatures with the utmost urgency, sacrificing efficiency in the name of heating expediency. This is suggested by the sort of boomerang shape as in Figure 21, where power increased with inlet temperature to a maximum of 5kW at 100F, before declining to 2kW at 120F. In the NEEA lab testing of an analogous single-family-sized Daikin, no such boomerang shape occurred. Power increased approximately linearly to the upper temperature limit of the equipment. This sort of behavior was not observed at Buildings A and D because the inlet water rarely strayed from around 120F.

Variable speed heat pumps can operate at higher efficiencies under “part-load.” The heat pump has a fixed outdoor unit heat exchanger size (in this case, the evaporator). When operating at a fraction of the maximum speed, the heat exchange is effectively larger, relatively to the load, than it is when the heat pump operates at maximum speed. The larger heat exchanger allows for more heat to be absorbed from the air at a lower work load and, hence, the higher efficiency.

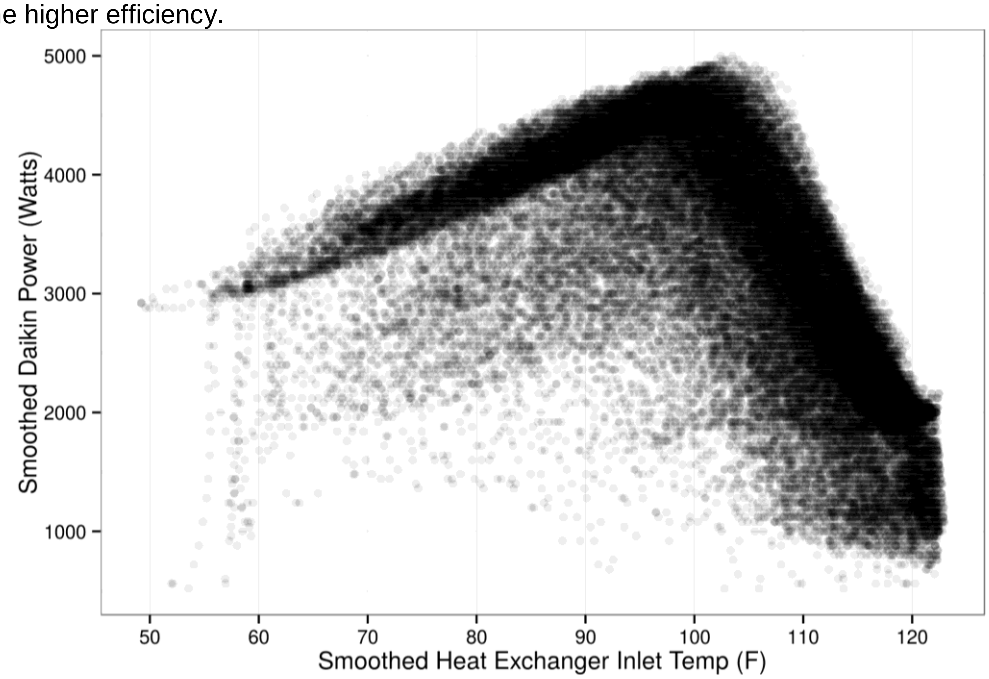


Figure 21. Building B Daikin Power by Heat Exchanger Inlet Temperature

Although by no means a rigorously confirmed result, this is our best explanation as to why heat pump efficiency at Building B unexpectedly failed to outperform the recirculation-based designs. This unanticipated result carried significant consequences on identifying the optimal temperature maintenance strategy.

4 Conclusions

This study explored and compared alternative temperature maintenance strategies for central domestic hot water systems. As an additional goal, the project also examined the viability of inverter-driven R-410a air-to-water-heat pumps to meet that load. A more precise experimental design would have isolated one objective at a time for greater explanatory power, especially in light of ambiguities observed over the course of the project but, in this case, the opportunity was valuable enough to pilot both research questions at once. Most generally, the findings suggest an attainable equipment COP between two and three for central domestic hot water heating with this type of equipment, with the pipe-within-a-pipe recirculation strategy leading to maximum energy reduction.

4.1 Limitations

Although we remain confident in our general findings, it is worth discussing several caveats encountered during the project. They serve to place the findings in better context and can also be taken as lessons learned for future work of this kind.

The most germane is that the heat plants studied – Daikin Althermas – are no longer sold or supported in the region. Many of the lessons learned over the course of the study dealt with the idiosyncrasies of this particular custom design: a Daikin Altherma heat plant run in “space heating” mode to meet the domestic hot water load of a small multifamily building by way of a 200 gallon storage tank, flat plate heat exchanger, analog tank aquastat, and Taco pump and switching relay. The difficulties with this configuration manifested most obviously in the challenge synchronizing operation of the Altherma side and the tank side of the flat plate heat exchanger.

