Laboratory Assessment of Demand Response Characteristics of Two CO_2 Heat Pump Water Heaters

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A Technology Innovation Project Report

The study described in the following report was funded by the Washington State University Energy Program under contract to Bonneville Power Administration (BPA) to provide an assessment of the state of technology development and the potential for emerging technologies to increase the efficiency of electricity use. BPA is undertaking a multi-year effort to identify, assess, and develop emerging technologies with significant potential for contributing to efficient use of electric power resources in the Northwest.

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Abstract

Water heaters are a natural fit for utility demand response (DR) programs. This project assessed the ability of two, advanced, CO_2 heat pump water heaters (HPWHs) to provide DR services. Using a two phase approach, the project first conducted a series of lab tests and, second, crafted a numerical simulation. The lab tests explored six, 24-hour long DR scenarios over a wide ambient temperature range, mapped the equipment coefficient of performance (COP) from 17°F to 95°F, and monitored water line temperatures, exposed to ambient air conditions, for freezing potential. The simulation, in exploring the two DR scenarios of oversupply and peak shifting, proved especially useful in demonstrating hot water availability (or lack thereof), calculating the shift in operating hours/temperatures, and calculating efficiency changes. Both phases of the work showed that the HPWHs are promising for use in DR applications. The project also demonstrated the simulation is a valuable tool in predicting the outcomes of running various DR scenarios.

Glossary of Acronyms and Abbreviations

A	amps
ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
BPA	Bonneville Power Administration
Btu	British thermal unit
C	Celsius
CO_2	carbon dioxide
COP	coefficient of performance
DAQ	data acquisition system
DEC	an event where generated power is higher than load
DHW	Domestic hot water
DOE	Department of Energy
DR	Demand Response
EF	Energy Factor
ERWH	Electric Resistance Water Heater
F	Fahrenheit
ft	feet
GAU	Sanden model 80 gallon heat pump water heater
GES	Sanden model 40 gallon heat pump water heater
GPD	gallons per day
GPM	gallons per minute
GWP	Global Warming Potential
HPWH	Heat Pump Water Heater
Hz	hertz
INC	an event where generated power is lower than load
kJ	kilojoule
kW	kilowatt
kWh	kilowatt hours
NEEA	Northwest Energy Efficiency Alliance
PNW	Pacific Northwest
RH	relative humidity
TC	thermocouple
WSU	Washington State University
V	volts

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Executive Summary

Demand Response (DR) has historically been a tool for providing grid services such as load balancing and peak curtailment. Storage water heaters are a natural choice for DR applications because they are by their very nature energy storage devices. Accordingly, electric resistance water heaters (ERWHs) have been studied thoroughly for their ability to contribute to DR (Diao et al. 2012). However, efficiency standards for water heaters are being implemented that will effectively replace some ERWHs with heat pump water heaters (HPWHs) (BTO 2015). The result has raised some questions about the amenability of HPWH's to DR programs. Several studies have researched the questions and found that, indeed, HPWH's can be used for DR programs (PNNL, 2013) (ECOFYS, 2014). This project assesses the particular case of using advanced CO_2 HPWHs and further confirms these results.

Under the *Demand Response Potential of Heat Pump Water Heaters* project funded by Bonneville Power Administration (BPA), the Washington State University Energy Program (WSU) contracted with Ecotope, Inc. and Cascade Engineering Services Inc. to conduct an assessment of two products built by Sanden International: the GES-15QTA (GES) and the GAU-315EQTA (GAU). The project built on two previous assessments of the equipment when used for traditional water heating applications (Larson 2013a and 2013b). Further, it was conducted in tandem with an investigation of the DR potential of the same water heaters in a controlled field test (see the companion report from Pacific Northwest National Lab, PNNL).

Ecotope employed a two stage approach to the work. The first measured detailed operational data in a series of lab tests run at controlled conditions. The second crafted a numerical simulation, calibrated to data collected in the first stage, to generalize the results and address more DR scenarios than could be tested in the lab.
The project found the HWPHs are suitable for a variety of DR scenarios. The transcritical CO_2 refrigerant cycle provides an even greater potential because it is inherently suited to heating the water to higher temperatures than other refrigerants giving program operators even more flexibility.

Lab Tests

To make the most of the lab testing time, Ecotope combined the oversupply mitigation and a peak-shifting DR profiles in to a single day of testing. In those tests the HPWH is allowed to run from midnight to 6AM and noon to 2PM only. The overnight run allows for oversupply mitigation and the mid-day run allows the water heater to operate, if needed, at a lower-load time. These tests observed a DR scenario interacting with a 3-person, 46 gpd draw profile. In that case, either tank handily provides enough hot water. Those tests demonstrated the energy storage "space" at the end of the day is only a function of the amount of hot water used during that day. They further revealed that the electric storage space and equipment power, for a given amount of cold water in the tank, are not constant. Rather, they are strong functions of outdoor temperature. Consequently, the COP map is needed to predict capacity reductions and energy shifts for any given scenario.

Additionally, the lab tests successfully mapped the HPWH coefficient of performance from 17°F to 95°F ambient air and water from 50°F to 140°F for both products. This is critical information which shows how much power and energy is used during a given set of conditions and provides the foundation for the numerical simulation.

A series of lab measurements, of particular interest to DR, where the water heater is forced off for extended periods, quantified the heat loss rate of the external water circulation lines. The data show that for installation locations where the outdoor temperature drops below freezing, the water lines need to be well insulated and either heated with a supplementary source or circulated periodically. The experiments suggest additional controls to operate the circulation pump could prevent freezing but that these controls would need to remain active under any DR scenario.

Simulation Findings

After using lab test data to validate the simulation's veracity, Ecotope exercised the simulation with two DR scenarios: oversupply and peak shifting. The simulation proved especially useful in demonstrating hot water availability (or lack thereof), calculating the shift in operating hours/temperatures, and calculating efficiency changes. Surprisingly, in the oversupply case, even though operation was shifted to colder temperatures, the DR scenario was more efficient than the base case. The simulation shows this is because the DR case delays operation, storing more cold water in the tank, reducing standby losses, and increasing recovery efficiency by sending relatively colder water to the compressor unit. The findings are for the Spokane and Portland climates, for a particular set of draw profiles, and so should be explored further in different scenarios. Other scenarios in different climates, with different DR schedules, and those in which the tank is “overheated” above its typical setpoint may show higher or lower efficiencies than the base case.

Desired Controls for Demand Response

After observing and simulating the Sanden HPWHs, a clear set of desired controls emerged. In short, to be useful and versatile, the HPWH should have two-way communications and a variable tank setpoint. The two-way communications needs to support four basic commands: status query, operation enable, force off, force on. To support the status query, the HPWH needs to be able to report its current power draw and tank temperatures. To provide maximum flexibility, the tank setpoint should be adjustable and settable remotely. The adjustable setpoint for the water heater will allow a wider range of possibilities. Ideally, the range should be from as low as the user wants to 190°F+. The extra hot setting enables a larger storage capacity. Along with the adjustable tank setpoint, the unit should have an integrated mixing valve which is adjustable to the user setpoint. Both the tank setpoint and the user setpoint need to be communicated to the utility with control of the tank setpoint given over to the utility. The difference in temperature, above the user setpoint, determines the amount of energy stored (or available) to the utility.

Future Work and Simulation Improvements

In sum, the Sanden HPWHs are promising for DR applications. Once equipment is available with onboard communications and the ability to heat water to very hot settings, those specific aspects should be investigated and used to augment the current body of work. The DR simulation should also be updated with more features in order to cover more scenarios and extend beyond this project’s scope. In particular, work should be initiated to introduce arbitrary hot water draw profiles to the simulation. To accurately simulate the entire water heater population (or a population of participants in a DR program), the simulation needs to run with the population’s hot water draw distribution and not just the thirty-five typical days used as examples in this project. The simulation could allow a unique draw at every minute of the year. These could be based on actual, field-observed draw patterns. In this way, even more DR scenarios could be tested out before being implemented in the field. The simulations would show which scenarios limited hot water availability and how much power and energy could be added or dropped.

1 Introduction

Demand Response (DR) has historically been a tool for providing grid services such as load balancing and peak curtailment. Storage water heaters are a natural choice for DR applications because they are by their very nature energy storage devices. Accordingly, electric resistance water heaters (ERWHs) have been studied thoroughly for their ability to contribute to DR (Diao et al. 2012). However, efficiency standards for water heaters are being implemented that will effectively replace some ERWHs with heat pump water heaters (HPWHs) (BTO 2015). The result has raised some questions about the amenability of HPWH's to DR programs. Several studies have researched the questions and found that, indeed, HPWH's can be used for DR programs (PNNL, 2013) (ECOFYS, 2014). This project assesses the particular case of using advanced CO_2 HPWHs and further confirms these results.

Under the *Demand Response Potential of Heat Pump Water Heaters* project funded by Bonneville Power Administration (BPA), the Washington State University Energy Program (WSU) contracted with Ecotope, Inc. and Cascade Engineering Services Inc. to conduct an assessment of two products built by Sanden International: the GES-15QTA (GES) and the GAU-315EQTA (GAU). The project built on two previous assessments of the equipment when used for traditional water heating applications (Larson 2013a and 2013b). Further, it was conducted in tandem with an investigation of the DR potential of the same water heaters in a controlled field test (see the companion report from Pacific Northwest National Lab, PNNL). Taken together, all the research provides a full picture of the DR possibilities of these two water heaters.

Ecotope drafted the lab test protocol within the context of the controlled field study. The PNNL lab houses explored the extreme end of the hot water draw pattern under a variety of ambient conditions. The lab tests set out to augment those findings by studying a typical hot water draw pattern under specific sets of conditions. The lab test goals were to identify the impact of DR on hot water delivery, heat pump water heater performance, the dynamic energy storage potential, and controls needed for optimum DR implementation. To do so, the Ecotope team used the detailed lab testing results to craft a numerical simulation to explore a set of general demand response scenarios. The calibrated simulation provides a valuable tool allowing utility researchers to explore scenarios beyond what was tested in either the controlled field or lab settings.

Cascade Engineering Services carried out the lab testing in accordance with regional standards and protocols used in previous testing in the Pacific Northwest for BPA and the Northwest Energy Efficiency Alliance (NEEA). The lab tests explored six, 24-hour long DR scenarios over a wide ambient temperature range, mapped the equipment coefficient of performance (COP) from 17°F to 95°F, and monitored water line temperatures, exposed to ambient air conditions, for freezing potential. A narrative and table describing all tests performed for this report is included in Appendix A: Lab Test Protocol. All the results, and those from previous studies, went into developing the numerical simulation to enable exploration of a variety of DR scenarios.

1.1 Background

There are several actions which constitute “Demand Response”: peak curtailment, INC events, and DEC events. In addition, water heaters also can be used for energy storage, which involves similar techniques. Peak curtailment, or peak load reduction, involves reducing the load at times of peak load. INC and DEC events are examples of Balancing Reserves, or load following, which are intended to respond to hourly or sub-hourly changes in generation capacity. INC events are when generation and load are mismatched due to higher load than generated power. DEC events are when generation and load are mismatched due to higher generated power than load.

Tank water heaters are inherently well suited for demand response because they are, inherently, energy storage devices. In typical operation, the amount of energy embodied in a hot water draw, is only a fraction of that stored in the water tank. For small household water uses relative to tank storage volume, a water heater may not need to run on a given day even without demand response control. In other words, there is enough hot water, or stored energy, from the previous day to meet the water needs of the current day. Clearly, then, there is an opportunity to control the time at which the water heater runs to optimize capacity available on the electric grid. The DR activity then becomes a balancing act between providing a useful service to the utility while not interrupting an occupant's hot water supply.

1.2 Research Plan Review and Overall Approach

The project set out to address the following research questions in the lab test:

- What is the dynamic energy storage capacity of the water heater under various operational parameters? This analysis will determine the maximum theoretical heat storage capacity and the practical working capacity.
- What is the impact on performance of increased tank loss, if any, due to increasing temperatures for energy storage?
- How does dispatchability integrate with the function of the water heater? Does a CEA 2045 communication port provide the needed information transfer in each direction? What sensors and other capability does this require?
- What are the demand response benefits and issues of the tested technology, and how might the tested technology be redesigned to further improve its demand response function, marketability and cost-effectiveness while retaining efficiency?
- How are the combined impact of dispatchable load following or balancing reserves and inherent efficiency combined and valued to determine the overall capacity reduction potential of HPWHs?
- What is the impact on heat pump water heater performance of operating at nighttime or off-peak hours? Are these different hours than it would normally operate? If so, is efficiency increased or reduced and how much due to differing outside air temperatures?

The PNNL controlled field study portion of the project was conducted first which lent considerable insight in to what the equipment capabilities were and what questions were best suited for answering in the lab setting. That study used a large, 130 gallon per day hot water load intended to push the equipment limits in oversupply mitigation and balancing INC events. Further, the test houses, subject to the daily and seasonal weather conditions around them, allowed PNNL to observe the equipment performance at a range of ambient conditions. The controlled field tests proved informative on this front and raised questions that could be more readily answered in a laboratory setting. With control over all environmental variables, the lab is the ideal place to research the operation of equipment for detailed performance factors. Toward that end, Ecotope drafted a lab test plan to target measurements at a specific set of ambient conditions to map both equipment COP and simulated DR scenarios.

To answer the full range of research questions, it became apparent that a two-pronged approach to the lab testing phase would be the most useful. The first part would be to record detailed equipment operational data from a series of test runs at controlled conditions. This would provide the data and serve as a calibration check for a numerical simulation. The second part, the numerical simulation, would be a tool allowing researchers to generalize the results and answer questions about many more DR scenarios than we could test in the lab. The simulation adds to the HPWH model Ecotope developed for integrated HPWHs. The model is both stand-alone and fully incorporated into the SEEM energy use simulation. With a working simulation, we can explore any number of DR and draw schedules. The simulation is designed to read user defined DR and draw schedules which means we can explore any number of balancing INC/DEC, over supply mitigation, or other effects on the water heater. Simulation outputs will show the change in operating times, efficiency, and water availability of the water heater.

The PNNL experience with the water heaters showed that investigation of two of the research questions would have to be delayed to future products. It was proposed for the equipment to have CEA 2045 communications protocols on board but, despite a good faith effort made by the manufacturer to obtain such control devices, they were not available for this project. Instead the lab programmed a set of relays to operate the water heaters. A similar controls question was a desire to test the equipment while heating water to extremely high tank temperatures. This was also not possible with this particular equipment although other CO_2 HPWH equipment manufactured by Sanden for the Japanese market routinely heats the water to 194 °F. Both of those concepts should be studied in future work.

1.3 Equipment Overview

The research investigated two pieces of equipment, both manufactured by Sanden International: the GES-15QTA and the GAU-315EQTA. Ecotope previously evaluated both units, investigating their function under standard water heating conditions (Larson 2013a and Larson 2013b). The reader is encouraged to reference those two previous studies for in-depth explanations of the equipment. Both water heaters use the same compressor and similar refrigeration-system components. They each use a transcritical CO_2 cycle to extract heat from the ambient air and transfer it to the water. Each product is designed so that the air-to-refrigerant and refrigerant-to-water heat exchange both take place in a single unit. A variable speed pump circulates water from the tank, past the “gas cooler” (heat exchanger) and returns the water to the top of the tank. The variable speed compressor and pump work to heat incoming cold water at any temperature to 149°F in a single pass through the heat exchanger.

The GES, built in France and sold in the European market, stores 40 gallons of hot water and is designed for installations in interior locations. It has two cube-shaped modules, both identically dimensioned, with one for the water tank and the other for the heat pump and heat exchanger. The modules may be stacked vertically or side-by-side. Further, the air supply to, and exhaust from, the evaporator may be connected to ducting. This ducting allows the equipment to be isolated from the building space conditioning system. The electrical connections on the unit required 230V, 16A, and 50Hz. To accommodate the different frequency of the European electrical grid, Cascade Engineering used a generator to specifically supply the desired electrical requirements.

