Combined Space and Water CO_2 Heat Pump System Performance Research

First Midterm Field Study Report

Bonneville Power Administration
Technology Innovation Project 326

Organization

Washington State University –
WSU Energy Program in Olympia, WA

Co-Sponsors

Avista Corp.
The Energy Trust of Oregon
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Contents

Tables

Figures

Abbreviations

AC	alternating current
BPA	Bonneville Power Administration
Btu	British thermal unit
CO_2	carbon dioxide
COP	coefficient of performance
DOE	U.S. Department of Energy
DR	demand response
EF	energy factor
ER	electric resistance
FEF	Field Energy Factor
GPD	gallon per day
GWP	Global Warming Potential
HFC	hydrofluorocarbons
HPWH	heat pump water heater
HSPF	Heating Seasonal Performance Factor
kWh	kilowatt hour
NEEA	Northwest Energy Efficiency Alliance
NSH	NEEA's Next Step Home Program
OAT	outside air temperatures
PNNL	Pacific Northwest National Laboratory
PSI	pound per square inch
TIP	Technology Innovation Program
UL	Underwriters Laboratory
WSU	Washington State University
XPB	Heat Exchange Pump Block

Introduction

This is the first field report in the Washington State University (WSU) Energy Program research into the performance of CO_2 refrigerant heat pumps used for combined space and water heating in high-efficiency new homes. The research is funded by the Bonneville Power Administration (BPA) through its Technology Innovation Program (TIP). The equipment being tested in this study is manufactured by Sanden International in Australia.

This research is based on previous research into CO_2 refrigerant heat pump technology conducted by WSU as TIP 292 that demonstrated the ability of the system to provide hot water to a large family during extremely cold weather while operating only 25% of the time. This capacity was corroborated during the demand response testing under TIP 302 at Pacific Northwest National Labs (PNNL) Lab Homes Test Center when the daily draw was 130 gallons, and the split system was able to meet the demand while turned off for up to 12 hours.

The ten sites were selected primarily from builders participating in the Northwest Energy Efficiency Alliance's Next Step Home (NSH) program. Recruitment took place in 2014 and 2015, primarily by CLEAResult, which operates NSH. WSU coordinated the development of engineering and monitoring plans by the project team, which included WSU, CLEAResult, NEEA, and Ecotope.

As of September 30, 2015, eight CO_2 refrigerant heat pump systems have been installed as combined space and water heaters in energy-efficient homes located in three states and in two of the Pacific Northwest heating climate zones. The two final sites are in McCall, Idaho, a heating Zone 3 climate. Monitoring has been installed at eight of these sites; the earliest, in Bellingham, Washington, has produced data since late December 2014.

The field study is designed to gather a full heating season of data from the systems. The data is analyzed at two interim points and will be brought together for a final analysis and report due in fall 2016. This report focuses on the Bellingham site because it has a data set spanning three seasons. The other monitoring systems were commissioned in summer 2015 and have insufficient data to enhance understanding of system performance during the time period covered by this report.

The project also includes a lab test at Cascade Engineering Services to examine the end uses and overall system functions in a controlled and highly documented environment. This test will be complete and a draft report issued in October, 2016.

Basis for Combined Space and Water Heating Experiment

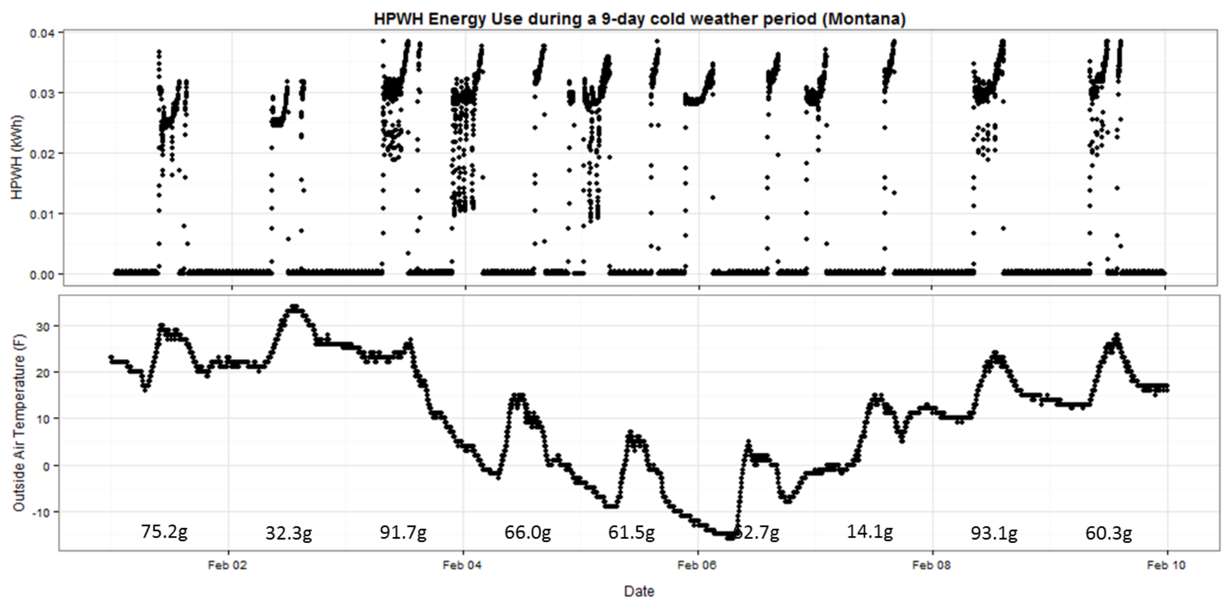
This research is based on the performance of the CO_2 refrigerant heat pump documented in:

- The lab and field tests done under TIP 292, which looked at performance as heat pump water heaters (HPWHs), and
- The controlled field tests performed by PNNL for TIP 302 to study the demand response (DR) performance of these systems while they functioned as HPWHs.

In both studies, specific findings indicated the technology had the capacity to provide heat to end uses while also providing a substantial hot water load.

In the original research under TIP 292, the specific finding was a very cold nine-day period at the Montana site when the outside air temperature (OAT) remained almost entirely below freezing and went as low as -16.5°F. The hot water load consists of a family of four, including two teenagers, who take an average of 22 showers per week. **Figure 1** shows this period. The top graph is the energy use by the system and when it was operating. The bottom shows the OAT (including total daily tempered water use along the y-axis) during this period, showing that compressor use was fairly regular.

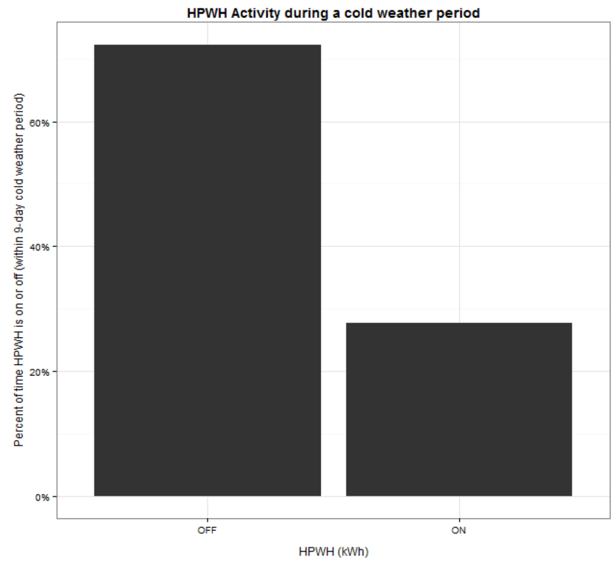
Figure 1. Hot Water Load During 9-Day Below-freezing OATs – Montana Site



It would seem that a system drawing all of the heat for this end use from this cold air source would be operating frequently. **Figure 2** answers this question by showing the percentage of time the system was on versus the time it was off. The tall bar represents 75% of the nine-day period when the heat pump was not operating. The short bar shows that it ran for only 25% of this period. The tall bar suggests that the heat pump could be providing heat for another use. This is the first solid evidence that the system could serve as a combined space and water heating system because it has this heating capacity even during very cold weather.