However, another issue in non-extensibility is the variable-speed nature of the equipment, along with the Altherma’s elaborate and often obtuse onboard control logic. The Altherma responded to the different levels of tank stratification stemming from the alternate temperature maintenance strategies with varying levels of urgency. In Buildings A and D, with well-mixed tanks, the Daikin tended to run at low speeds for long, uninterrupted intervals. This is in general the most efficient operating scenario for a variable speed heat pump. In contrast, with the temperature-stratified tank of Building B, the Daikin, upon encountering colder inlet water, would ramp up to max power and run for a shorter duration at a higher intensity. This is in general a less efficient operating scenario, and apparently negated the potential benefit of additional tank stratification with the heat trace design. Unfortunately, these sorts of insights do not necessarily translate forward to further inquiries in the absence of the Daikin Altherma equipment. It is not clear the extent to which other inverter-driven R-410a heat plants would respond similarly to varying levels of tank stratification, or the extent to which other heat plants would pose commissioning challenges in setting up controls.

Another caveat is that the amount of domestic hot water usage varied widely between largely identical buildings, at times to a degree bordering on comedy. The occupants of Building B sometimes used as many as 700 gallons of hot water on a given day, while the occupants of Building D sometimes used as few as 50. This was the difference between families and some combination of snowbirds, retirees, and vacant apartments. The investigation of identical buildings should have theoretically allowed for a clear, direct comparison that identified an unambiguously winning strategy, but this was not possible in the face of such widely varying DHW demand. Because the efficiency of a heat pump changes widely with system conditions it was not possible to decompose the load in a way that one could with a boiler. With heat pumps, everything is interconnected.

In addition, the measurements of heat losses at the buildings were themselves mysterious. Why were the measured recirculation losses at Building A so strongly seasonal in a way that the other buildings were not? Some seasonality is expected but not to the degree observed. Further investigation could be warranted in future studies. Even under suspicion of the measured maintenance losses, though, the three systems at least ranked in the correct order, with traditional recirculation showing the highest losses, heat traces the lowest, and pipe-within-a-pipe intermediate.

4.2 Optimal System

In terms of selecting an optimal temperature maintenance strategy, the essential tradeoff in comparing a recirculation loop to heat trace is that between DHW efficiency and temperature maintenance efficiency. With a recirculation loop (traditional or pipe-within-a-pipe), the entirety of the load is met with heat pump efficiency. With heat trace, the DHW load is met with heat pump efficiency, while the temperature maintenance load is met with electric resistance. There are two added wrinkles. One is that the heat trace load will always be lower, as warm water is delivered out to the fixtures, but not returned to the central plant. The other is that the presence of warm, recirculation water has the potential to adversely affect the heat pump efficiency. We saw at the RCC sites that an R-134a system optimized for single-pass, high temperature-lift heating malfunctioned, at times catastrophically, in the presence of abundant, warm recirculation water (Oram and Heller 2015). In contrast, the Altherma systems were unfazed by warm recirculation return water. As such, it would appear likely that heat pump systems optimized for multi-pass heating of fairly warm water would perform best with a recirculation based temperature maintenance strategy, while systems optimized for single-pass, high temperature-lift heating would benefit from heat trace.

In this sense we suggest that the selection of temperature maintenance should be intertwined with the selection of heat plant. Since the Altherma was able to adequately cope with warm recirculation return water with no decrement on COP, this implies that the pipe-within-a-pipe strategy was optimal of the three. All else equal, it is more advantageous to meet a 1400 Watt load with a COP of 2.5 than an 800 Watt load with a COP of one. The Altherma's admirable performance dealing with warm recirculation return water implies that the heat trace would have had to reduce the load by a factor of 2.5 or more to prove optimal, which defies plausibility.

4.3 Reducing the Load

Beyond properly pairing a heat pump system with an appropriate temperature maintenance strategy, it also seems likely that more effort should be taken to reduce the temperature maintenance load in the first place. One can conceptually decompose the total energy use associated with domestic hot water into three pillars: the hot water load, the distribution load, and the heating system thermal efficiency. Modern building techniques target the first through efficient appliances and low-flow fixtures, and the nascent adoption of heat pump water heating technologies has been targeting the third in an ongoing process.