The GAU, currently built and sold in Australia, stores 80 gallons of hot water and has a heat exchange unit fully split from the hot water tank. Typically, the outdoor unit will be placed on the house exterior with water lines running between it and the water tank, placed inside. The electrical connections accepted the standard power input available in the lab – 240V, 15A, at 60Hz.

Both water heaters are directed at markets outside the United States which results in different design decisions than typical of equipment sold within the US. For example, the tanks do not have electric resistance elements and have a fixed temperature set point at 149°F. We evaluated the unit as-is, however, any equipment destined for the United States would likely have a slightly different configuration of tank size, controls, and set point possibilities.

Table 1. Basic Equipment Characteristics

Component	**GES-15QTA**	**GAU-315 EQTA**
Tank Volume (Gallons)	39.7	84.6
Resistance Elements	None	None
Heat Pump* (W)	1,000 – 2,200	900 – 2,400
Heating Capacity at 67.5°F (kW)	4.1	4.2
Energy Factor at 67.5°F	3.34	3.38
Standby (W)	< 1	< 1
Tank Heat Loss Rate (Btu/hrF)	2.2	4.7
Refrigerant	R-744 (CO_2)	R-744 (CO_2)

*Includes compressor, circulation pump, and fan for both products. Range depends on water and ambient temperature.

2 Methods

In order to determine the viability of the Sanden HPWH for Demand Response (DR) a bipartite approach was developed, involving a set of lab tests and a suite of simulations. Although both the GES and GAU units have been tested in the lab before, a number of additional tests were designed to extend the range of temperatures where the HPWH's response was well known. Further tests were designed to characterize how the units would respond to a conceivable DR protocol.

2.1 Test plan

Ecotope drafted a set of laboratory tests to produce more information about how the COP depends on the ambient temperature. An accurate mapping of COP is necessary for the construction of an accurate simulation. Further, the test plan called for additional temperature measurements on the water transfer line which increased the testing value. Not only could the heat loss rate of the water transfer lines be measured at several temperatures, but knowing the temperature of the water going in to the gas cooler enables much better measurements of the COP.

Advanced tests were designed using sample draw profiles and a DR schedule which only powered the unit at certain times during the test, representative of allowing the unit to run during off-peak hours. These tests provide an indication of the ability of the unit to shift demand and store energy, and they also provide useful information for calibrating the simulation.

A complete narrative and description of the tests can be found in Appendix A: Lab Test Protocol.

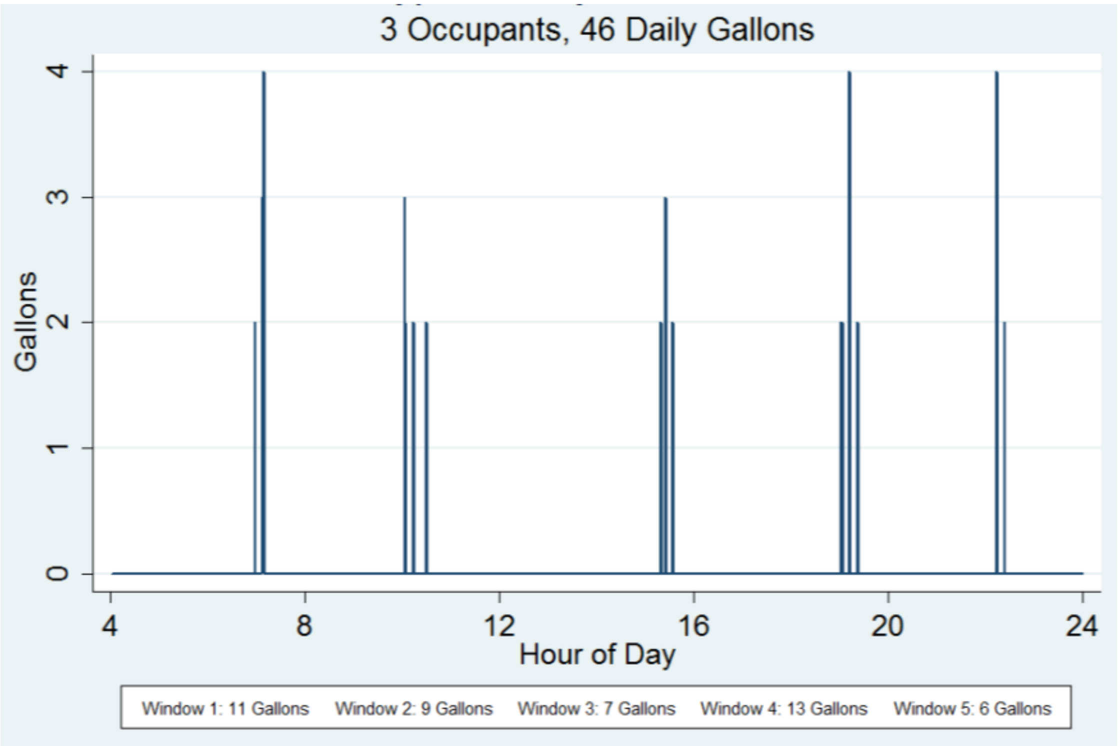
2.1.1 COP Mapping Tests

The COP mapping tests are used to obtain information on the equipment efficiency. The measurement is made by observing the rate at which the compressor heats water while simultaneously recording the input power. The COP varies according to the incoming water temperature and the ambient temperature; typically the ambient temperature is held constant while the water is heated. The test begins with a cold tank of water and concludes once the tank has reached setpoint. We conducted tests at 17 °F, 35 °F, and 95 °F for both units to augment the tests already completed at 50 °F, and 67.5 °F (Larson 2013a and 2013b). Knowing the efficiency as a function of outdoor temperature is key to understanding the change in energy use as DR profiles change the time of day (and, hence, temperature) in which the HPWH operates.

2.1.2 Draw Profile and Demand Response Tests

The draw profile tests are direct demand response experiments. Each takes place over twenty-four hours and consists of two schedules. The first is the water draw schedule. Ecotope selected a 46 gallon per day hot water draw profile. It is the typical draw pattern of a 3-person household as observed in PNW field studies (Ecotope 2015). The average occupancy house, of 2.7 people, uses 42 gallons so this is only slightly more. In contrast to the extreme 130 gallon per day profile, this is more typical of households. Figure 1 displays the draw profile showing five clusters of draws throughout the day.

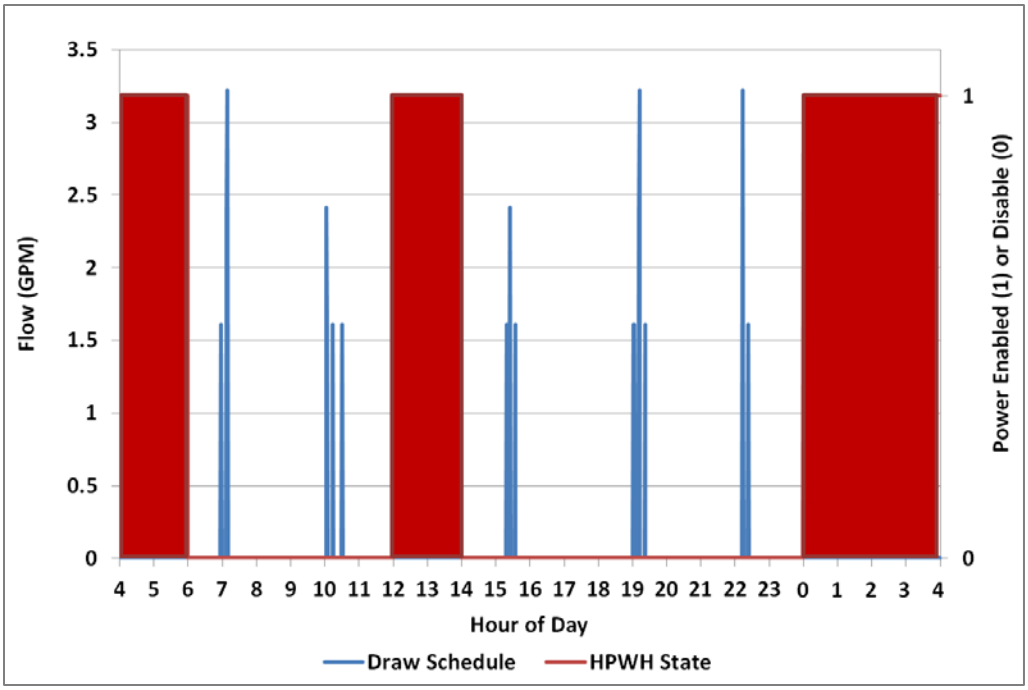
Figure 1. Hot Water Draw Profile



The second schedule is for demand response. We explored a dual DR scenario of oversupply mitigation and peak shifting. The water heater was allowed to operate from midnight to 6AM (oversupply period) and then again from noon to 2PM. It was forced off the rest of the time, coinciding with the typical peak power demand periods. In this way, we are also able to create “space” in the water heater in which it can soak up extra power in the overnight period.

Figure 2 shows the DR scenario overlaid on the draw pattern. Note that for ease of lab testing purposes, the experiments began at the equivalent of 4AM. The water heater is scheduled to be mostly off throughout the day and is certainly so for all the draw events. The lab tests show how much water is available in the tank after each event, if it can meet the daily load, and how much energy storage capacity is left at the end of a typical day for use in soaking up extra energy overnight. Also note that the hot water draw volumes have been modulated to account for the tank delivering 149 °F water whereas the typical hot water use is around 125 °F. Accordingly, the flow volumes are reduced because it is assumed colder water will be mixed with the extra hot water to create the desired tempered water condition.

Figure 2. Lab Test Draw and DR Schedule



2.1.3 Water Circulation Line Temperature Tests

The split-system GAU heat exchanger is installed outside the house with water lines connecting it to the water tank. Those water lines are installed with insulation but, nevertheless, exposed to outside temperatures. Whenever the water heater is off, the water lines are stagnant and cool down. If a demand response scenario calls for the water heater to be off for prolonged periods when it is cold outside, there is a chance the water may freeze. To quantify just how long it would take to freeze, the lab tests measured the heat loss rate of the waterlines. Cascade Engineering installed thermocouples on the water lines, underneath R-5 insulation, halfway between the outdoor unit and the “house wall” (the thermal chamber wall). During the draw profile tests, the lab logged data throughout the equipment off periods.

2.2 Lab Testing Setup

Ecotope collaborated with Cascade Engineering and WSU to devise methods and protocols suitable for carrying out the testing plan. The general approach and methodological overview for this test are provided here. All figures and schematics in this section are courtesy of Cascade Engineering.

The GAU water heater, with an outdoor heat exchanger, presents a unique challenge to HPWH testing. Typical integrated HPWHs, including the GES, place the air-to-refrigerant heat exchanger inside the conditioned space along with the tank. The GAU heat exchanger is intended to be installed outside the house; therefore, the most important temperatures to control for the GAU tests are those for the air surrounding the heat exchanger. Accordingly, the test plan placed the outdoor unit inside the thermal chamber where it is tightly controlled. The hot water tank itself is placed next to the chamber in the large lab space. That lab space is kept thermally controlled only by a space heating thermostat. The temperature varied from 60°F to 70°F. The small changes in temperature will lead to slight changes in the heat loss through the tank but the impacts on the overall system efficiency measurements are minimal.

Figure 3. Sanden GAU Outdoor Unit Installed Inside Thermal Chamber

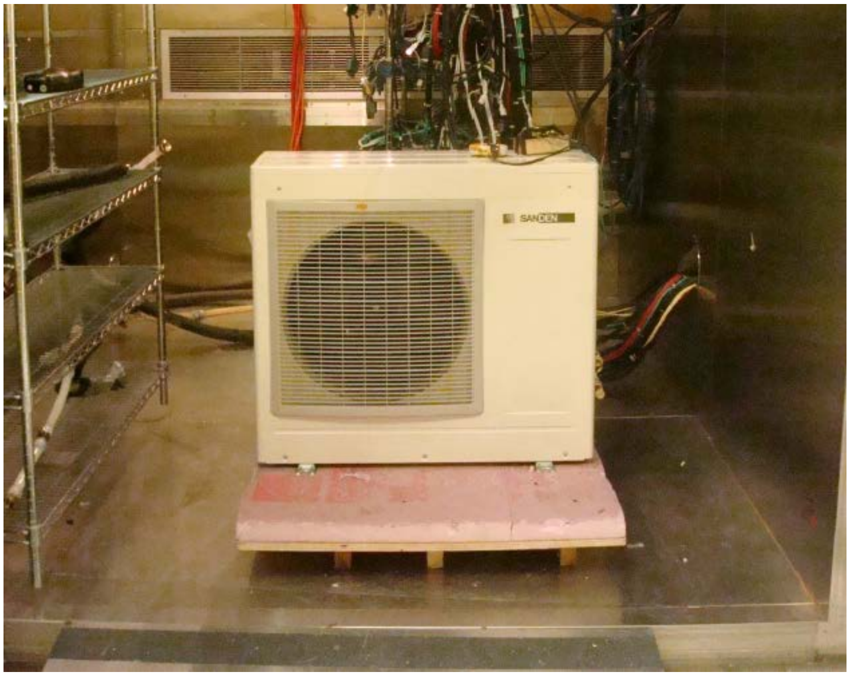
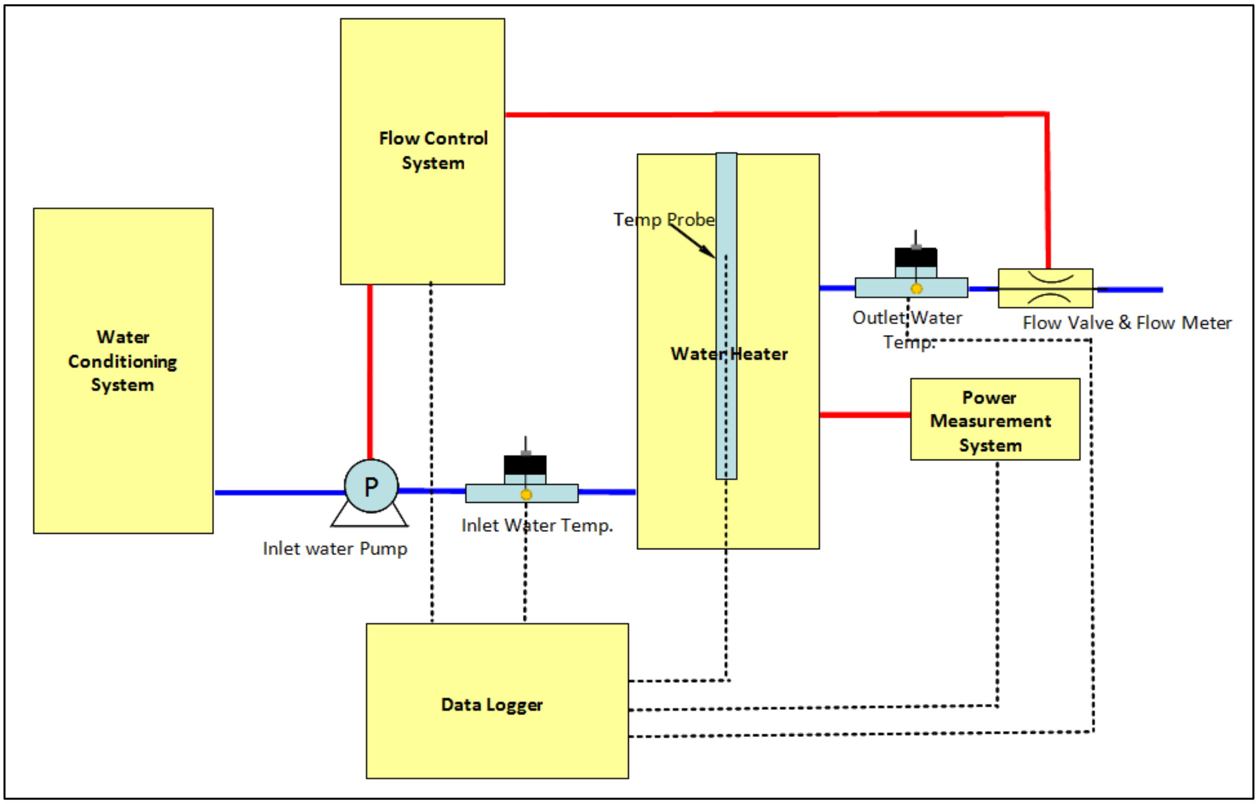