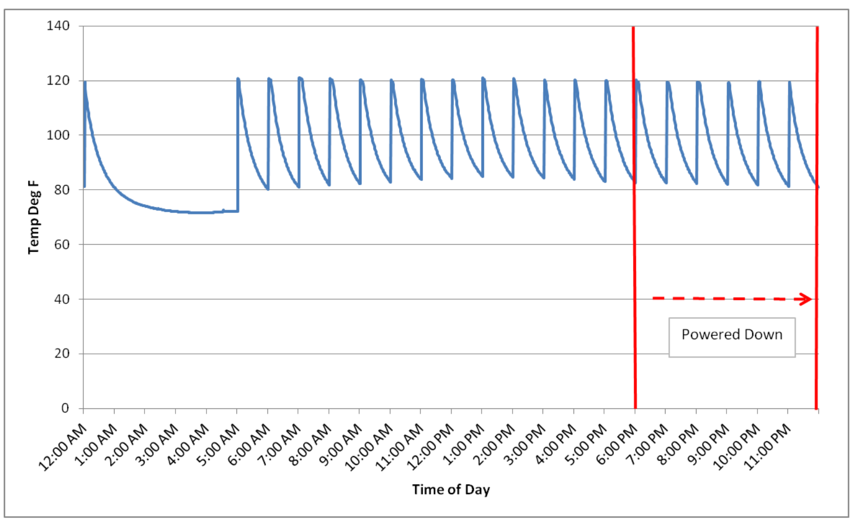
The second specific finding is from the demand response research at PNNL for TIP 302. This set of experiments was based on a daily draw of 130 gallons of hot water in order to test the system under very high use conditions. Given that the average hot water use in the Pacific Northwest is 42 gallons per day (GPD), the test condition could be considered extreme.

Figure 2. Percentage of Time HPWH On/Off During Cold Weather Period



The Oversupply Mitigation test is designed to test the capacity of systems to store energy when there is a surplus of generation. To create a storage bank for night time generation, the split system water heater was turned off for up to 12 hours while still supplying 130 GPD. **Figure 3** shows its ability to deliver water at the set temperature without missing a draw. This ability verifies the field results at the Montana site.

Figure 3. Ability of HPWH to Deliver Hot Water at Setpoint Temperature



Field Study

Ten split system CO_2 refrigerant HPWHs are or will be installed in nine highly efficient new homes and one high-efficiency retrofit home across the region beginning in fall 2014. These homes are located in Bellingham, WA; Coeur d'Alene, ID; McCall, ID; Milwaukie, OR; Olympia, WA; Seattle, WA; and Tacoma, WA. The field study is designed to test the performance of the technology in all three of the Pacific Northwest's heating climate zones. The host organizations are Avista, Energy Trust of Oregon, Puget Sound Energy, and Tacoma Public Utilities.

Description

Site Selection

Ten sites were recruited and analyzed through NEEA's NSH program, which is managed by CLEAResult. For each home, CLEAResult staff determined the heat loss rate and annual load using SEEM™, a simulation tool developed by Ecotope, Inc., and calculated the design heat load using SpecPro©, by Bruce Manclark. The final determination of whether the home would be part of the combined space and water heating experiment was made by Ken Eklund of WSU.

Five of the homes are in the NSH program and built according to its specifications. The four other new homes are built to Passive House™ standards. The one retrofit home in the program, located in Olympia, is a prototype for retrofit application of the combined space and water heating concept.

Code Issues and Solutions

The CO_2 HPWH used in these experiments is not UL listed. Electrical and building permits were obtained for each of the ten installations. The situation was complicated by the fact that the HPWH was providing space heat as well as hot water. The addition of the second use made obtaining permits in most jurisdictions more difficult than installing the combined systems simply as water heaters, as was done in TIP 292 and TIP 302. As in those earlier projects, the building official is required to exercise discretion under Section 104 of the International Residential Code, which allows use of alternate materials and systems.

Ken Eklund at WSU worked with building officials. The initial permit in Bellingham took eight months to obtain. It required obtaining engineered drawings of the system, which proved instrumental in obtaining that permit and all the ones that followed. The engineering was done by Jonathan Heller, PE, at Ecotope. At the Idaho sites, the building official was local and the electrical official was a state inspector. Obtaining these permits required working with both jurisdictions, but once the Coeur d'Alene site was permitted, the McCall permits proved easy because the state officials were already educated and on board.

Sanden International, the manufacturer of the HPWH, is working on obtaining UL listing for the split system installed in these projects. It is a long and expensive process, and much of the knowledge and experience obtained in these TIP projects is being incorporated into the equipment that will ultimately be UL listed and sold in this country.

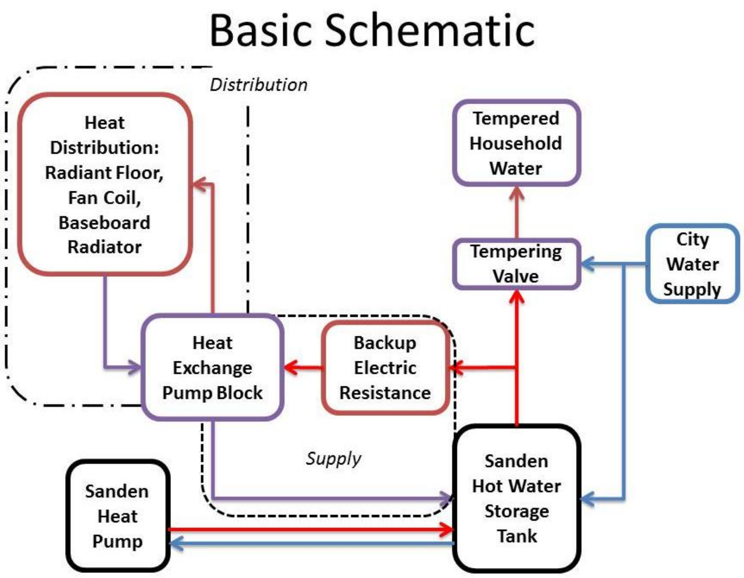
System Design and Installation

The combined space and water heating system adds a heating loop to the HPWH. This heating loop consists of two parts:

- The supply side moves heated water from the tank to a heat exchanger, and
- The distribution loop delivers heat to the heat distribution system.

The design includes a backup heater between the tank and the heat exchanger. **Figure 4** shows a basic schematic of the combined system.

Figure 4. Schematic of the Combined Space and Water Heating System



A significant amount of system design – more aptly termed evolution – took place in the context of the Bellingham installation. The technical design committee consisted of Ken Eklund, WSU; Jonathan Heller and Ben Larson, Ecotope; Mark Jerome, CLEAResult; Charlie Stephens, NEEA; and John Miles, Sanden. Weekly calls to exchange ideas and make design decisions took place with frequent email traffic in between for several months in fall 2014.

The original design proposed for the Bellingham system called for replacing the Sanden tank with a tank that had an integral heat exchanger. The Sanden tank is equipped with a precisely located sensor that alerts the system controller when to operate the outdoor unit and the tank is carefully engineered to maintain stratification necessary for system operation. To ensure proper operation and maintain the system warranty, the original design was tabled.

A great deal of discussion took place concerning the best way to return water from the radiant floor space heating system to the Sanden tank. Sanden's concern was that returning warm water to the bottom of the tank would:

- Interfere with defrost function in cold weather, because warmer water causes the system to misread the temperature and turn off the defrost; and

- Reduce efficiency in operation, which depends on providing high temperature gradient to the outside heat exchanger, which is designed to heat water in a single pass.

Figure 5. Diversion Fitting

It was decided to return heating loop water to the top of the tank. This caused warm water to mix with hot, and resulted in some cool showers at the Bellingham site. A device called a diversion fitting was finally developed and built by WSU to direct the incoming warm water down toward the center of the tank so it could find its proper stratification level (**Figure 5**). A copy of this device is currently installed at seven sites.

The backup tank was equipped with heating elements to provide backup heat if the HPWH could not provide sufficient hot water for space heating. After the Bellingham installation, the design team decided it would be simpler and better to use an electric resistance (ER) demand heater for backup. This has been done in all subsequent installations except for the Olympia site, which has no backup heating.