It may also be valuable, however, to focus more effort on reducing the distribution load which this study first addressed with aggressive pipe insulation and through the pipe-within-a-pipe and heat trace alternatives. This research combined with the RCC research suggests that, in new construction, the recirculation load for a central hot water plant may at times be almost equivalent to the actual hot water demand. Although the usage data collected at these buildings suggested limited returns available from demand-based recirculation strategies, targeting a reduction in heat loss rate through stringent requirements on insulation and thermal bridging could ultimately prove valuable. For example, at the buildings in the wintertime, the pipes in the parking garage carry 120F water through a 40F space – an 80 degree temperature difference! The combination of heat pump technology with ambitious pipe insulation specifications and an optimal temperature maintenance strategy would likely yield impressive reductions in domestic hot water energy usage. Best design practices should also seek to minimize the length of hot water pipes, for example by locating bathrooms in neighboring apartments to be adjacent.

4.4 Overall

This research reiterates the viability of air-to-water heat pumps located in below-grade parking structures in the Puget Sound region for multifamily domestic hot water heating, and points toward the need to identify reliable equipment and designs to specify in such scenarios going forward. Additionally, care should be taken to match equipment with its corresponding, optimal temperature maintenance strategy, which will require a nuanced understanding of how different heat pump designs respond to different approaches for temperature maintenance. Equipment similar to the Daikin Altherma should be paired with a pipe-within-a-pipe recirculation loop to achieve maximum energy reduction, although the savings margin compared to traditional recirculation is small enough that the additional expense may or may not be cost effective for a given project. Single-pass heat pump water heaters should be paired with a heat trace design to bolster heat pump efficiency. Finally, as the distribution load was measured to rank comparable to the DHW load itself, care should be taken to reduce piping losses where wherever possible.