Figure 4. Hot Water Tank Instrumented and Installed Adjacent to Thermal Chamber

Figure 5. The Sanden GES integrated unit installed in the thermal chamber

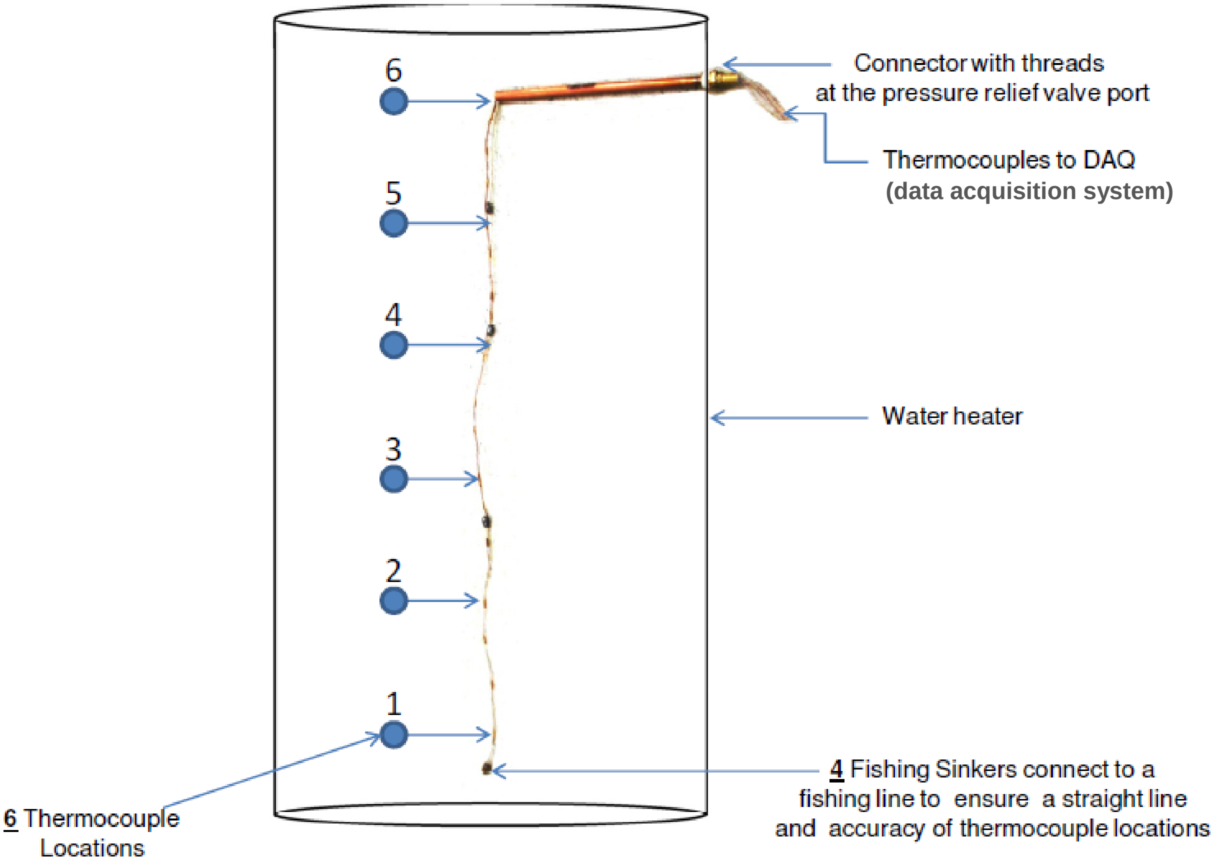
Figure 6 shows a schematic of the general test setup. Cascade Engineering installed an instrumentation package to measure the required points specified by the DOE test standard, as well as additional points to gain further insight into HPWH operation.

Figure 6. General Test Setup



The series of six thermocouples positioned at equal water volume segments measuring tank water temperature warrants special mention. Most electric water heaters have an anode rod port at the top of the tank which offers convenient access for inserting a straight thermocouple tree near the central axis. Because the Sanden tanks are all stainless steel, and there are no resistance heating elements, there is no need for an anode rod. Without the convenient anode port, Cascade Engineering used two different methods, one for each tank. Figure 7 illustrates the unique "fishing rod" approach for the large 80 gallon GAU tank. The thermocouples hang freely in the tank so, to keep them positioned, the lab attached weights to the bottom of the thermocouple wire.

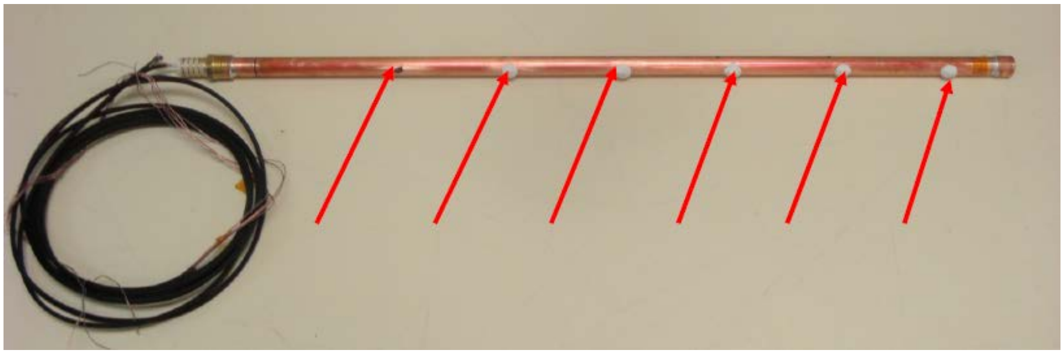
Figure 7. Tank Thermocouple Setup



For the GES tank, Cascade Engineering machined a custom lid with an access port similar in dimensions to ones used for an anode road and placed and used it in place of the lid shipped with the tank. Figure 8 shows the custom lid and how it provides access for a traditional, rigid thermocouple tree.

Figure 8. Custom Lid for 40 Gallon GES Tank Thermocouple Tree Access

Figure 9. Thermocouple Temperature Tree for GES 40 gallon Tank



Cascade Engineering measured inlet and outlet water temperatures with thermocouples immersed in the supply and outlet lines. Three thermocouples mounted to the surface of the evaporator coil at the refrigerant inlet, outlet, and midpoint monitored the coil temperature to indicate the potential for frosting conditions. Power for the equipment was monitored for the entire unit including the compressor, fan, and pump all at once.

Cascade Engineering conditioned and stored tempered water in a large tank to be supplied to the water heater at the desired inlet temperature. A pump and a series of flow control valves in the inlet and outlet water piping control the water flow rate. A flow meter measures and reports the actual water flow. The data acquisition (DAQ) system collects all the measurements at three-second intervals and logs them to a file. In a post processing step, Ecotope merged the temperature log of the thermal chamber with the DAQ log file to create a complete dataset for analysis.

2.2.1 Test Equipment and Specifications

In alignment with the type of test conducted, Cascade Engineering carried out the testing at two different locations within its facility:

- Inside an ESPEC Model # EWSX499-30CA walk-in thermal chamber;
- In a large lab space kept at room-temperature conditions.

Various other measurements were collected as described previously, using equipment which is specified in Appendix B: Measurement Instrumentation List. This appendix provides a complete list of sensors, including others in addition to those mentioned here, plus their rated accuracies.

2.3 Simulation Approach and Development

The number of possible water draw profiles and DR events that could be used with a HPWH is far larger than many days, or even weeks, of testing in the laboratory could investigate. In order to obtain generalized estimates for how much energy can be stored or shifted, or what the performance impact on the HPWH would be due to a change in operation, Ecotope crafted a numerical simulation. From this, it can be determined what the effects of the DR schedule are on the delivery of hot water, the power usage, and the efficiency. The unique utility of the simulation is the ability to run situations that are identical except for the DR schedule. These can all be compared and contrasted with baseline simulations using no DR, which is a useful tool for estimating the impact DR would have. The results from a properly calibrated simulation are more generally applicable than lab tests, which are conducted over short periods of time at only a few specified temperatures.

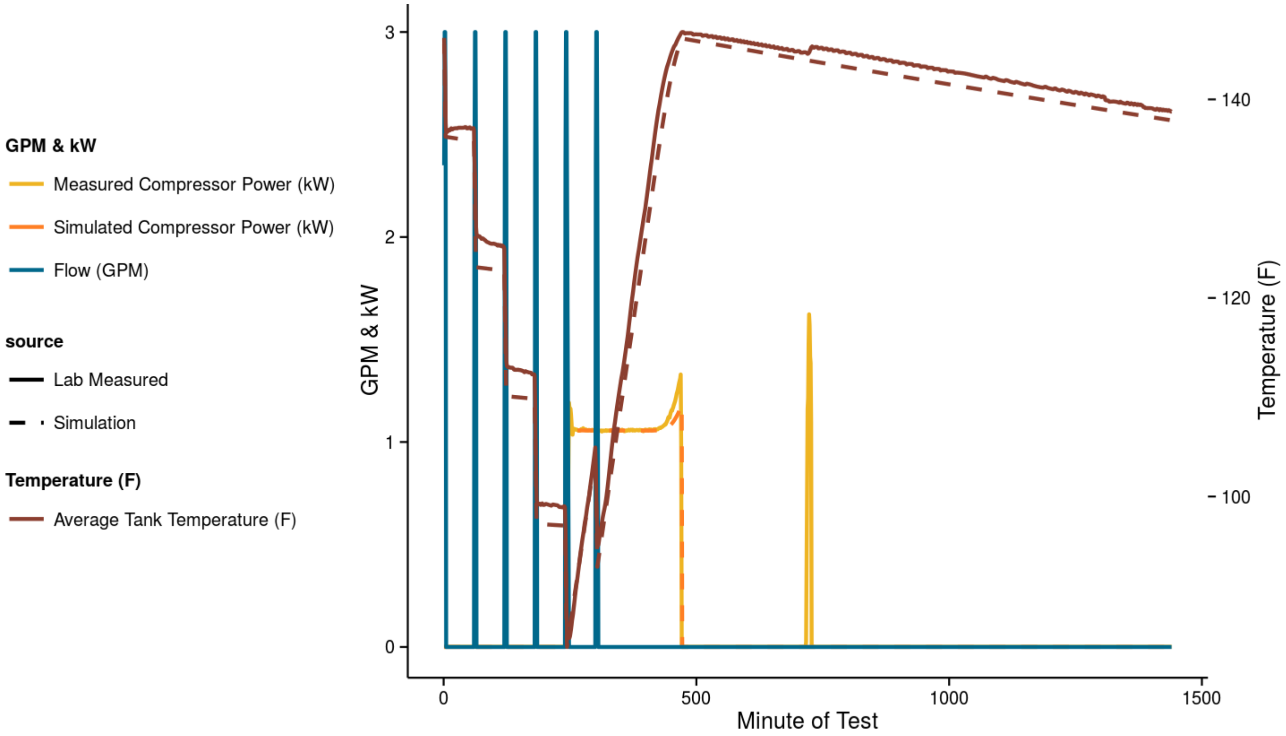
Ecotope designed the simulation to take ambient conditions, water flows, and a DR schedule to simulate the working of the Sanden HPWH. We used the simulation to explore oversupply mitigation, peak shifting, and general storage scenarios in Portland, OR and Spokane, WA climates with a wide range of hot water draw profiles. The results presented in Section 4 where made entirely possible by the simulation.

2.3.1 Water Heater Efficiency, Controls, and Calibration

Integral to the simulation is a model of how the much water the equipment can heat for a given set of ambient conditions. The COP mapping tests provide this data so that output capacity and input power can be determined as a function of ambient temperature. Further it is necessary to know when the water heater turns on. Previous studies showed the GAU has a single thermistor monitoring the tank temperature located approximately 1/3 of the water volume (29 gallons) from the top of the tank. When that thermistor senses a water temperature below 113°F (45°C), the unit turns on the compressor to begin heating. When the tank reaches the setpoint of 149°F, the heat pump switches off. The GES control is similar except that its single thermistor monitors the temperature at the half-height point.

Figure 10 demonstrates how well calibrated the simulation is to the lab test data. It illustrates both the agreement of the COP mapping and the controls. The lab test shown is the DOE Energy Factor test which has six 10.7 gallon draws spaced one hour apart followed by 18 hours of standby (total test time is 24 hours or 1440 minutes). In the figure, the measured data is in solid lines and the simulated data is in dashed lines. Overlapping lines indicates excellent calibration. The water draw events are the blue, vertical lines. During the fifth draw, the tank is cold enough to trigger the compressor (yellow line). It turns on at ~1.1kW to run for the next 3.5 hours. The input power is a function of ambient air and tank water temperature and the dashed gold line shows the simulated input power matches the measured power. Moreover, at the end of the heating cycle when the water temperature rises, so does the measured and modeled input power. The tank temperature, in brown, further demonstrates the veracity of the simulation. For a given input power, there is a given output capacity (or COP), which is evident by the slope of the average tank temperature versus time. If the simulated output capacity, and COP, were too large, the slope of the dashed line would be steeper than the solid line and vice versa if it were too small. The matching slopes indicates excellent agreement and gives us confidence that the simulation is calibrated to measured data and can be used to make accurate predictions about the equipment performance.

Figure 10. Measured and Modeled Draw Pattern Test – GAU 80 Gallon Tank



2.3.2 Integration with SEEM (a whole house simulation tool)

Ecotope has previously developed a numerical simulation of water heater performance to evaluate the conservation potential of HPWHs. The simulation is integrated with the SEEM residential energy use simulation to provide accurate and reliable estimates of heating, cooling, and DHW energy use. Given a draw schedule and climate as inputs, it simulates the energy use of a number of HPWH products. This provided the ideal platform to add a model for the Sanden water heaters. For use in the simulation, we added equipment-specific performance curves and control strategies. A standardized set of hot water draw patterns, based on field observations, was previously established and was used in all the simulations (Ecotope 2015).

To update the simulation for this project, we added the capability to set a demand response schedule. The schedule is specified minute-by-minute over an entire day and then repeated throughout the course of the simulation (a full year). Currently, as programmed, the schedule can either “allow” or “disallow” water heater operation. It does not have the third option, which is to “force on” the water in what might occur in a DEC event. Possible future work could add the third option and include a setpoint schedule so the tank temperature may also be ramped up and down. Likewise, future work would include fully customized DR schedules so they change day-by-day or even, minute-by-minute.

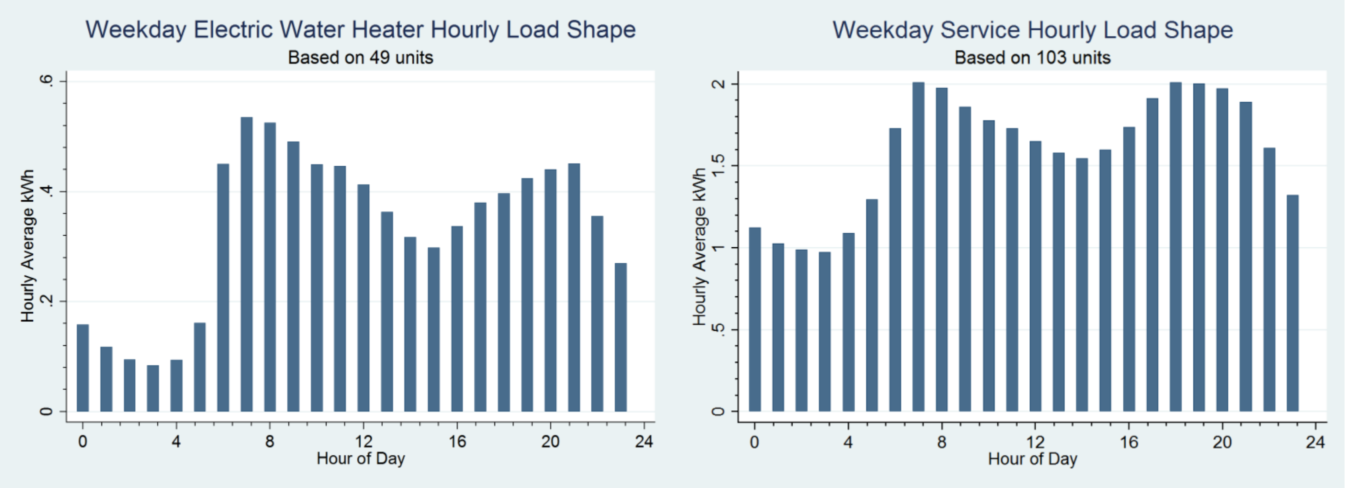
2.3.3 Demand Response Profiles and Schedules

The simulation creates the possibility to explore any combination of demand response profiles. For this project, we examine oversupply mitigation (a type of DEC event) and peak shifting (a type of INC event).