The Bellingham site will be retrofitted in early October 2015 to move the heating loop return from the top of the tank to the bottom, and replace the auxiliary tank with a backup demand heater. Relocating the heating loop return is based on the combined space and water heating lab test conducted by Ecotope in August 2015, which showed clearly that returning 70°F-80°F water to the bottom of the storage tank is more efficient than returning it to the top of the tank or introducing it through a diversion fitting.

The common denominator of all ten installations is the guidance of Mark Jerome on site. He makes sure that all the connections are properly made, the temperature wells and flowmeters for the monitoring are placed correctly, and the TACO X-Block is wired and programmed properly. Mr. Jerome has participated in all of the installations of this technology in the Pacific Northwest to date.

Challenges in Monitoring

NEEA provided all of the monitoring equipment and supported the installation, calibration, and monitoring of that equipment by WSU. The monitoring used for all ten sites is the same as that used for the detailed monitoring done by NEEA in its first generation of NSH, including four of the NSH homes in this study.

The equipment was originally designed primarily for use by home owners to monitor energy use, and has been expanded through its use in the NSH program to provide a wide array of monitoring services. The monitoring equipment requires Internet access in order to operate, which means that the home must be occupied and have Internet installed and accessible which can delay monitoring installation.

At the time of this report, eight of the HPWH systems are installed and all of them have monitoring systems installed, although five of them were installed in September 2015.

The lead monitoring installer is David Hales of WSU. He is assisted by Luke Howard and Andy Gordon. Mr. Hales also installed monitoring for TIP 292.

Field Study Details

Site Summaries

The specific sites are typical of the regional heating zones they represent, as shown in **Table 1**. Most of the sites in Heating Zone 1 are warmer than the median value for that zone but represent the most populated areas in the region. Bellingham and Olympia are colder than the median. Coeur d'Alene is a solid representative of Heating Zone 2 and McCall, Idaho is colder than the Heating Zone 3 median.

Characteristics of the Bellingham test site are summarized in **Table 2**.

Table 1. Heating Zones of Ten Test Sites

Heating Zone	Number of Sites	Median HDD^{65} [1]	Site Location	Site HDD^{65}
Heating Zone 1	1	5,182	Milwaukie, OR	4,461
Heating Zone 1	3	5,182	Seattle, WA	4,867
Heating Zone 1	1	5,182	Tacoma, WA	4,696
Heating Zone 1	1	5,182	Bellingham, WA	5,622
Heating Zone 1	1	5,182	Olympia, WA	5,655
Heating Zone 2	1	6,824	Coeur d'Alene, ID	6,239
Heating Zone 3	2	8,363	McCall, ID	8,851

Table 2. Test Site Characteristics

	Bellingham
Adults	2
Children ≤12	2
Teen	0
Months of Occupancy	9
Age of House	2015
Conditioned Floor Area	2,057
Number of Stories	2
Number of Bedrooms	3
Number of Full Baths	1
Number of Half Baths	1
Heating System	Radiant Floor

Data provided only for occupied sites with operating monitoring as of April 2015.

[1] Source: Northwest Power and Conservation Council, 6th Power Plan Assumptions

Monitoring Setup

The field study is designed to monitor the systems for at least one full heating season. This first midterm report covers initial monitoring at one site from December 2014 through June 30, 2015. Data points include:

- Water flow, time and volume
  - Through hot water tank measured at the cold water inlet
  - Through space heating supply loop measured on return to tank
  - Through space heat distribution loop measured on return to heat exchanger
- Temperatures
  - Cold water supply
  - Hot water to tempering valve
  - Tempered water to house
  - Outside air temperature
  - Inside air temperature near the hot water tank
  - Hot water to heat exchanger
  - Return water from heat exchanger to hot water tank
  - Hot water to heating distribution system
  - Return water from heating distribution to heat exchanger
- Power measurements
  - Time and amperage of compressor, fan, and pump electricity use measured together
  - Time and amperage of outdoor pipe freeze protection (heat tape) electricity use
  - Time and amperage of backup heating loop electricity use (at all but one site)
  - Time and amperage of heat exchange supply and distribution pumps and controllers

The field monitoring setup is illustrated in **Figure 6**. The main monitoring collection device is a SiteSage Energy Monitor with Internet connection so data can be downloaded daily and settings on the logger can be controlled remotely. This quality assurance ensures that issues are identified and corrected as soon as possible. The following monitoring equipment is used:

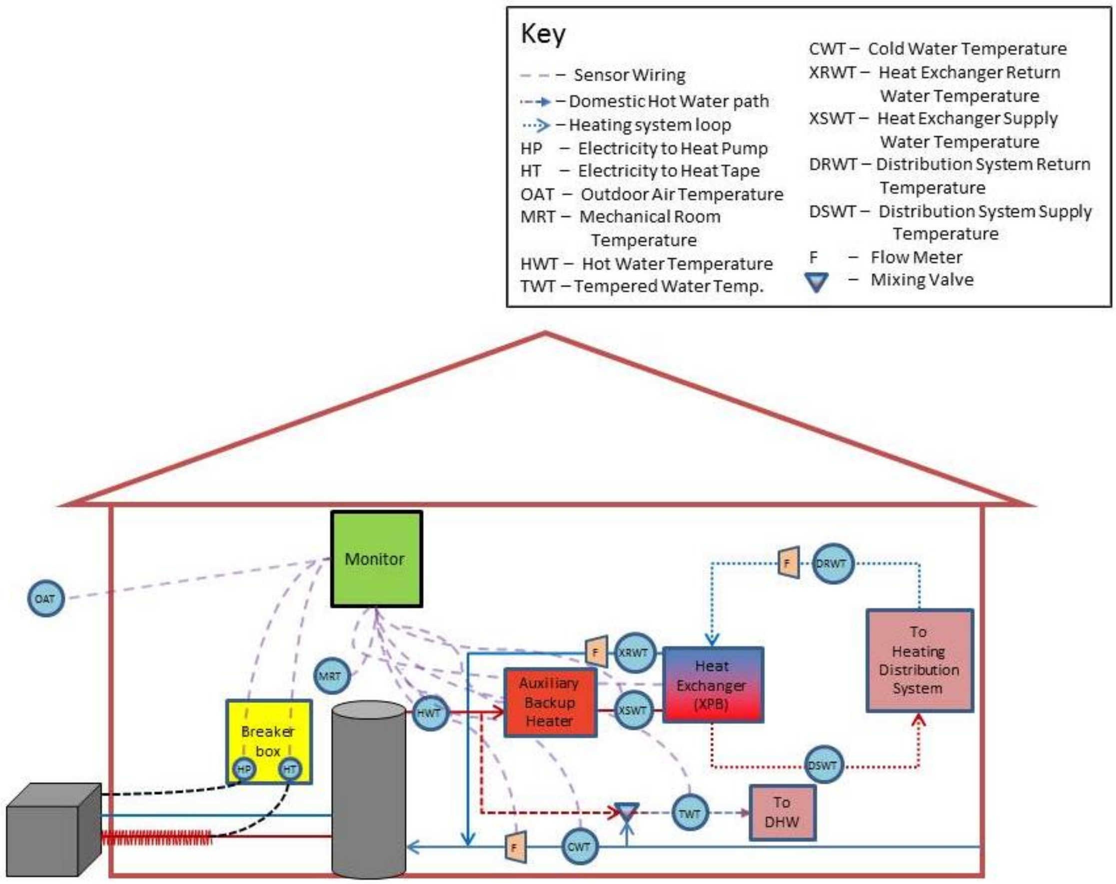
- Emonitor + Gateway
- INDAC sensor controller
- (2) Temperature + %RH 1-wire sensors (indoor and outdoor)
- (3) Temperature wells with 1-wire temperature sensors
- (2) Grundfos flow sensors + temp model VFS 2-40
- (1) Grundfos flow sensor +Temp model VFS 1-20

The Emonitor logs:

- Energy used by HPWH
- Energy used for frost protection
- Energy used by distribution pumps
- Energy used for back up ER water heating (if any)

In some instances, on-site HOBOlink® monitoring is also required to capture all data streams. These data are downloaded manually at several-month increments.