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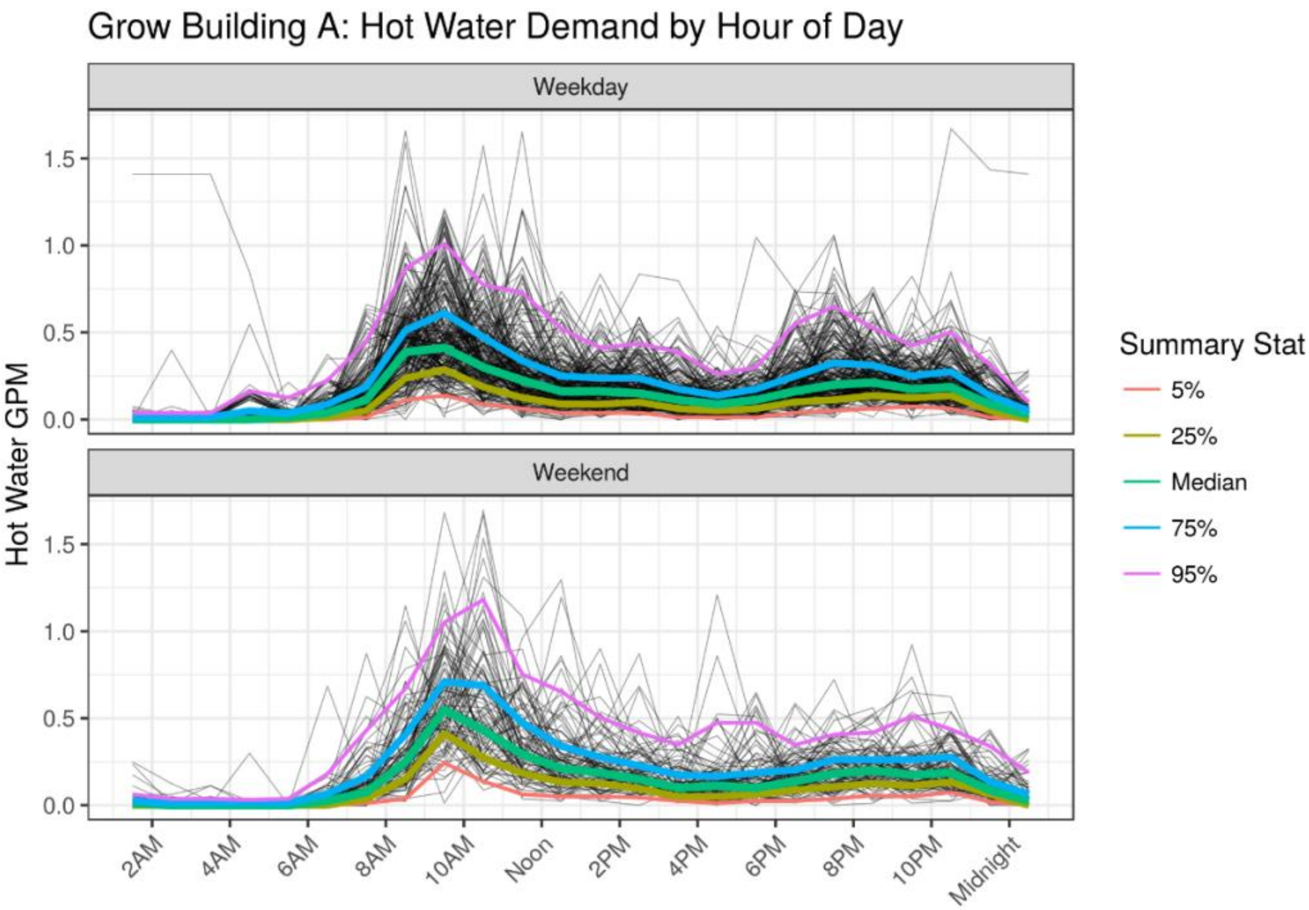
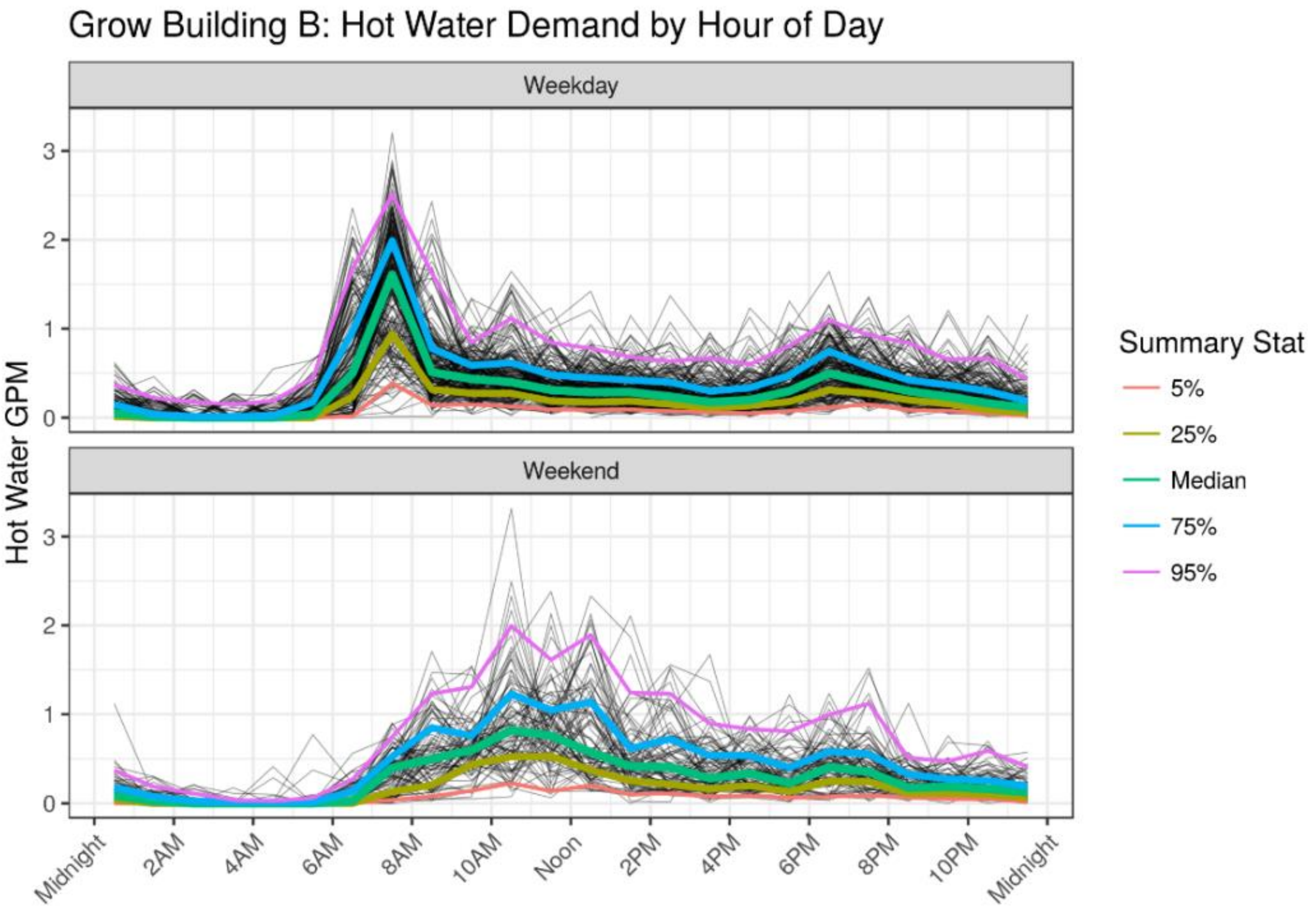
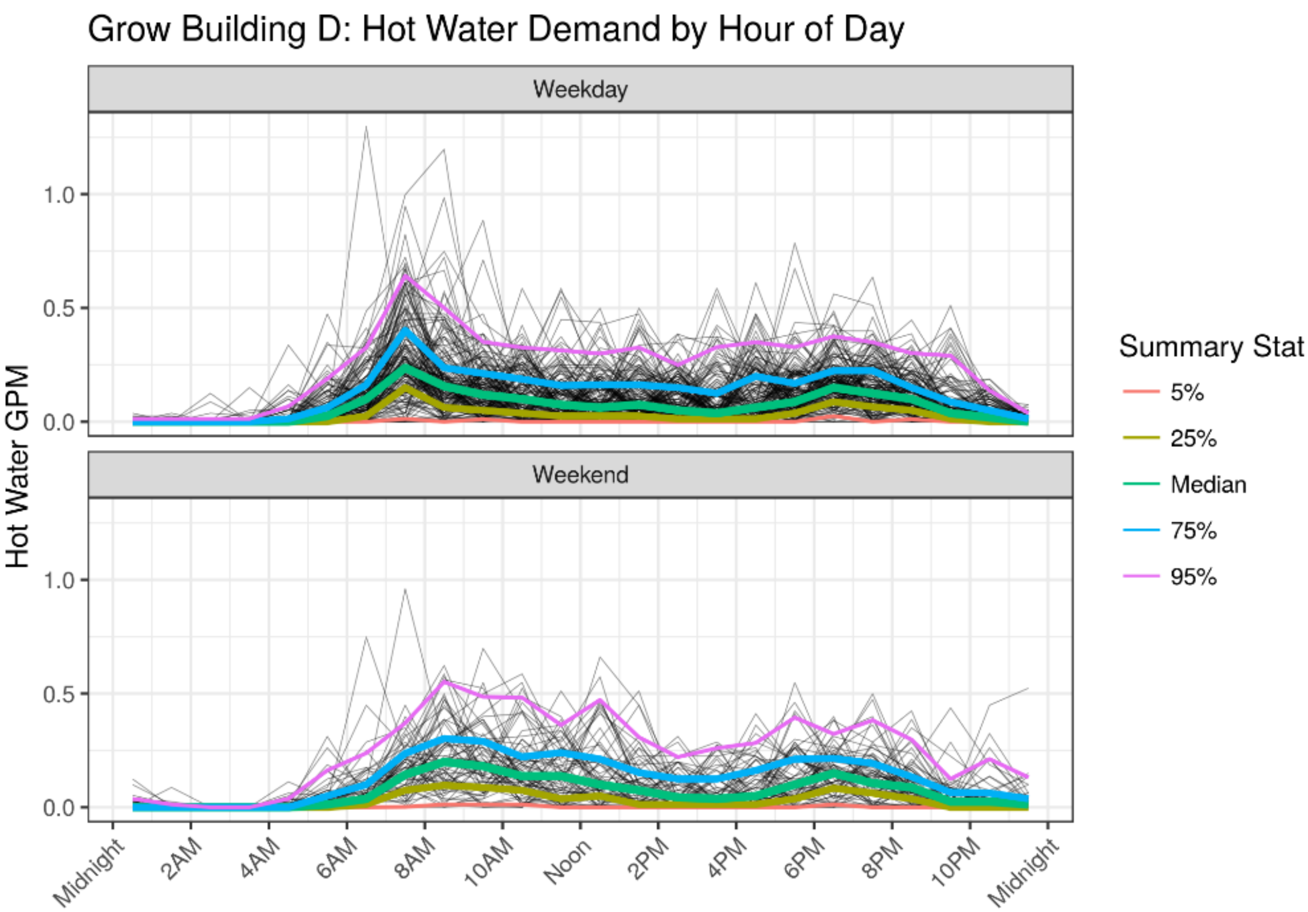
Appendix A: Supplemental Graphs




Grow Building B: Hot Water Demand by Hour of Day
Weekday
Weekend
Hot Water GPM
3
2
1
0
Midnight
2AM
4AM
6AM
8AM
10AM
Noon
2PM
4PM
6PM
8PM
10PM
Midnight
Summary Stat
5%
25%
Median
75%
95%



Grow Building D: Hot Water Demand by Hour of Day
Weekday
Weekend
Hot Water GPM
1.0
0.5
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Midnight
2AM
4AM
6AM
8AM
10AM
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5%
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