In the oversupply schedule, we run simulations with the water heater off from 6AM to midnight. The simulations will then show us how much hot water, from our standardized draw profiles, can be drawn from the tank without turning cold. Having the equipment off creates energy storage space inside the tank. Then, overnight, the equipment is allowed to reheat. We can compare the energy usage in the DR scenario to a baseline scenario, without a DR schedule, to see how it changed. We expect the energy to change because the water heater is running at different ambient air conditions which change its efficiency.

For the peak shifting scenario, we prevent the water heater from operating during peak electric load hours. Figure 11, using data from the Residential Baseline Stock Assessment Metering project, shows the overall, weekday residential morning peak is during the 7AM and 8AM hours. The electric resistance water heater use also peaks precisely at those times. In the evenings, the peaks are different with the overall load peaking in the 6PM, 7PM, and 8PM hours and the water heater peaking in the 8PM and 9PM hours. Demand response is a grid-level enterprise so we focus on the overall peaks for our scenario and prevent the water heater from operating from 7AM to 9AM (2 hours) and 6PM to 9PM (3 hours). The water heater may freely operate at any other times. Likely, this will cause the water heater to turn on immediately after the load curtailment period ends, however, different size storage tanks and different hot water use patterns could lead to different results.

Figure 11. Annual Average Electric Water Heater and House Service Hourly Load Shape



3 Findings: Lab Test Results

3.1 COP Mapping Results

The Sanden HPWHs heat water uses an uncommon topology: Cold water from the bottom of the tank is pumped to the gas cooler in the outdoor unit, heated to setpoint in a single pass, and then discharged at the top of the tank. One of the principal advantages to this is that the HPWH is always heating the coldest water in the tank, which is a more effective use of the heat exchanger. Since the gas cooler inlet water temperature remains constant throughout much of a heating cycle, standard COP tests, based on one recovery cycle, mostly provide information about a single point on the Inlet Water Temperature vs COP graph. This presents a challenge to gathering enough data to produce an accurate model. Nevertheless, more than one inlet water temperature is seen towards the end of a reheat cycle when the bottom of the tank finally gets hot. This time period provides the opportunity to map COPs at the higher inlet water temperatures. For several tests, the water transfer lines to and from the compressor unit had their temperatures monitored, a fact which enabled precise COP measurements.

Figure 12 and Figure 13 show the test results of all the COP tests from the current, and previous, projects which give the complete map. Each figure summarizes the COP mapping results for each piece of equipment. Testing was conducted at up to five ambient air conditions (given in the figure legends). The warmer ambient temperatures gave the expected higher COP. In fact, the COP doubles when moving from the extreme ends of the test spectrum: 17°F to 95°F. Moreover, the mapping highlights another dimension of the COP dependence: that of the water temperature entering the gas cooler. The hotter the inlet water, the lower the COP. For example, the split system GAU graph shows that at 35°F ambient air (green points), the COP is three if the water being heated enters the gas cooler at 90°F. If that entering water temperature is 130°F, the COP drops to 2 for the same ambient air temperature. This dependency is a characteristic of all HPWHs regardless of refrigerant type. Last, each of the figures is truncated at the low-end of the water temperature because the testing showed the COP to be nearly constant for water temperatures below that point.

Figure 12. COP Map for Sanden GES 40-gallon Tank

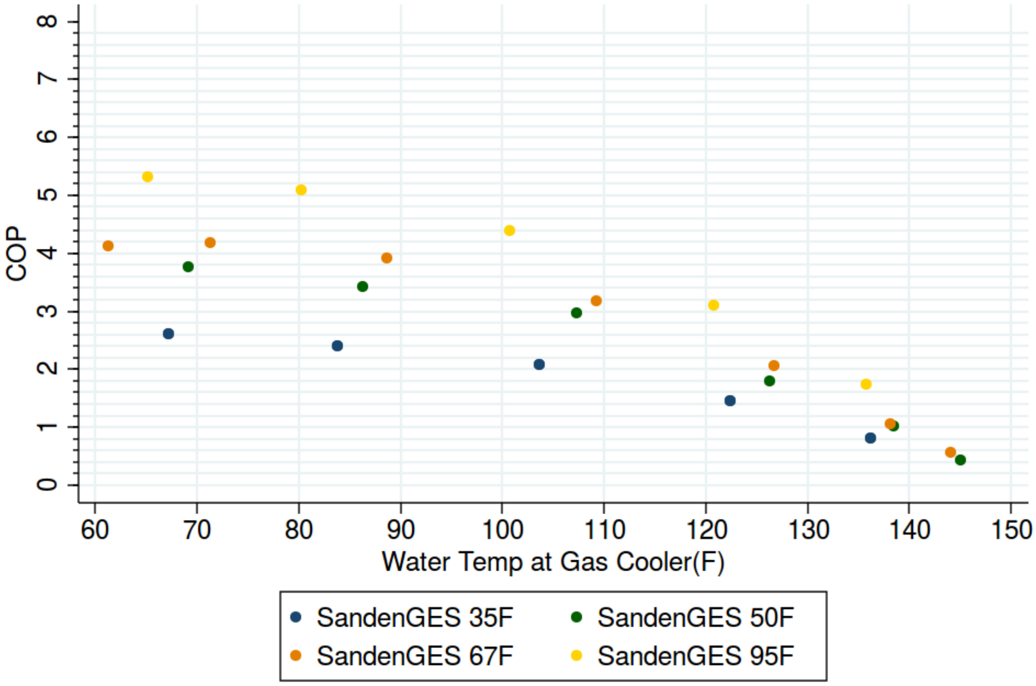
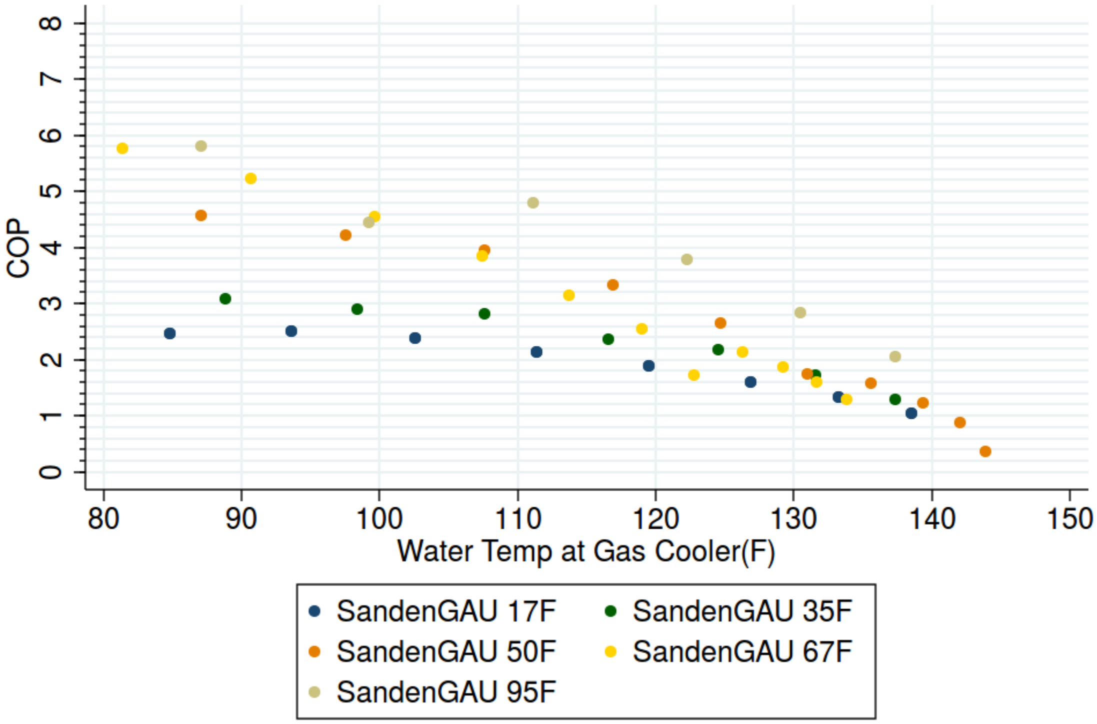


Figure 13. COP Map for Sanden GAU 80-gallon Tank



3.2 Demand Response Profiles and Hot Water Draw Pattern Tests

The demand response profile, imposed on the hot water draw pattern, test results are shown in the following series of graphs. The DR profiles combine oversupply mitigation and a peak-shifting INC event in to a single day of testing. The HPWH is allowed to run from midnight to 6AM and noon to 2PM only. The overnight run allows for oversupply mitigation and the mid-day run allows the water heater to operate, if needed, at a lower-load time.

Each unit has tests at three different ambient temperatures: 35 °F, 50 °F, and 67 °F. Both the DR pattern and draw profile were the same across all tests. The 40 gallon Sanden GES is the first set of three graphs followed by the 80 gallon Sanden GAU. In each graph, the blue, vertical lines are the water draw events, the orange line is the HPWH power draw, the blue dots are the outlet water temperatures, the thick, purple line is the average tank temperature, and the thin, purple lines are the six thermocouples inside the tank. The shaded, orange area on the graphs indicates when the equipment is allowed to run.

The GES 40 gallon unit is remarkably consistent across all three of the tests. The equipment provides water through the morning use period, using about 40% of all the hot water in the tank. When it is allowed to recover at noon, it does so immediately. For the afternoon/evening period, over 55% of the tank is used and, again, when allowed at midnight, the tank recovers immediately. In all cases, the tank provides enough hot water to meet the demand. Given how much water is used in the profile, the tank could conceivably meet the entire daily demand without operating mid-day but that sets the upper limit on the hot water supply. The only noticeable difference between the three tests is the power draw of the heat pump which is higher at lower temperatures.

Figure 14. GES 40 Gallon Tank DR Profile Test at 35°F

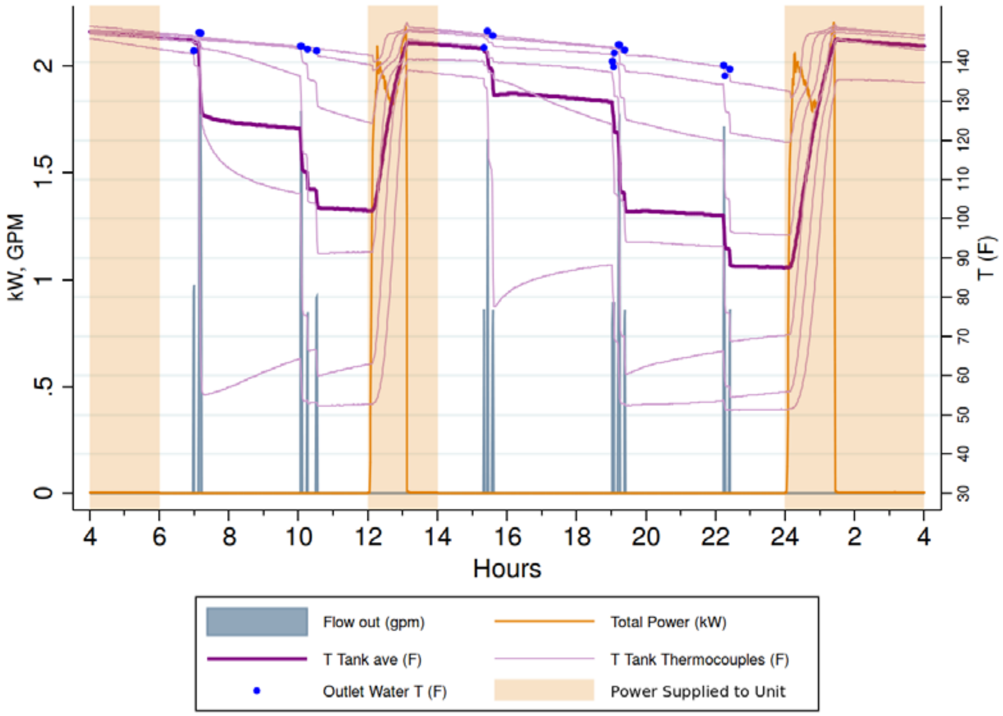


Figure 15. GES 40 Gallon Tank DR Profile Test at 50°F

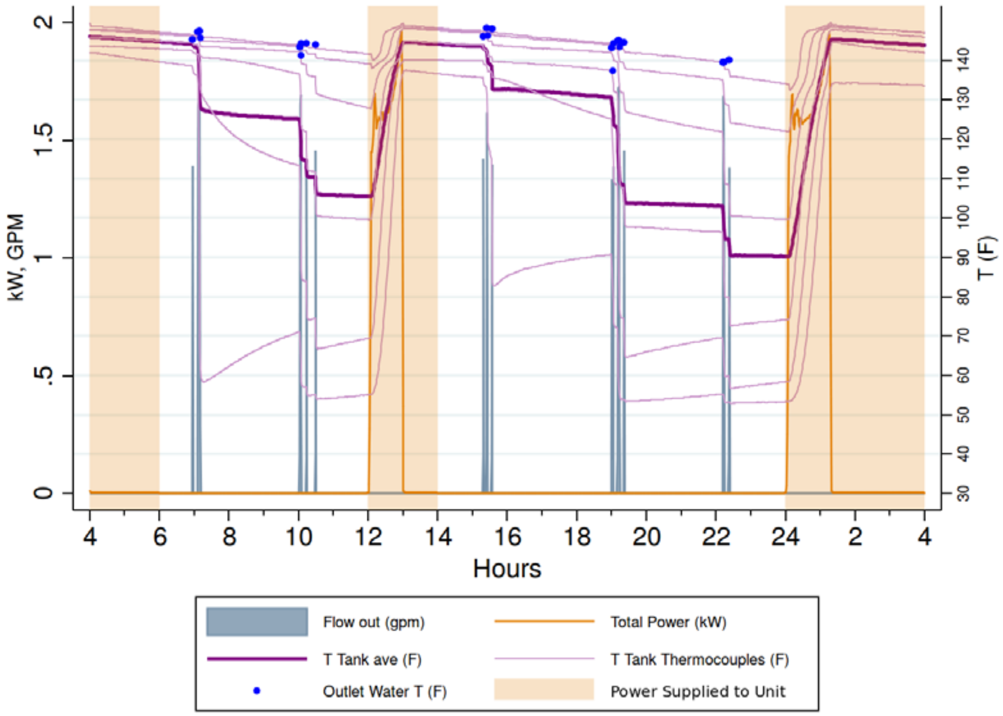
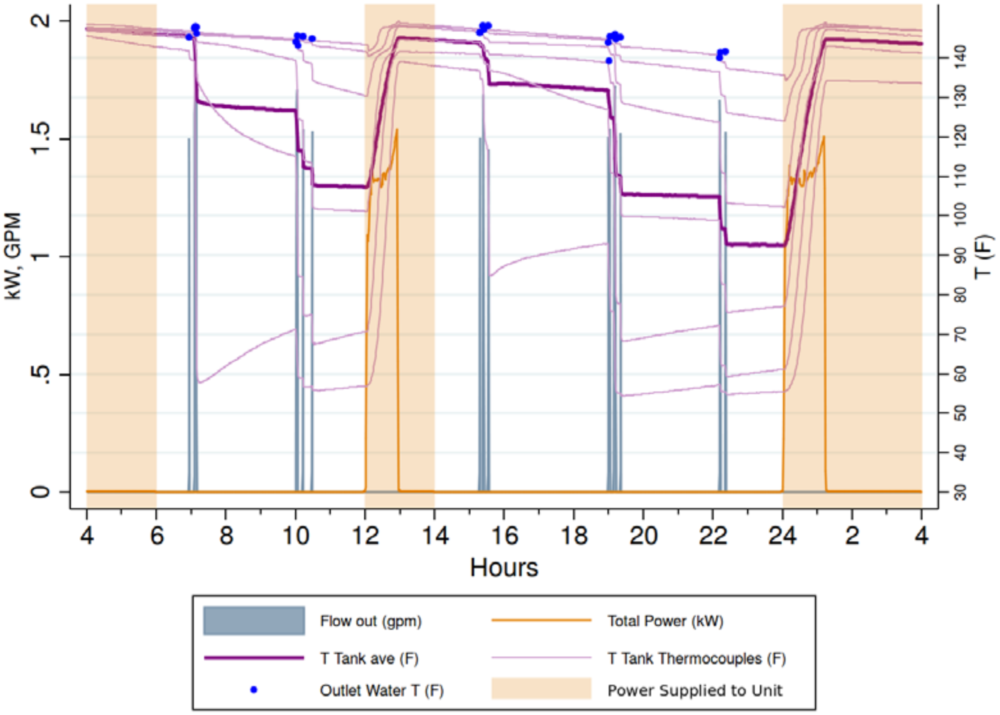


Figure 16. GES 40 Gallon Tank DR Profile Test at 67.5°F



In contrast to the GES tests, the GAU behaves differently in every test. In the 35°F test, the equipment runs only during the mid-day period. In the 50°F scenario, it runs both during the mid-day and overnight periods, and for the 67.5°F scenario, it runs only during the overnight period. The difference in operation is baffling with even a close examination of the tank temperature profiles unable to reveal any rationale. The equipment installation manual suggests that, if the electric supply has been disabled to the unit, once restored, the heat pump will engage regardless of tank temperature. The GES behaves as such, but the temperatures in that tank are also always cold enough to warrant operation. The GAU heat pump sometimes engages immediately after electricity is restored to the unit, sometimes it waits 10+ minutes before operating and, occasionally, doesn't run at all. If the GAU were operating purely on water temperature measurements in these tests, the equipment would not turn on. To do so, water approximately 1/3 of the height from the top of the tank (between the fourth and fifth thermocouples) must be below 113°F (45°C).