Figure 6. Field Monitoring Setup



Description of Analyses

The midterm analyses are designed to focus on the field monitoring while it takes place in order to provide quality assurance, develop analysis procedures, and organize reporting for the project. The period covered by this analysis is from the time monitoring began at the Bellingham site on December 30, 2014 through June 30, 2015.

The analysis in this report examines the performance of the system for both space and water heating and a number of its operating parameters, including the temperature of the system supply water, heated water, and tempered water; and the calculated volume of water used to temper the temperature of the hot water before use. Tempering was required due to the high (approaching 150°F) temperature of the heated water. The total volume of water used and daily use averages are also calculated for domestic hot water. In addition, the characteristics of the space heating loop are examined for temperatures, operating parameters, and energy used under representative conditions.

How to Rate a Combination System for Efficiency?

Using one system for two purposes seems inherently efficient in terms of resource allocation, installation, and cost effectiveness, but this is not the main point of this research. The chief concern is how well the system performs each function – space and water heating. Each of these operations has its own efficiency measures:

- For space heating, heat pumps are measured in terms of Coefficient of Performance (COP). The heating efficiency of air source heat pumps is also rated with Heating Seasonal Performance Factor (HSPF).
- Water heaters are officially rated according to Energy Factor (EF). HPWHs are also evaluated by the amount of electricity used to heat a gallon (or 100 gallons) of water to use temperature. In previous reports, WSU has measured site performance in terms of Field Energy Factors (FEFs).

Because one system is providing both space and water heating, it is impossible to allocate the input energy precisely to one use or the other. Estimates are done for the following measures together with a combined efficiency assessment.

Space Heating Efficiency

Coefficient of Performance

COP, a standard measure of heat pump efficiency, is the ratio of heat energy produced to electricity used for operation. The limitation of this measurement is that it does not, without further detail, provide information about the conditions under which the COP was measured. Since many factors impact heat pump performance, COP generally is not the best comparison standard for heat pumps that will operate under varying conditions. In this report, COP is defined within the context in which it was calculated.

Heating Seasonal Performance Factor

HSPF provides a seasonal view of air source heat pump heating performance. All of the heat energy delivered during the season in British thermal units (Btu) is divided by the total number of kilowatt hours (kWh) used by the system.

Water Heating Efficiency

Energy Use per Unit of Hot Water

The Pacific Northwest is the national center for HPWH testing, deployment, and problem solving. The Northern Climate Specification is a case in point (NEEA, undated). Another example is the field research funded by BPA and NEEA (Fluid Market Strategies and NEEA, 2013). Several field studies on HPWH performance report performance in a number of ways, as does this study. One performance measures is energy use normalized by flow, created by Ecotope (Ibid., pp. vii, 41, and 74). The advantage of this unit is that it allows a true comparison of performance by energy per unit of water heated.

This report examines energy use per gallon, and this brings it into conversation with other HPWH research, including that done under TIP 302, where electricity input per gallon was measured, and other regional studies. These resources, data, and findings will be brought together in a comprehensive discussion that examines the question of relative efficiency of different water heaters.

Energy Factor vs. Coefficient of Performance

The lab test report from the study focusing on CO_2 HPWH performance (Larson, 2013) refers to both COP and EF in a laboratory context.

- COP is the ratio of the energy produced by the water heater to the energy used to operate the heat pump. In the lab, temperature sensors in the tank allow researchers to look directly at the water temperature so they can calculate the energy in the water.
- The EF is specified by a U.S. Department of Energy (DOE) 24-hour lab test with a certain hot water draw pattern and monitoring period to observe tank heat losses.
- In this report, the efficiency is labeled a Field Efficiency Factor (FEF) because it consists of observations at a range of OATs and draw schedules. Further, it includes tank and plumbing losses as they occurred in field conditions. The term FEF builds on the DOE term “Energy Factor” as a performance indicator in actual use. The FEF more closely approximates home use than a COP because it incorporates loss from cooling pipes between draws, cold supply water in winter, and other factors that impact energy use in the field. In analyzing this data, one challenge is dividing the tank and piping losses between the end uses.

Analysis Protocols

In this report, the data from the Bellingham site is used, but the next Interim Field Study and the final report will include data from all sites. Data from the first day or more was dropped to eliminate readings affected by set-up and testing of instrumentation. Measured flow and temperature values are used to calculate the following variables.

Domestic Hot Water

- Average temperatures by flow event or by day for cold water supply, hot water, and tempered water for the domestic hot water supply.
- Thermal energy required to heat cold supply water for each flow event.
- Volume of water added to temper hot water for each flow event.
- Volume of total water for each flow event.

To calculate representative temperatures for cold supply water, hot water, and tempered water for water heating, at least three consecutive flow measurements were required. Mean temperatures were then calculated by dropping the initial temperature reading and averaging over the remaining readings for a given flow event (or draw). These remaining readings were also used to approximate daily average temperatures for cold water, hot water, and tempered water. Daily averages were used as the representative mean water temperatures for short-duration draws that were less than three consecutive minutes. When only intermittent short (less than three minutes) draws occurred during a given day, the mean of daily average water temperatures from surrounding days was used.

Because only water volume flowing into and out of the HPWH tank was metered via data loggers, additional water added to temper the hot water flowing to the home was calculated for each flow event by using the known water flow (gallons) and the difference between the daily average tempered water flow to the house and the daily average cold or hot water temperatures, respectively. Total water flow for each flow event was then the sum of the cold water flow and the added water.

Average water temperatures were used to calculate the thermal energy needed to heat the cold water for each draw. The energy load needed to heat the cold water supply for each flow event (Qdhw) was calculated as:

Load = Flow Volume x 8.34 x (Temperature 1 – Temperature 2) x 1 Btu/lb/°F, where

8.34 lb/gal is the density of water, and flow volume and average water temperature variables are:

Load (BTU)	Flow Volume	Temperature 1	Temperature 2
Qdhw	Tank inlet	Tank outlet	Tank inlet

Space Heat

Measured variables in relation to space heat use are:

- Volume of water returning from the heat exchanger to the tank
- Volume of water flowing from the heat distribution loop to the heat exchanger
- Temperatures on both the supply and return sides of the supply and distribution loops
- Space temperatures (mechanical room, living area, etc.)
- Outside air temperatures
- TACO X-Block (XPB) electricity use (kWh)
- Heat tape electricity use (kWh)
- Auxiliary heating element electricity use (kWh)

For this report, supplemental daily solar radiation (W/m^2) data were collected from a local Weather Underground weather station.

Measured flow and temperature values are used to calculate average temperatures by flow event or by day for tank hot water to, and return water from, the heat exchanger and for distribution loop hot water from, and return water to, the heat exchanger.

Several load variables were derived from average water temperatures from, and returning to, the tank. Energy loads for the auxiliary tank, distribution loop, and supply loop were calculated using the generic calculation shown above, and the following flow volume and average water temperature variables:

Load (BTU)	Flow Volume	Temperature 1	Temperature 2
Qaux_tank	Supply after heat exchanger	Tank outlet	Supply before heat exchanger
Qdistribution	Distribution before heat exchanger	Distribution after heat exchanger	Distribution before heat exchanger
Qsupply	Supply after heat exchanger	Tank outlet	Supply after heat exchanger

Measured and derived values were summarized both daily and weekly.