Although somewhat consternating, the different scenarios are fortuitous because they demonstrate all the ways in which water can be left unheated during, and at the end of, a day. The unheated water is the available energy storage space for oversupply mitigation. Last, like the GES tests, the other noticeable difference is the equipment power consumption as the ambient conditions change.

Figure 17. GAU 80 Gallon Tank DR Profile Test at 35°F

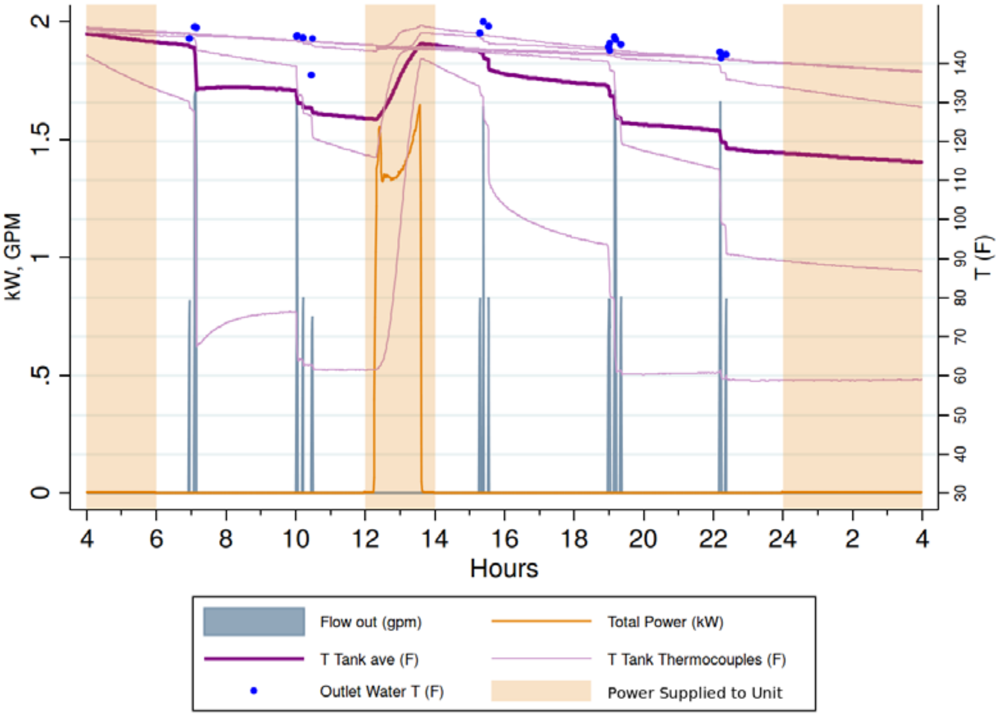


Figure 18. GAU 80 Gallon Tank DR Profile Test at 50°F

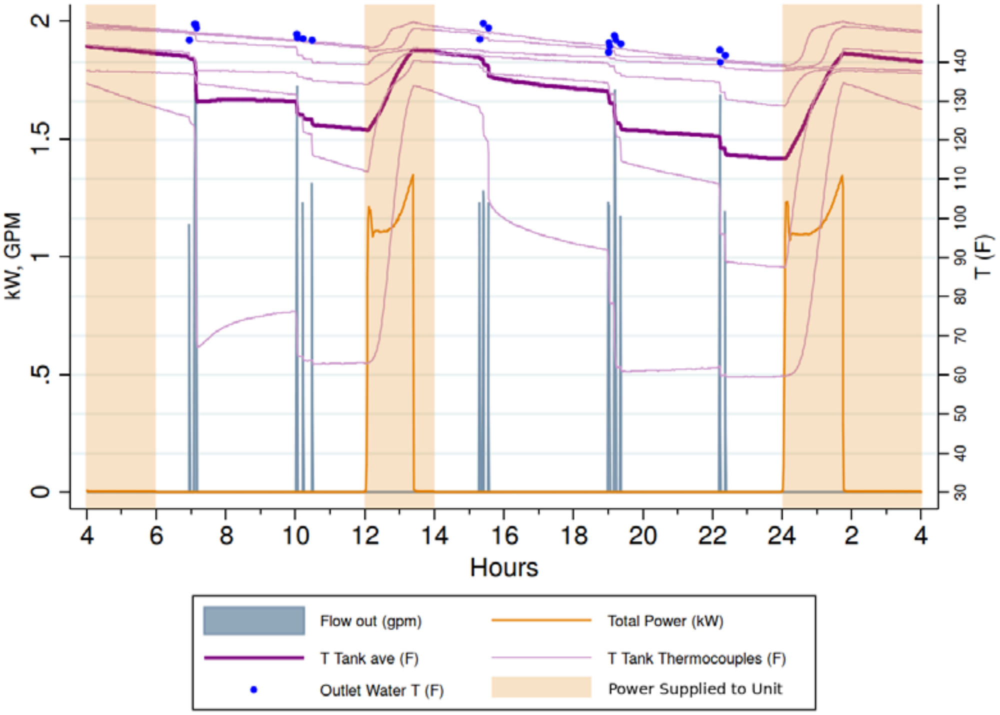
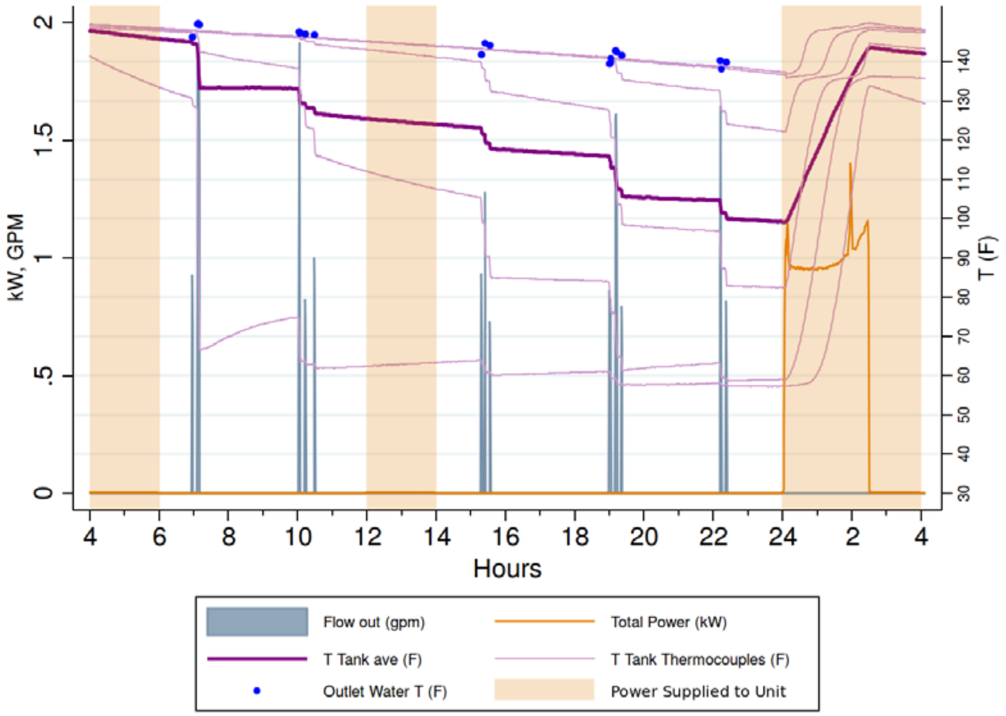


Figure 19. GAU 80 Gallon Tank DR Profile Test at 67.5°F



3.2.1 Hot Water Availability

A major concern of DR programs is that the hot water supply will be exhausted. Despite the DR profile preventing the unit from heating water, the units never returned cold water in the lab tests. Table 2 lists the minimum and mean delivered water temperatures for the lab tests. None of the minimum temperatures drop below 136 °F. The Sanden units have a fixed setpoint of 149 °F, so this represents a 13 F drop over the course of the day. The temperature decreases because of heat loss through the storage tank. Clearly a lack of hot water is not a concern with the amount of water drawn per day tested, which is the average amount for a three person home.

Table 2: Minimum and Mean Outlet Temperatures

Ambient Temperature (F)	GAU - 80 gallon		GES - 40 gallon	
	Minimum Outlet Temperature (F)	Mean Outlet Temperature (F)	Minimum Outlet Temperature (F)	Mean Outlet Temperature (F)
35	136.9	145.9	136.4	143.4
50	139.8	145.9	137.3	148.3
67	138.2	144.1	139.3	148.3

3.2.2 Measured Energy Use, Efficiency, and Storage Capacity

There are a number of useful quantities that can be extracted from demand response and hot water draw pattern tests. Summarized in Table 3, they will be discussed in more detail in the following subsections. Briefly, the terms in the table are defined as follows:

- Recovery Efficiency (RE) is the ratio of hot water energy output to electrical input energy for a discreet draw and recovery event (this can be thought of as the heat pump system efficiency). The RE in Table 3 was calculated for the first recovery event in the tests.
- Available Heat Storage Capacity at End of Day (Qtankstor) is defined as the difference in average tank temperature, at the end of the test, from the setpoint multiplied by the mass and heat capacity of the water in the tank. Qtankstor = (Tsetpoint – Tave) * M_{water} *Cp_{water}. Tsetpoint is always 149°F with this equipment.
- Available Electrical Storage Capacity (Qelecstor) is the amount of energy it would take the heat pump to reheat all the water to setpoint. For resistance heating elements, this is always equal to Qtankstor. For heat pumps it is: Qelecstor = Qtankstor/RE.
- Total Electrical Energy used in the test is simply the measured energy used by the heat pump, Qtot.
- Total Delivered Hot Water Energy is the energy content in the hot water Qdel = (Tout-Tin)*Mout*Cp_{water}.
- System COP is the efficiency over the entire test incorporating the effects of tank standby losses. As such, the system COP is necessarily lower than the Recovery Efficiency. Further, the system COP is only meaningfully defined if the tank temperatures at the start and end of the test period are the same. Since not all tests concluded this way, we make an adjustment by adding Qelecstor to Qtot. COPsys = Qdel / (Qelecstor + Qtot).

Table 3. Draw Profile and DR Test Summary Results

Ambient T (F)	Recovery Efficiency	Available Heat Storage Capacity at end of Day (kJ)	Available Electric Capacity at end of Day (kWh)	Total Electric Energy used in Test (kWh)	Total Delivered Hot Water Energy (kJ)	System COP	Average Power when Running (kW)
	RE	**Qtankstor**	**Qelecstor**	**Qtot**	**Qdel**	**COPsys**	**-**
GAU 80 Gallon Tank							
35	2.1	23,365	3.09	1.90[*]	29,062	1.6	1.4
50	2.68	24,593	2.55	3.53	29,801	2.15	1.1
67	3.68	36,427	2.75	2.47	28,939	2.88	1
GES 40 Gallon Tank							
35	2.13	21,419	2.79	4.55	31,090	1.8	1.8
50	2.48	20,489	2.29	3.61	29,185	2.19	1.6
67	3.03	19,659	1.8	2.82	29,577	2.8	1.3

3.2.2.1 Measured Energy Use and Efficiency

As seen in the COP mapping, the measured electrical energy use is expected to increase as the ambient temperature decreases. The energy increase is mainly caused by the unit increasing power to the compressor at cold ambient temperature in order to keep a constant amount of output capacity. This is clearly reflected in the electrical energy usage of the 40 gallon unit; the energy used increases from 2.82 kWh to 4.55 kWh as the temperature decreases from 67 °F to 35 °F. Magnitudes for the 80 gallon unit are similar, excluding the 35 °F ambient test. This test uses only 1.9 kWh because the tank did not recover its temperature to setpoint by the end of the test, leaving a substantial amount of cold water, and “saving” a significant amount of energy on that day. In

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[*] Unlike the other tests, for the 35°F test, the GAU 80 gallon tank did not recover its temperature to setpoint by the end of the test whereby “saving” energy. This test had the largest adjustment applied to its system COP calculation to create a fair comparison across all tests. See section 3.2.2.1.

a longer test, or a real installation, the unit would have eventually reached the point at which it would engage the compressor, heating the water, but the timing of the test, in this case, did not permit it.

We expect a similar effect in the trend of the System COP, which is the coefficient of performance of the entire system over the whole test period, taking into account tank heat (UA) losses. This is clearly observed, with warmer temperatures having increased COP. In fact, the System COP between the two models is quite similar, well within expected errors, with the exception of the 35 °F case. This minor discrepancy can be explained by the occurrence explained in the previous paragraph, namely that the water was not heated all the way by the end of the test. Although the system COP calculation adjusts for that, the adjustment is inevitably only an approximation to measurement. Overall, there is also good agreement with efficiency measures from previous work (Larson 2013a and 2013b).

3.2.2.2 Measured Energy Storage Capacity

Knowing how much energy storage space is available in the water heater at the end of a day is important for implementing oversupply mitigation. The heat storage space is the amount of energy required to heat the tank from its current temperature to the setpoint. In the graphs (Figure 14 through Figure 19), this is the average temperature at hour 24 (corresponding to midnight). Up to that point, the water heater has been off for ten hours or more. From Table 3, we see the heat storage space ranges from 20,000kJ to 36,000kJ depending on tank size and temperature. In a tank with resistance heat, that is also equal to the electric storage space (or energy shift) available. With a heat pump, the electric storage is less because the heat pump operates with efficiency above 100%. The amount of electric storage, however, depends greatly on the ambient temperature. At 67 °F, the tank could soak up an extra 1.8 kWh from the grid but at 35 °F, a lower efficiency condition, the space is 2.8 kWh. The variable speed compressor runs faster or slower to maintain output capacity, which results in changing levels of power consumption in concert with COP changes. Not only does the energy shift change as a function of outdoor temperature but so does the power.