System Efficiencies

FEF efficiencies were calculated as:

FEF_{HPWH} = Qdhw + Qsupply / Qinput, where Qinput is the sum of HPWH and heat tape (kWh)

FEF_{SYSTEM} = Qdhw + Qdistribution / Qinput, where Qinput is the sum of HPWH, auxiliary tank, heat exchanger, and heat tape (kWh)

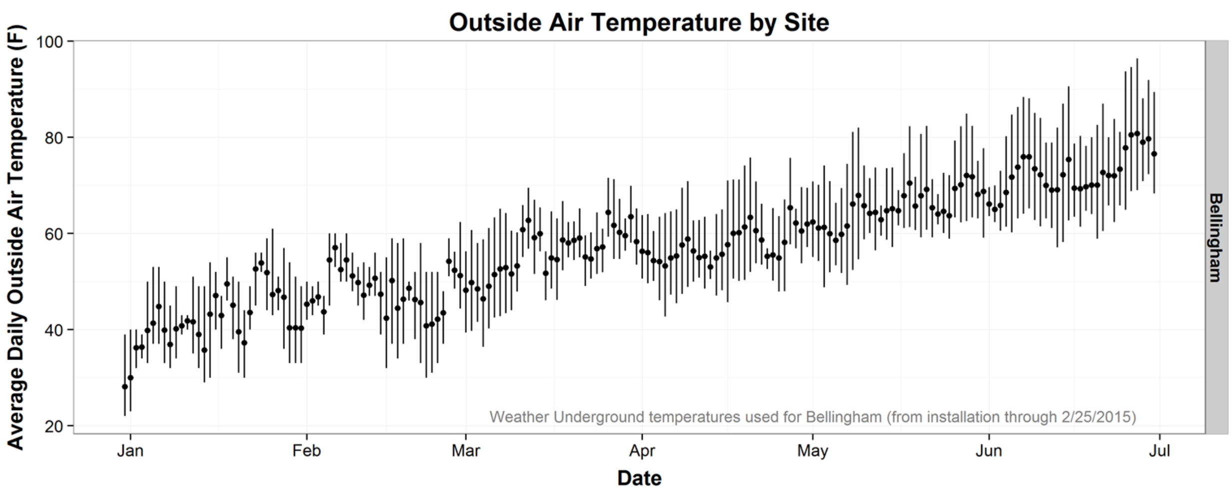
Results

Data summaries and calculations for six months of data collected at the Bellingham site are presented here. Site Summaries

Outside Air Temperature

Figure 7 shows the daily average temperature from the Bellingham site through June 30, 2015. Each day has a bar – the dot is the average temperature for that day, and the bar extends to the daily extreme temperatures.

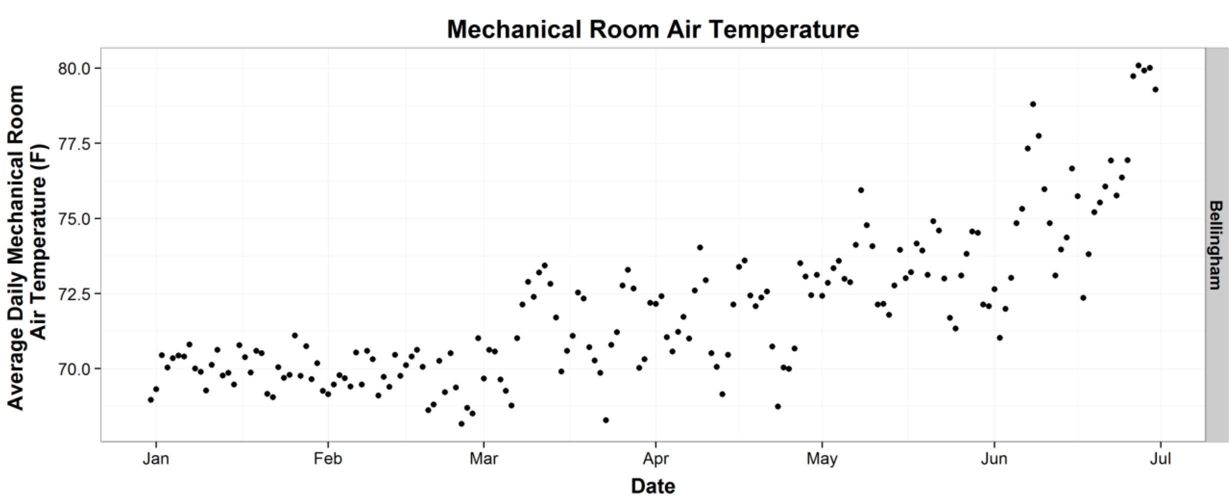
Figure 7. Daily Average Temperature at the Bellingham, WA Site through June 30, 2015



Mechanical Room Summaries (from Metered Readings)

The space surrounding the tank impacts the heat loss rate from the tank and piping. **Figure 8** shows the indoor air temperature of the space where the tank resides. Temperatures were generally above 65°F during the heating season and increased in the spring and summer.

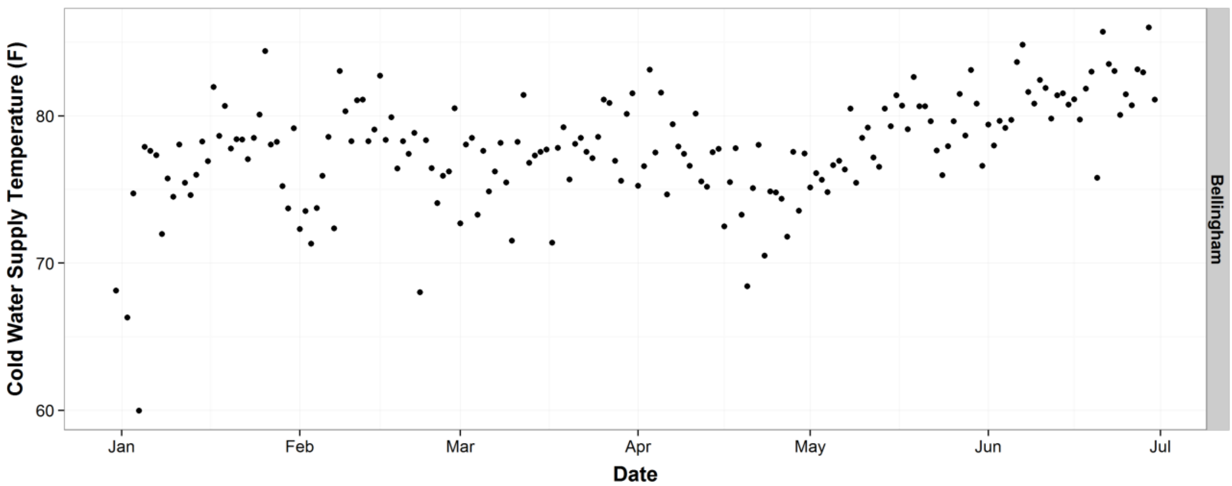
Figure 8. Temperature of Space Surrounding the Tank in Bellingham, WA



Cold Water Supply Temperatures (from Flow Event Averages)

The plot in **Figure 9** shows the average cold water supply temperatures at the site. According to the manufacturer of the HPWH, the temperature of the incoming water impacts the system efficiency due to the thermodynamic properties of CO_2 at the pressures used in the system. The water supply at the Bellingham site is rainwater that is stored in above-ground cisterns and then held in a pressurization tank in conditioned space. The resulting higher temperatures are barely within the recommended range of coolness.

Figure 9. Average Cold Water Supply Temperature in Bellingham, WA (mean = 77.8°F)

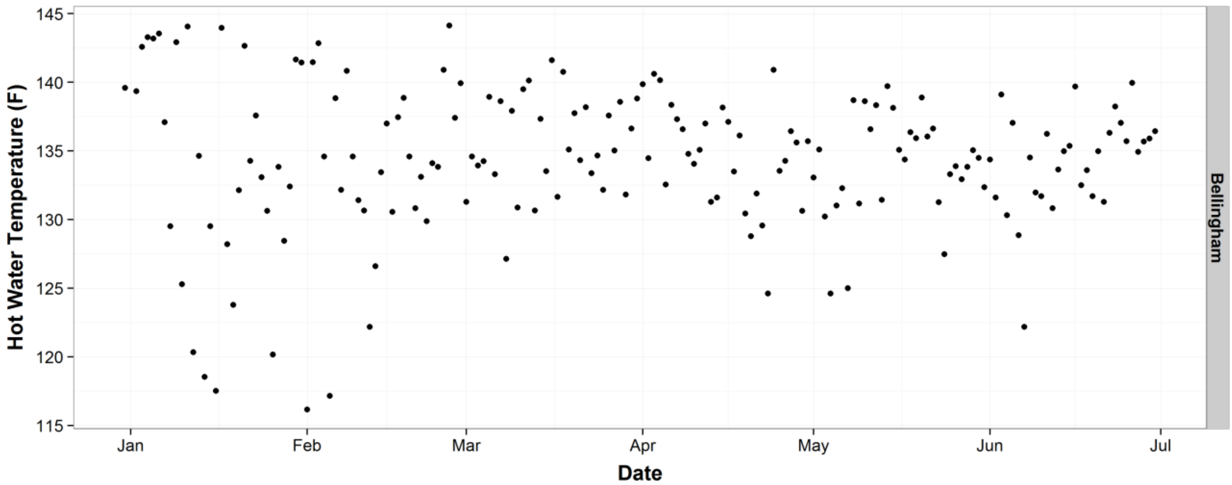


The reading of inlet water temperature can be impacted by the sensor heating up due to its location in a pipe connected to a tank of very hot water. That pipe is heated by conduction from the water heater, and this masks the true temperature of the incoming water. This effect is reduced by requiring a minimum of three consecutive readings for calculating average temperatures. However, outliers caused by tank heating may still be apparent in the temperatures used in the calculations, although the errors are lower than those that result from instantaneous temperatures.