An even starker example of the temperature dependence is with the GAU 80 gallon tank and the 35°F and 67°F temperatures. In the 67°F case, the heat pump did not run in the middle of the day leaving more cold water in the tank than any other test. Despite it having heated 50% more water in the comparable test, the actual electric energy input capacity is less than the 35°F case due to the increased COP at 67°F.

Table 2 also shows a key point: on a continuing basis, the size of the water heater storage tank is irrelevant to the amount of available energy storage. The primary determinant of the amount of energy that can be absorbed in an oversupply scenario is how much water was used the day before.[†] When that hot water is used, and the incoming cold is not heated, there is useful storage space available. Excluding the 67°F test for the big tank, the amount of storage available at the end of the day is largely similar between the tank sizes. One reason the 80 gallon tank has more available is because it loses more heat in standby. Once oversupply mitigation is started and continues day after day, the only way to increase end of day storage capacity is to increase the hot water use. Consequently, houses with higher than average hot water use are actually better candidates to provide this service to the utility.

3.3 Circulation Line Temperatures

The Sanden split-system water heater has a pair of lines which transfer water from the tank to the compressor and back. Since the compressor unit is intended to be located outside, there is a possibility that the water in these lines could freeze given cold weather and a long period with no water flowing through the lines. This is especially acute for DR applications if the DR schedule is such that it prevents water heater operation for long periods of the day. In the lab, as in typical field installations, the lines were insulated with approximately R-5 foam. The temperature of these transfer lines was then monitored during the operation of the unit in order to investigate the possibility of freezing. It was quickly seen from Figure 20 that the transfer line which brings cold water from the tank to the compressor would be the first line to freeze. The hot transfer line starts and stays

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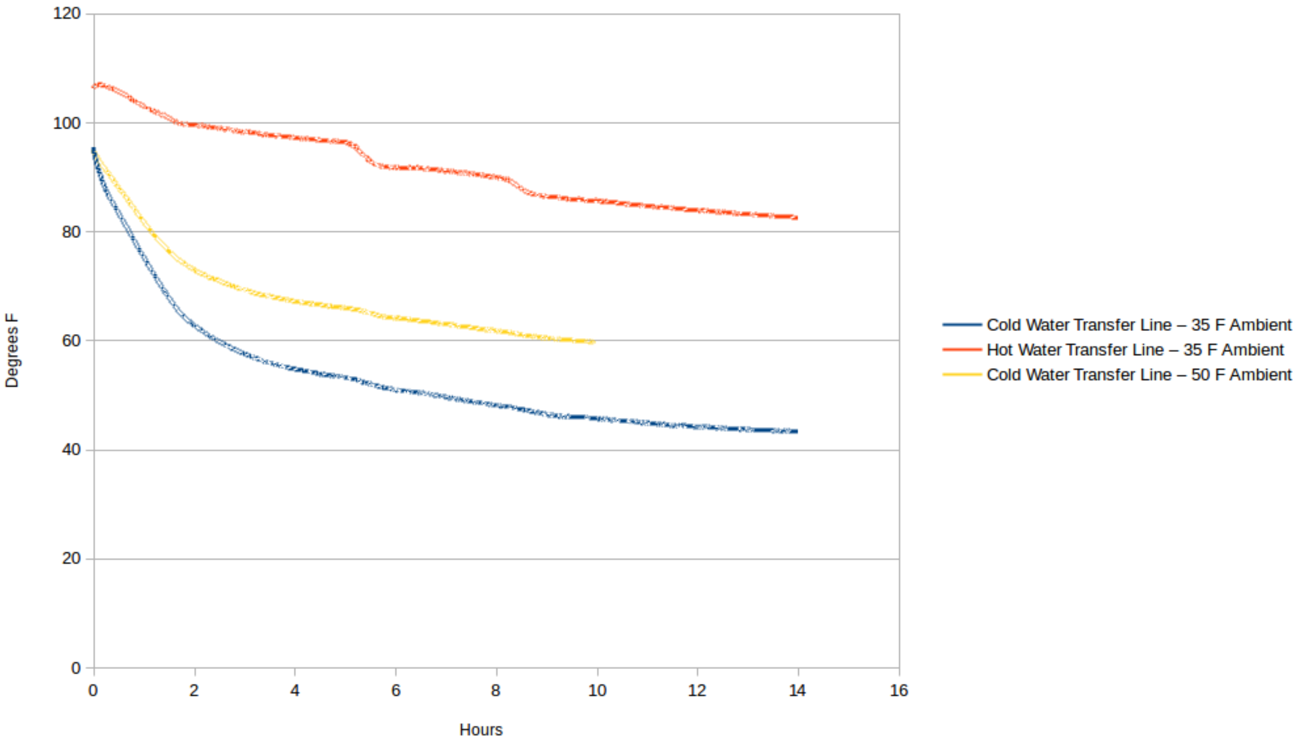
[†] Tank heat losses are a secondary determinant of storage space roughly ranging from 1-1.5kWh of heat loss which corresponds with 0.3-0.5kWh of electric storage.

warmer. Figure 20 shows the temperature profile of the transfer lines, with the 0 hour mark starting just after compressor cut-off. The hot line does not start at the setpoint, 149 °F, due to the fact that the compressor ramps down for several minutes before cutting off completely. Since Figure 20 begins after complete compressor cutoff, this ramp down is not shown, and the hot line starts around 110 °F. The irregularities are due to draws which occurred during the test, not flows through the transfer lines.

Figure 20. GAU Split-System Water Transfer Line Temperature Profile



As seen in Figure 20, the temperature of the cold transfer line drops quickly for the first three hours after compressor cut-off. This drop is not fitted well by an exponential function, most likely due to various heat exchange effects like conduction along the transfer line and convection in and around the heat exchanger. When the data is modified by subtracting the ambient temperature, we see that, after the initial drop, the temperatures end up approximately the same amount above the ambient and follow an exponential curve with similar time constants. Figure 21 shows this data along with the exponential fits. Using this exponential fit, estimates can be made about how long the transfer line could be stagnant before freezing at various ambient temperatures. Table 4 has these estimates; among the assumptions made are that “freezing” is the point at which the temperature of the line reaches 32 °F, and that the temperature will reach 25 °F above ambient in 3.3 hours, as was seen in the two measured cases. Starting from that point, the exponential fit was used to calculate how quickly the temperature will drop.

Figure 21. Cold Water Line Temperature Decay, Adjusted for Ambient

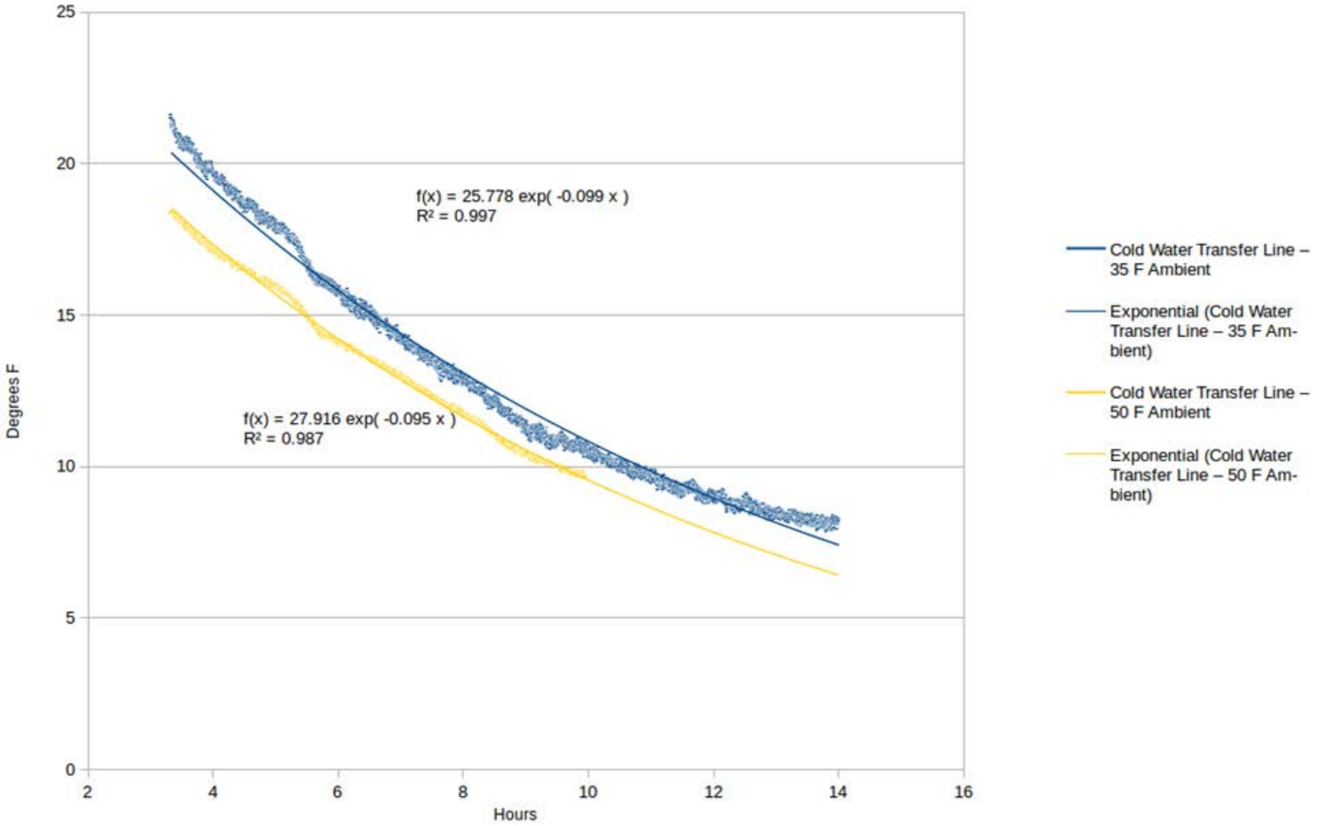


Table 4. Estimated times for stagnant water to freeze under several ambient conditions

Ambient Temperature (F)	Time to Freeze (hours)
30	29.1
25	16.4
20	11
15	7.5
10	4.9

The values in Table 4, while only estimates, nevertheless provide a good indicator of the risk level for various temperatures. At 10 °F, the transfer line could freeze in less than five hours, which is not an uncommon interval between compressor activations. There is less danger in regular operation down to 20 °F where the time is predicted to be eleven hours; however, power outage situations could cause trouble with freezing of the lines or evaporator. This is clearly an issue that would need to be addressed for installations where very cold temperatures are frequent and there are prolonged off periods. A simple remedy is to use the water circulation pump to periodically move hot water through the lines. A control could monitor the outdoor temperature and activate the circulation pump to move a gallon or less of hot water through the lines. This would only be needed daily, assuming no water heater operation, for temperatures near 30°F and more frequently for colder temperatures.

4 Findings: Simulation Results

As discussed in the methods section, a simulation creates the possibility to explore any combination of demand response profiles and hot water draw patterns. This leverages the lab measurements, allowing us do more than make conclusions about the limited set of lab tests. To answer the research questions posed in section 1.2 and demonstrate the simulation capabilities, we examined oversupply mitigation and peak shifting scenarios, a type of INC event. For the oversupply scenario, the water heater is allowed to run, as needed by its own controller, from midnight to 6AM and disallowed to operate at any other time. For the peak shifting scenario, the water heater is disallowed from operating between 7AM-9AM and 6PM-9PM and is allowed to run, as needed, at any other time. Other scenarios can be explored with the simulation. Ecotope selected the ones here to be similar to the lab tests and adhere more closely to the current equipment's capabilities.

Both scenarios were simulated in the Portland, OR and Spokane, WA to explore differences in climate which could impact the operating efficiency. Further, and with greater variability than climate, the simulations explore different hot water draw profiles. Previous research by Ecotope on hot water draw patterns created typical profiles for 1, 2, 3, 4, and 5+ person households averaging 23, 34, 46, 57, and 72 gallons per day respectively (Ecotope 2015). Moreover, each profile was designed with seven unique days of draw events with each day containing a different total flow to encapsulate some of the variability seen in actual houses. Consequently, there are thirty-five unique days that the simulation explores. Nevertheless, hot water draw patterns are highly variable – even more so than what is captured with thirty-five days. Future projects should consider the full range of draws found in houses. The current work starts with the typical days as a way to introduce the simulation and simplify the interpretation of outputs.

The simulation results provide a host of useful findings. First, they show the water heater operation at sub-daily time intervals so specific events can be analyzed such as under what days, and conditions, the tank runs out of hot water or how much hot water is left in the tank at the end of day. Next, the simulations, run with multiple inputs, draw patterns, and taken over an entire year, can show, in aggregate, DR impacts on performance. These include shifts in energy use, efficiency, and hot water availability as a function of household size. The changes are primarily driven by differences in operating hours and, hence, outdoor temperatures. Then, the simulation also shows dynamic energy storage capacity and power reduction potentials. Last, the current simulation suggests what control capabilities would be required of the HPWH to expand its usefulness.

4.1 Simulation Outputs

As is inherently the case with numerical simulations, any calculated values can be output, graphed, and analyzed. Throughout the following sections, the reader is encouraged to remember these are simulated 'data' as opposed to measured data. The output is a direct product of input choices and assumptions. Figure 22 through Figure 26 provide a detailed look at the simulation workings for the selected DR scenarios.

Starting with the output at a basic, hourly level, Figure 22 graphs a typical oversupply event using the 3 person draw pattern in Spokane and the 80 gallon GAU tank. Both the baseline (no-DR) and DR case are plotted. The shaded area indicates when the HPWH is allowed to operate. The lowest plot in the tryptic shows the HPWH power draw. In the base case, the water heater turns on at 3PM to run until 7PM (blue circles). In the DR case, it is not permitted to run during that time so shifts operation to the overnight period (blue triangles). The top of the triptych shows both outlet water and tank average temperature while the middle graph shows the number of gallons of hot water used per hour which is the same between the baseline and DR case.

Figure 23 is similar to Figure 22 but shows an example of a peak shifting event. The shaded area again indicates when the water heater is allowed to run. In the base case, the HPWH normally would engage at 6AM running through 9AM. In the DR case, the HPWH engages shortly before the 7AM hour but is forced off by the DR profile (a so-called shed event). It remains off until 9AM when it is allowed to engage again.