Hot Water Supply and Tempered Temperatures

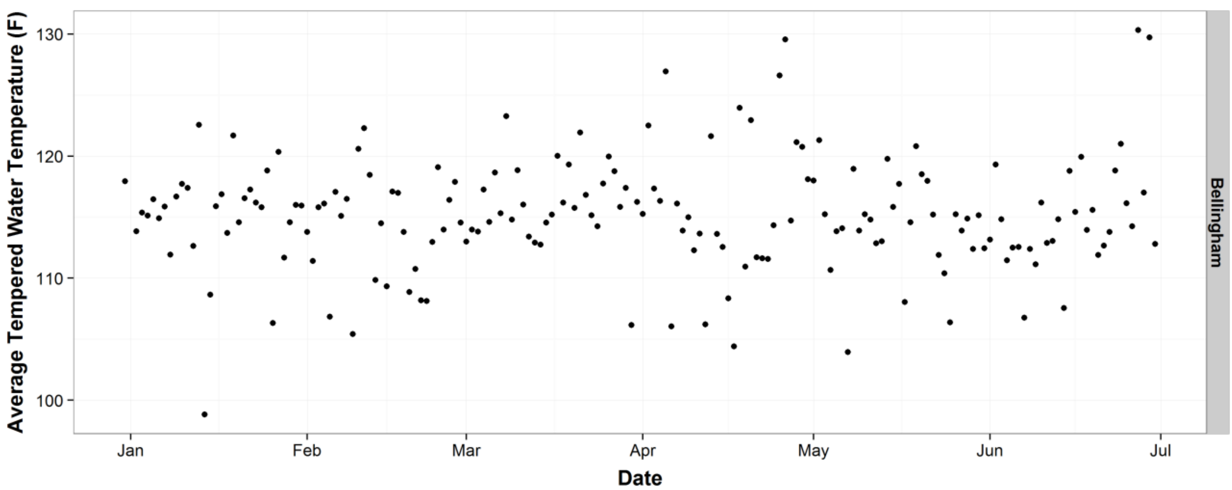
Figure 10 shows the daily average hot water supply temperature. Note that it ranges substantially more than in the hot water-only sites in TIP 292. This may be due to the introduction of the heating loop return at approximately 70°F during the heating season. The drop in temperature during May and June is not explained, although those values are within the system dead band.

Figure 10. Average Daily Hot Water Supply Temperature in Bellingham, WA



Each household in the study is equipped with a tempering valve to reduce the hot water supply temperature, which generally averages almost 150°F, to a safer use temperature by mixing it with cold water. The mixed temperature is set by the homeowner. As shown in **Figure 11**, the average delivered temperature ranged between 105°F and 125°F, with excursions as low as 98°F and as high as 130°F.

Figure 11. Average Daily Tempered Water Temperature in Bellingham, WA



Household Water and Water Heater Energy Use

Without a tempering valve, the volume of hot water supplied to the occupants is exactly the same as the volume of cold supply water provided to the water heater. The tempering valve adds cold water to the hot water supply to bring the temperature down to the temperature desired by the user. It is possible to calculate the amount of added cold water when the amount of hot water plus the temperature of the hot water supply, the cold water temperature, and the temperature of the water flowing out of the tempering valve are known. In this case, all three temperatures are directly monitored, and daily average temperatures are used to calculate cold water added to the tempering valve and the resultant total household tempered water use. Figure 12 shows the household tempered water use at the Bellingham site.

Figure 12. Tempered Water Use at the Bellingham Site

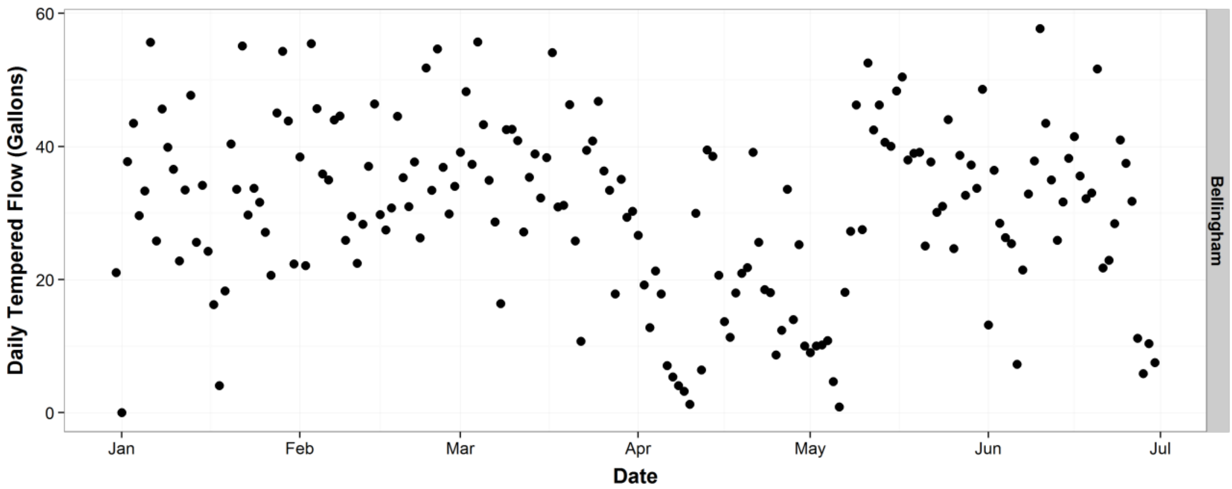


Table 3 shows the total measured cold water supply to the water heater, which is also the hot water supply volume from the tank to the tempering valve, the calculated volume of the cold water mixed with the hot water from the tank, and the total household tempered water used in GPD for the non-heating season only (March 15 onwards). This daily tempered water use is about half the average 15 GPD per person. It raises concerns about the accuracy of the monitoring, which will be addressed in the site visit scheduled for October 2015.

Table 3. Total Measured Cold Water Supply and Calculated Tempering Water

Site	Total Cold Water Supply Water, GPD	Calculated Total Water added to Tempering Valve, GPD	Total Household Tempered Water, GPD
Bellingham	18.1	9.47	27.57

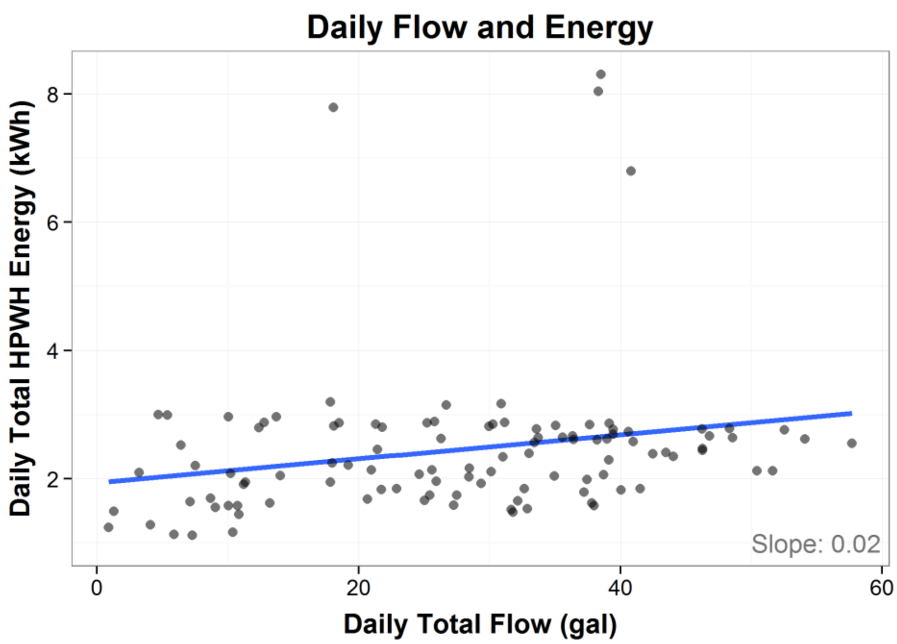
System Performance

System performance integrates daily water flow with the heating energy. **Figure 13** demonstrates a measure of efficiency in the daily amount of energy used per gallon. Different amounts of energy are used on some days even though flow rates and the OAT are the same. Daily energy and water use in large tanks is often not regular – hot water is carried over from a previous day, which reduces the energy needed to heat it back up to the desired output temperature.