Figure 22. Simulated Output for an Oversupply Event – 3 Person Draw Pattern in Spokane, Sanden GAU

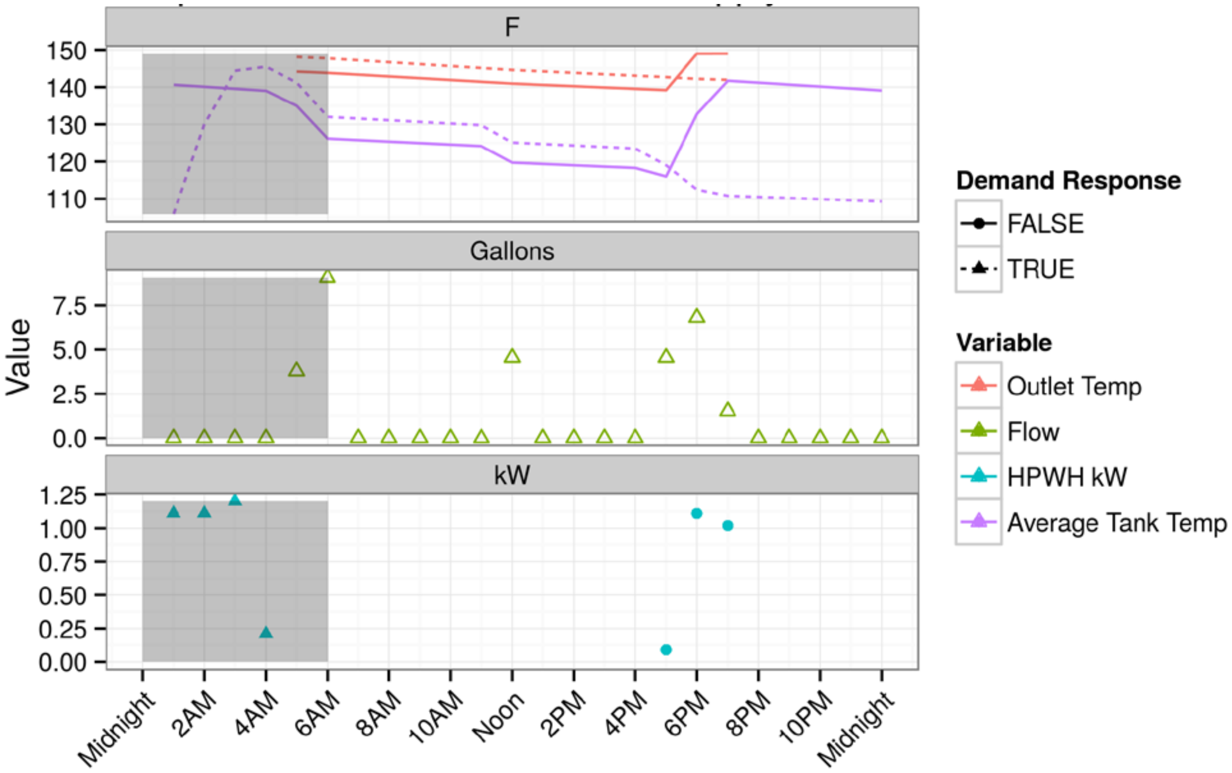
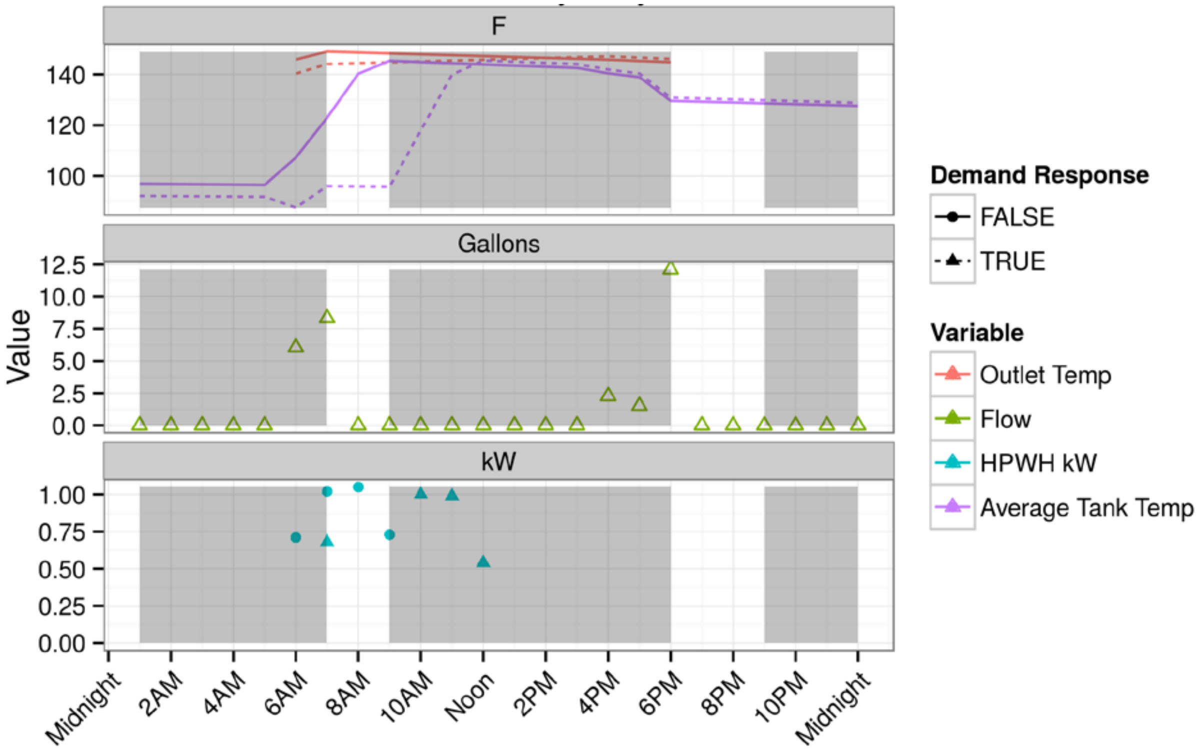


Figure 23. Simulated Output for a Peak Shifting Event – 3 Person Draw Pattern in Portland, Sanden GAU



When using water heaters to provide a demand response service, the utmost concern is to make sure the hot water needs of the occupants are known and met as expected. In other words, if the occupant would normally have access to hot water, imposing a DR schedule that changes the availability is likely not desired. The simulation outputs show hot water outlet temperature and can determine when DR schedules may limit the ability of the water heater to meet demand. Subsequently, the simulation can be used as a tool to refine either the DR schedules or the water heater controls.

Figure 24 and Figure 25 show the hot water temperature at each flow event for every day of the simulated year in the oversupply scenario. They are for the Spokane climate with the 80-gallon GAU tank with 3-person and 4-person households respectively. Each day is represented by a line in the graph which connects points marking the delivered water temperature. In the 3-person base case (Figure 24, right hand side), the outlet water temperature (before tempering) is always available between 139°F and 149°F. This shows the water heater operating as it normally would. In the DR case, the simulation predicts the outlet water temperatures will drop during the day as the tank cools slightly and that sometimes the temperature falls to below 120°F. In any event, it is always useable in the 3-person draw profiles considered. In contrast, Figure 25 shows that under the 4 person draw profile, there are multiple days where the available hot water temperature drops below 105°F (notice y-axis scale change from previous figure). In these cases, due to the imposed DR schedule, the water heater is not meeting the occupants' hot water needs. The 5-person draw patterns show even more such days. The results show a different DR strategy is needed for those days.

Figure 24. Simulated Outlet Temperature – Oversupply Event, 3-Person Draw in Spokane, Sanden GAU

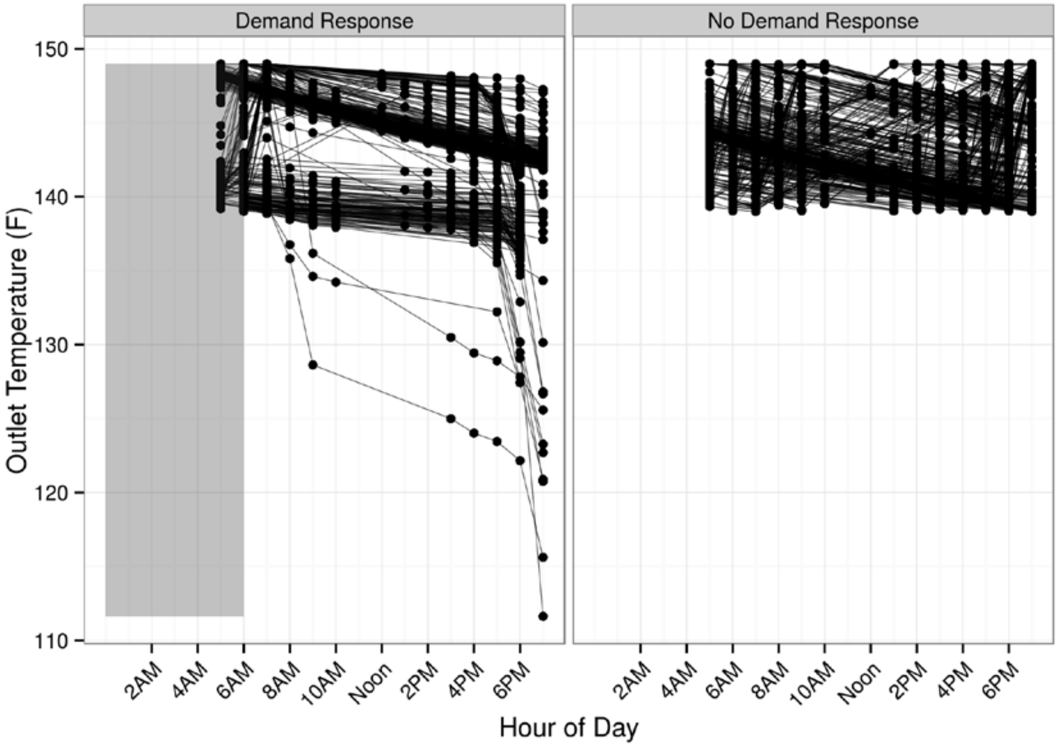
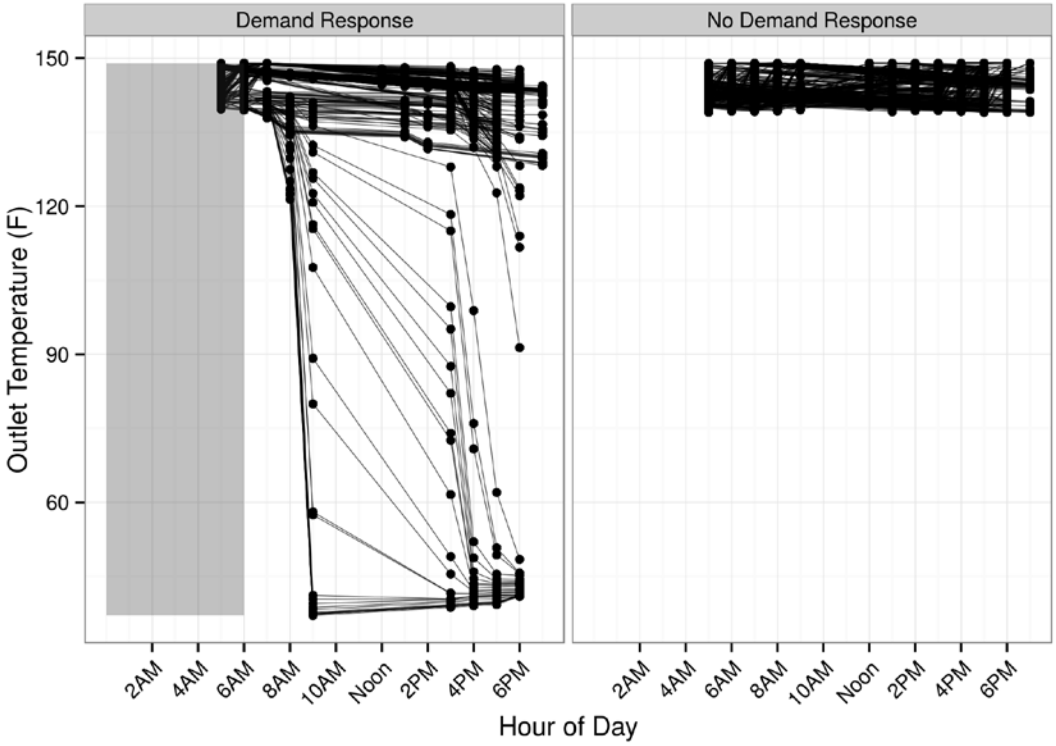
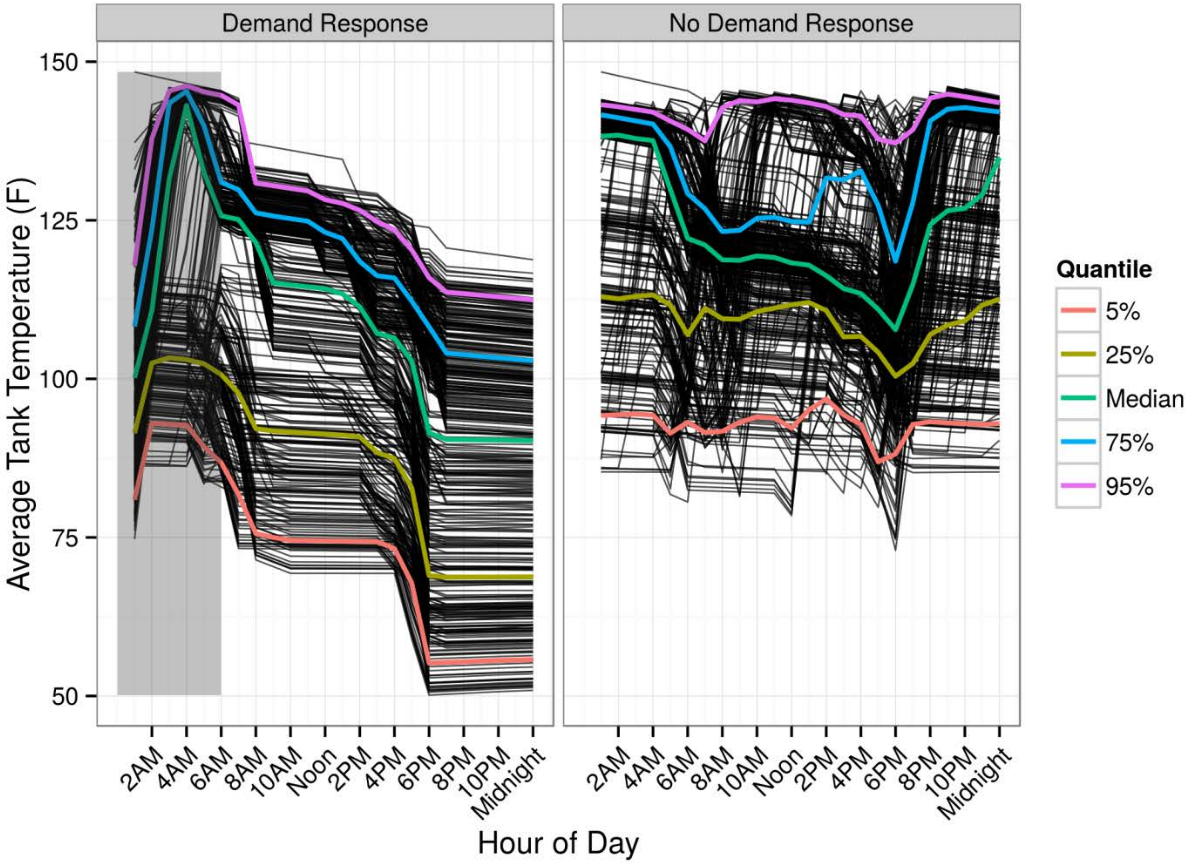


Figure 25. Simulated Outlet Temperature – Oversupply Event, 4-Person Draw in Spokane, Sanden GAU



The simulation necessarily calculates the average tank temperature over every minute of the year. In fact, it calculates the temperature at ninety-six different tank heights. Figure 26 plots the average hourly tank temperature for each day of the year (each is a single black line) for the 3-person draw pattern in Spokane. Draw events are indicated by a rapid decrease in tank temperature. The colored lines indicate quantile distributions of temperatures. There is a range of average tank temperatures due to three causes: the seven unique days of draw patterns, the dead band in the water heater control, and the changing inlet water temperature from the simulation. Also note that there are no water draws after 7PM in these patterns. Further, the tank temperature doesn't exclusively indicate the hot water availability because the tank is highly stratified. There is almost always some useable hot water at the top of the tank even though most of the tank is cold. See the corresponding Figure 24 for the hot water availability.

Figure 26. Average Tank Temperature during Oversupply Scenario for 3-person Draw Profile in Spokane



Comparing the DR to no-DR case reveals the expected results. In the no-DR case, the water heater operates at will, maintaining a generally stable tank temperature. For the DR case, starting at 6AM, the tank gets progressively colder until midnight when it is allowed to operate. In most of the cases, the tank is sufficiently cold at midnight to warrant immediate operation. In comparing the median tank temperatures, it is also clear in the DR case, the tank sits at an overall lower temperature which, advantageously, reduces energy lost in standby.

4.2 DR Pattern Impacts on Performance

In any DR scenario, the HPWH is asked to run at times it wouldn't choose. under its default controls. The HPWH efficiency depends strongly on the ambient temperature. When the operation shifts in time, the ambient conditions change and so does the equipment efficiency. The strongest effects will be for the largest changes in operation. Accordingly, this results section focuses on the oversupply scenario where the water heater is prevented from running during the daytime hours and shifted exclusively to nighttime operation. At night, outdoor air temperatures are colder so one would expect a decrease in system efficiency.