The data used here does not include the energy used by heat tape; it is simply the water flow through the hot water system and the energy used to heat it, including standby losses in tanks and pipes. Energy used for freeze protection by the unit itself, including defrost and recirculation of hot water through the outdoor unit when the system drops in temperature, is already in the performance calculations.

Figure 13 shows the amount of tempered water used per day on the X axis and the kWh used on that day on the Y axis. Data shown is for the spring and summer months (after March 15, 2015). A linear fit shows the relationship between kWh and gallons of hot water used. The slope of the line in **Figure 13** is actually kWh per gallon of water heated including tanl and piping losses. The higher energy values (>6 kWh) coincide with days when the heating system was active in late March and April. The slope indicates the efficiency of the system mainly as a water heater and strictly during the warmer months. This slope is considerably lower than similar non-heating season metrics for the sites included in TIP 292, as is the Bellingham daily average HPWH energy use of 4.95 kWh (for installation through June 30, 2015). WSU is currently investigating these results.

Figure 13. Water Flow through the Hot Water System and the Energy Used to Heat It

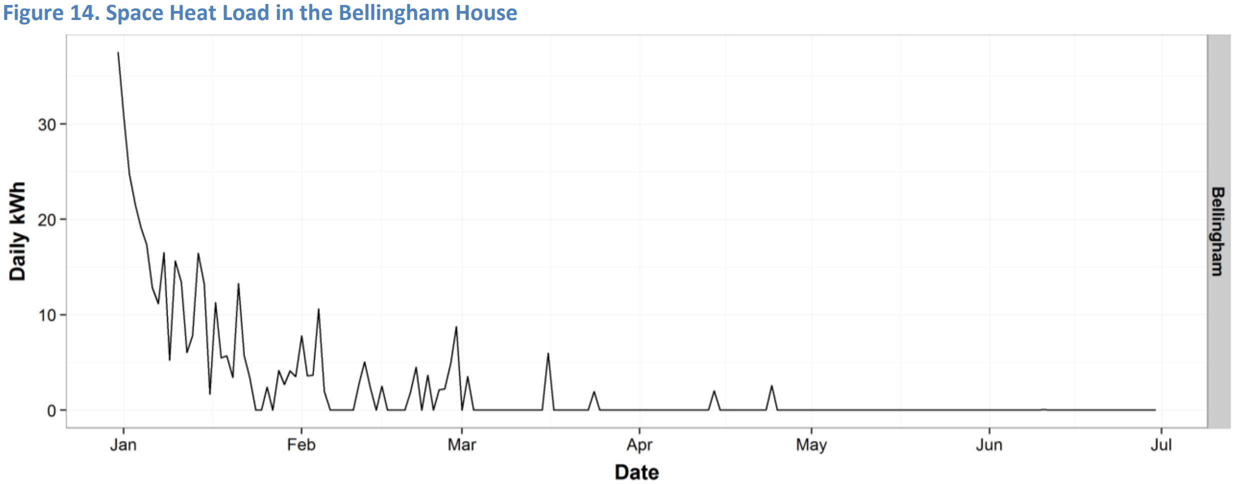


Space Heat

Monitoring was installed in late December 2014 and was able to capture cold weather data from that time through March 2015. Analysis focused on developing procedures and understanding the data. Every building is unique, and the Bellingham site created unique challenges that make it very difficult to assess heating system performance.

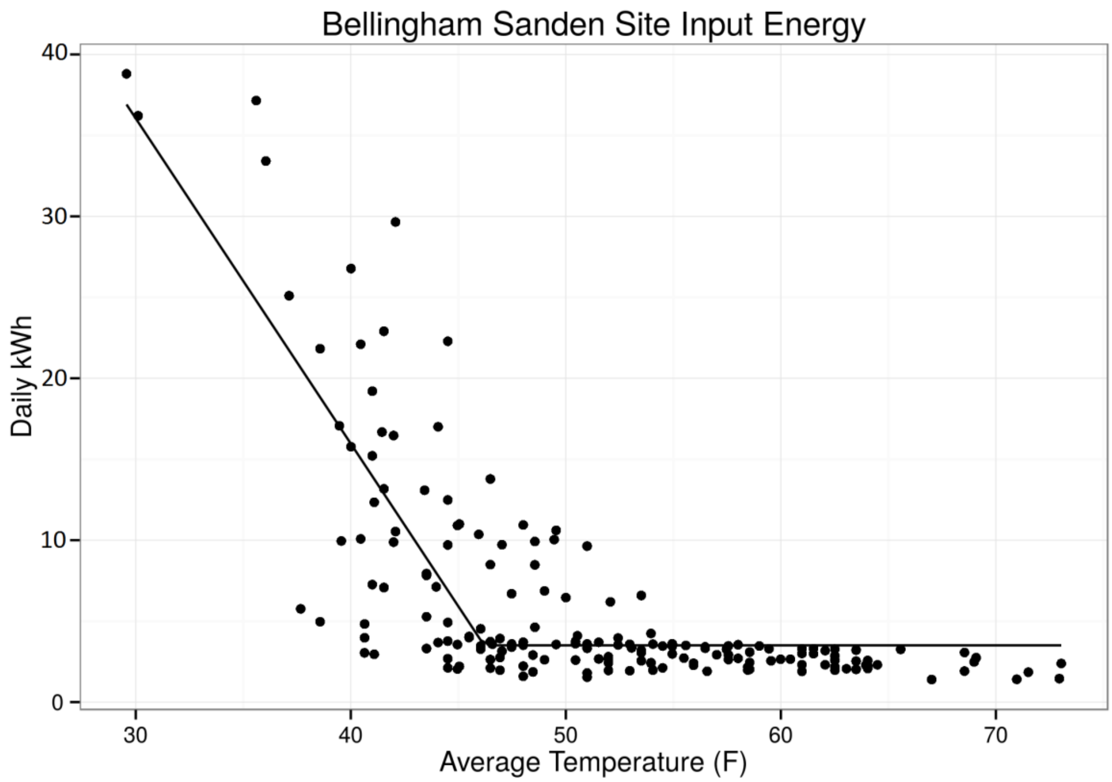
Figure 14 shows the space heat load in Bellingham from January through June 2015. As expected, this load is high in the winter months and declines precipitously in spring to zero load in summer.

Figure 14. Space Heat Load in the Bellingham House



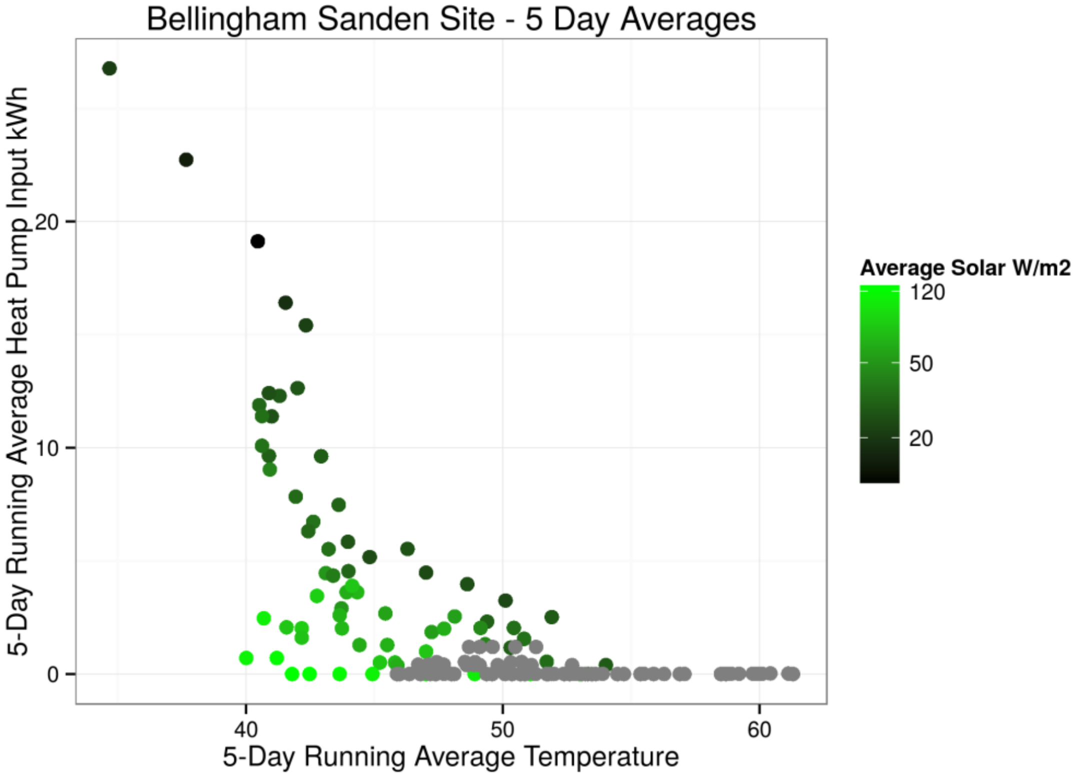
When load is modeled with temperature, the analysis becomes complicated. **Figure 15** shows a degree day model fit between input energy (for space and water heat) and local daily average temperatures. Above 55°F, the consistent <3 kWh energy load is energy used to supply hot water to the house. Higher energy values at temperatures under 50°F demonstrate combined space and water heat. There is poor fit between heating load and the heating curve of the building, which is especially apparent for days with average OATS between 40°F and 45°F. The home does not have a wood stove, yet the sub-45°F days where little to no space heating load was recorded suggests either periods of vacancy, intermittent heating system operation, or an alternative heat source.

Figure 15. Energy Load Modeled with Temperature in the Bellingham House



When solar gains were factored into the analysis, the mystery was solved. **Figure 16** correlates solar radiation (data retrieved from Weather Underground) with heat pump energy use by temperature. Note the days with high-intensity solar radiation that have no heat pump operation. Days shown in gray were not compared to solar radiation data.

Figure 16. Influence of Solar Gain on Energy Load at the Bellingham House



The Bellingham house is a passive solar design with most of the windows facing south. The data from winter 2014-2015 suggest that solar radiation is acting as a substantial supplementary heating source.

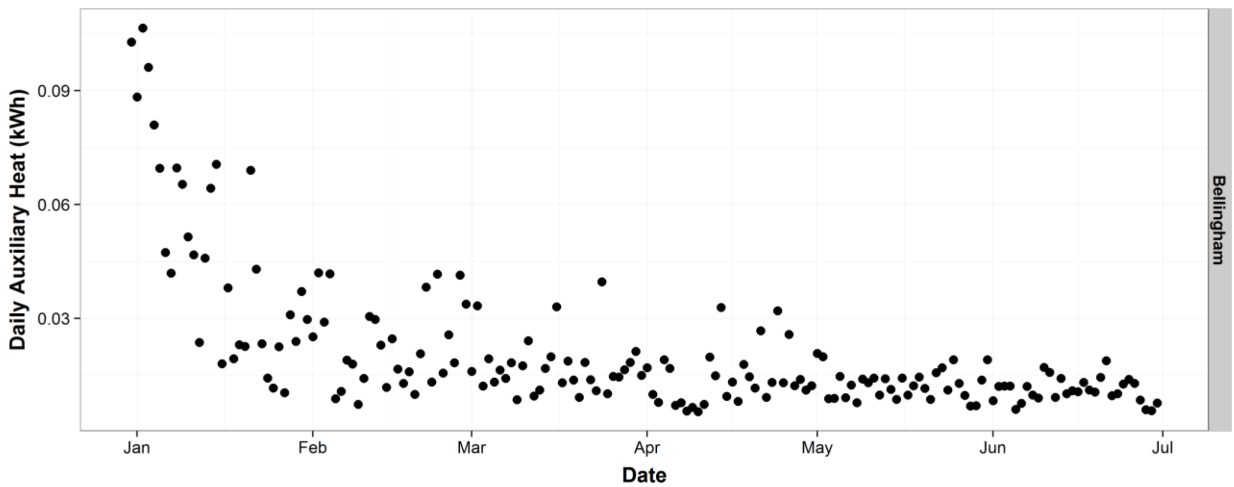
Figure 17. Passive Solar Home Used for this Analysis in Bellingham

Auxiliary Space Heat

The system was installed with an auxiliary tank, which was in place for the monitoring period covered in this report. The tank was plumbed with the hot water inlet from the heat pump tank at the top of the auxiliary tank and the heating supply water take from the bottom of the auxiliary tank. This was probably not the optimal plumbing route, but the system worked quite well despite that setup.

The auxiliary tank had a 4.5 kW element that provided backup heat to the radiant floor distribution system. The operation of that element is shown in Figure 18.

Figure 18. Energy Use by the Auxiliary Space Heat System at the Bellingham House



The maximum daily use occurred during January 2015 and reached 0.11 kWh. Total use during the heating season was less than 3 kWh. Unfortunately, the system was not switched off during the spring and summer, and it continued to switch on and off to keep the auxiliary tank warm.

System Efficiencies – FEFs and HSPFs

FEFs and HSPFs are not currently presented because characteristics unique to this site must be addressed. Additionally, several original installation configurations require adjustment to operate optimally both for system design and on-site monitoring.

Conclusion and Recommendations

The Bellingham HPWH provided space and water heat for a family of four in an energy-efficient passive solar home with minimal backup heat.

The combined space and water heating design and installation is an ongoing process. Thus far, WSU has collected performance data on one house; based on field monitoring and lab tests, the system plumbing will be changed in advance of the coming heating season. Similar changes have been made in the system design at the two houses in McCall, which are scheduled for installation in October 2015. The conclusion is that this is a new technology that is still under development.

Monitoring these systems is complex, and monitoring accuracy, especially of flow measurement, is under review. The best approach is to have each system commissioned onsite using ultrasonic flow meters. This is possible, but expensive.

References

Ecotope and NEEA, 2015. *Heat Pump Water Heater Model Validation Study*, March 2, 2015. http://neea.org/docs/default-source/reports/heat-pump-water-heater-saving-validation-study.pdf?sfvrsn=8

Eklund, K.; Banks, A.; 2015. *Advanced Heat Pump Water Heater Research First Midterm Field Study Report,* October 30, 2014; updated March 19, 2015. http://www.energy.wsu.edu/documents/FirstMidtermReportonMonitoringofAdvancedHPWHfromInstallationthruMarch2014-Final.pdf

Fluid Market Strategies and NEEA, 2013. *Heat Pump Water Heater Field Study Report*. October 22, 2013. http://neea.org/docs/default-source/reports/heat-pump-water-heater-field-study-report.pdf?sfvrsn=5

Larson, B., 2013. *Laboratory Assessment of Sanden GAU Heat Pump Water Heater*. A Report of BPA Technology Innovation Project #292. Prepared by Ecotope, Inc. for the WSU Energy Program under contract to BPA. September 18, 2013. http://www.energy.wsu.edu/documents/Sanden_CO2_split_HWPH_lab_report_Final_Sept%202013.pdf

NEEA, undated. Northern Climate Specification Media Backgrounder. http://neea.org/docs/northern-climate-heat-pump-water-heater-specification/northern-climate-specification-media-backgrounder.pdf