4.2.1 Efficiency

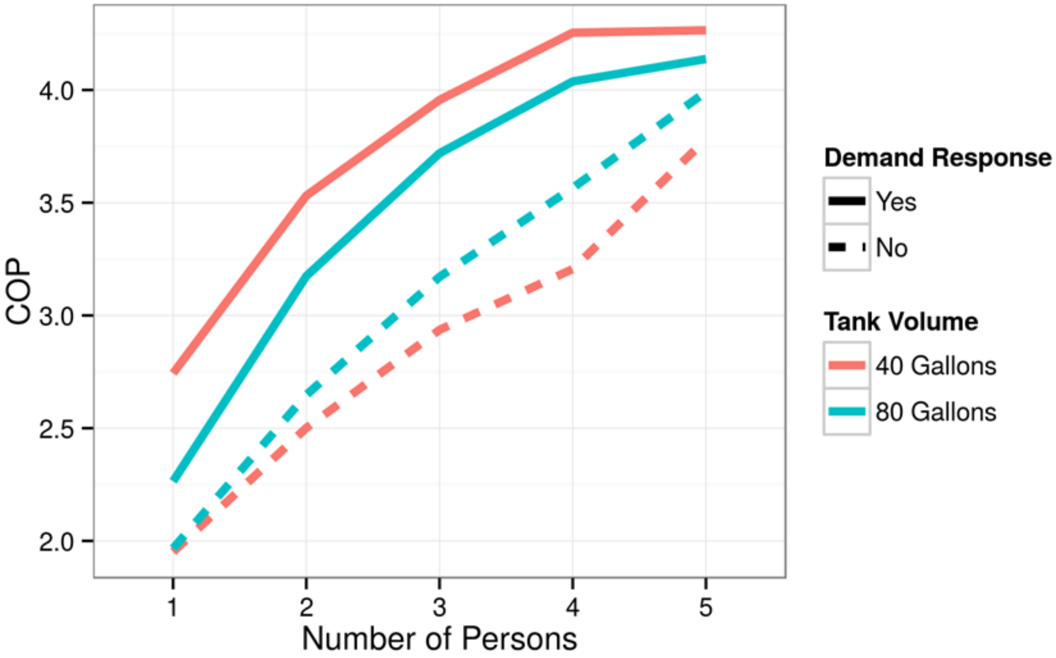
The annual system COP is defined as the energy content of the total water used divided by total energy input. Because the tanks lose heat to the surroundings, annual system COPs are always less than the COP when just the heat pump is running. Figure 27 plots the average, annual COP for the oversupply scenario in Portland for all draw patterns. The baseline is dashed, the DR case in solid lines, the 40 gallon tank in red, and the 80 gallon tank in blue. Strikingly, the DR case has higher overall efficiencies for this scenario than the base case. The DR profile prevents the water heater from operating most of the day, keeping the average tank temperature lower, and significantly reducing standby energy losses. Overall, this amounts to up to several hundred kWhs less loss depending on the household size. The lower losses even overcome the reductions in operating efficiency caused by forcing the HPWH to operate at colder, nighttime temperatures.

Of further note are the seemingly low COPs for the lower occupancy households. This result is not unique to the Sanden HPWHs but rather applies to all storage tank water heaters. The lower occupancies use far less water so much of the energy is spent heating the tank and then lost to the surroundings without ever being used by the occupant. Resistance heat tanks will have a COP of 0.8 or lower (Ecotope 2015). Another reason the COPs are lower with fewer people is that the tank conducts relative more standby recoveries, with much warmer water in the tank. Section 3.1 described how sensitive the COP was to the water temperature.

In the peak shifting scenario (not shown), the change in COP is small but, again, the DR case is slightly more efficient. This is true likely because the DR profile delays HPWH operation slightly, thereby decreasing standby losses and increasing COP when the unit runs.

The results further imply that up to the point of barely missing the hot water requested, storage water heaters could benefit from reduced temperatures. Moreover, the simulation shows where that critical point is.

Figure 27. System Annual COP in Oversupply vs Number of Occupants – Portland Climate

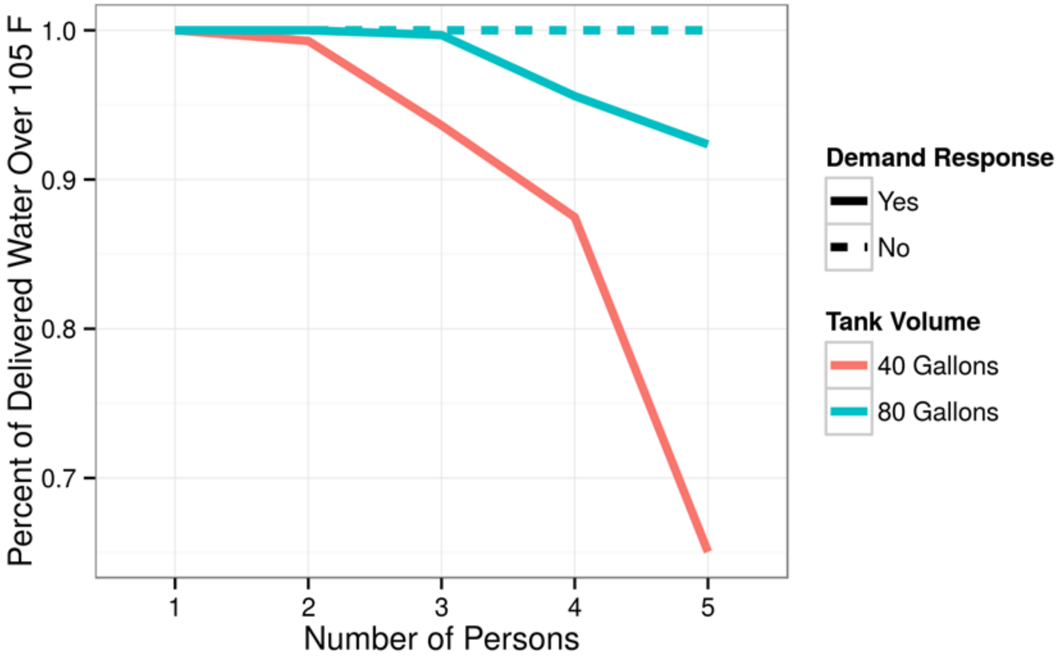


4.2.2 Hot Water Availability

Figure 28 generalizes the simulation outputs on hot water availability (it is a companion graph to Figure 27). It shows the percent of all water delivered that was at least 105°F or higher (the generally agreed upon threshold of useable hot water). The base case is plotted as dashed lines and always delivers enough hot water. The DR cases are the solid lines with red for the smaller tank and blue for the larger tank. The small tank provides hot water nearly all the time for 1 and 2 people but misses 6%, 12%, and 35% of the time for 3-, 4-, and 5-person households. Clearly this oversupply scenario is too much for the large households and this tank. The large tank misses only on the 4- and 5-person draws at 5% and 7% short. The takeaway in this case is that either the DR schedules need to allow for some operation during the day or the hot water storage capacity needs to be increased, either through more volume or a higher setpoint, so the tank can coast all the way through the day.

Figure 28 showed only the oversupply case. The data for the peak shifting show that hot water is always available in all cases because the DR pattern only delays HPWH operation by, at most, three hours.

Figure 28. Hot Water Availability in Oversupply vs Number of Occupants – Portland Climate



4.2.3 Changes in Operating Hours & Temperatures

With a heat pump-only water heater, forcing operation at different hours than the default is likely to change the ambient temperatures under which it operates and, hence, the efficiency. The water heater and DR simulation calculates exactly what the cumulative, annual shift would be, using Typical Meteorological Year weather, for any scenario. Figure 29 presents the distributions of operating hours and temperatures over an entire year for three cases: baseline (default), peak shift, and oversupply. The hour of day is the left plot while the 5 F wide temperature bin is the right plot. Figure 29 considers the GAU 80 gallon tank with the 5+ person draw profile in Spokane.

The baseline hours of operation show the expected, dual peak while temperature distribution shows the peak is in the 40-45°F bin. The vertical axis is the fraction of all annual energy input used in a particular bin. For example, 15% of all input heating electricity is used when it is 40-45° outside and the neighboring five bins each use 10% of the annual energy. For the peak shifting scenario, in the two morning and three evening hours there is clearly no operation. That runtime is delayed later and stacks up in the hours following the peak curtailment.

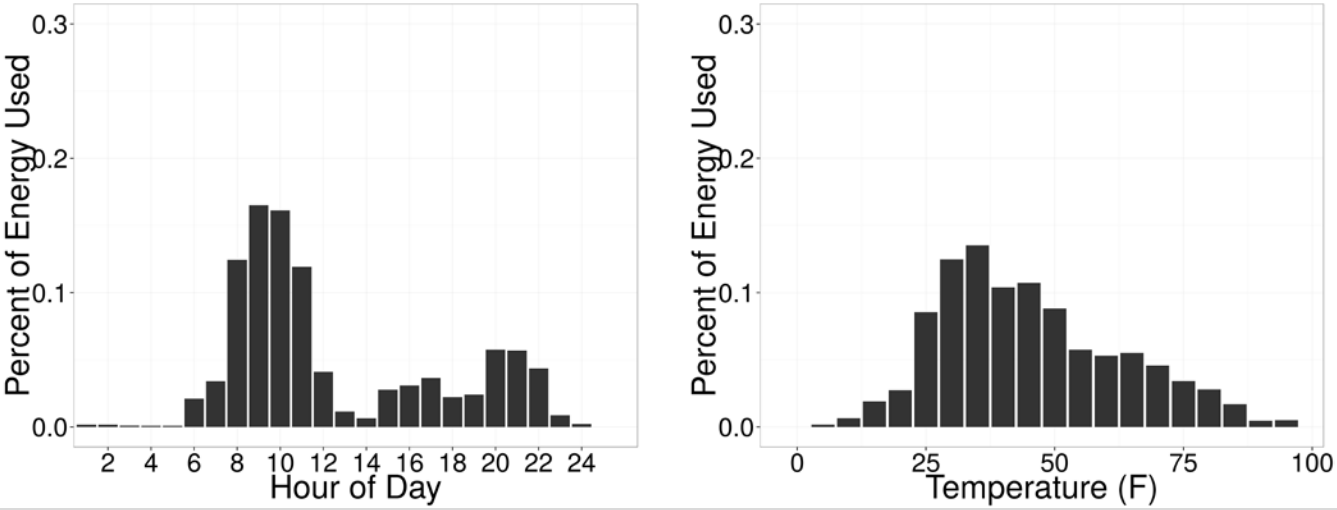
Correspondingly, there is almost no change in the operating temperature bins. There is a slight shift towards warmer temperatures which follows since there is more mid-morning operation and those hours are warmer than early morning. The oversupply distributions show the largest changes. Runtime hours, as expected, are clustered in the first six hours of the day. It is somewhat surprising there is any operation in the sixth hour since the water heater almost always operates at midnight, as soon as it is able. Moving to the overnight hours, means the temperatures will decrease as is borne out in the graph. The peak still occurs at the same spot but the distribution is more tightly centered around the lower end and there are practically no operating hours above 65°F.

The outputs for all the other simulations in this project are similar, regardless of draw volume or tank size. The Portland climates have similar operating hours but the temperature bins are warmer. Further, the baseline operating hours distribution is a function of when hot water is used so the familiar, dual peak will always be the default case.

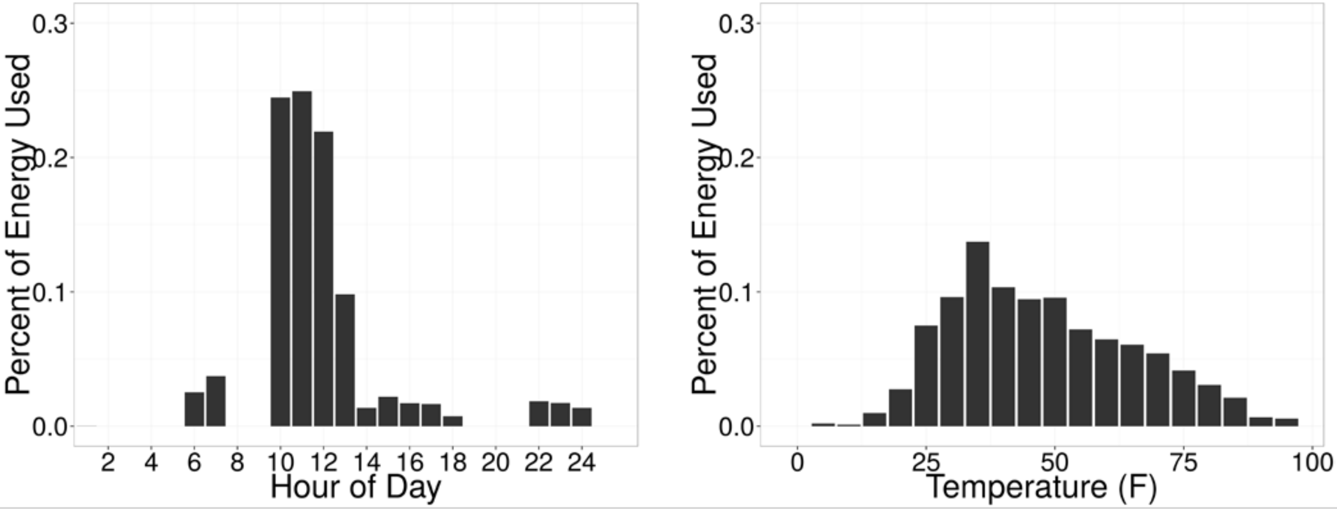
For the oversupply case, in light of the operating shift to colder temperature bins, it is even more surprising that it has overall, higher annual COPs as described in section 4.2.1. Despite the colder operating temperatures, the colder tank temperature profile and resulting lower standby losses combine to make the efficiency higher than the baseline case.

Figure 29. Operating Hours and Temperature Shifts – 5+ Person Draw, 80 gallon tank, Spokane

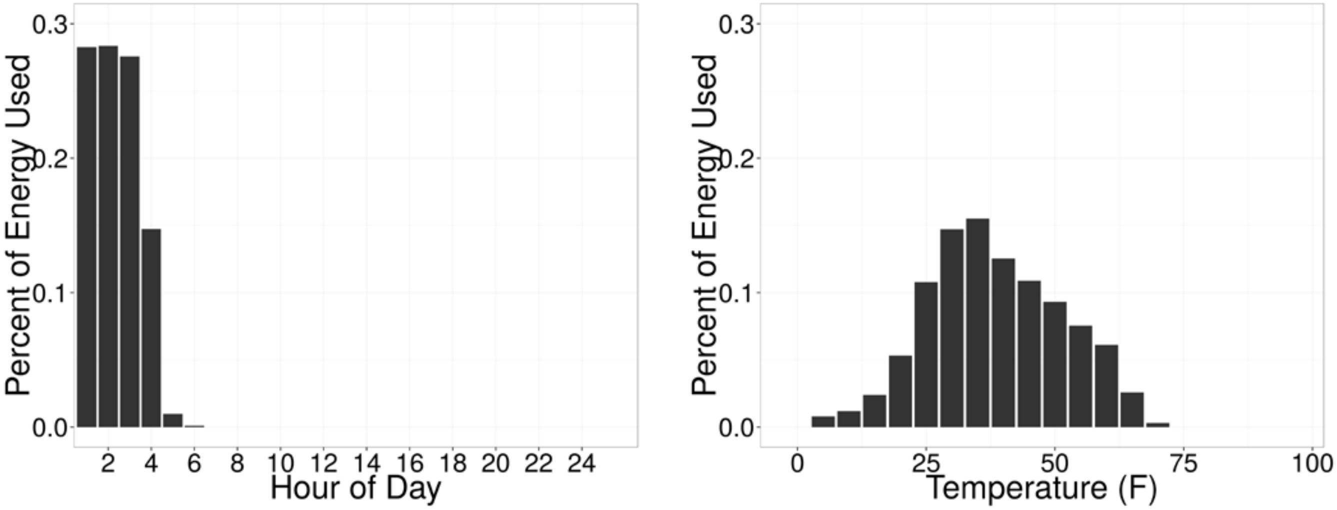
Baseline



Peak Shift



Oversupply



4.3 Dynamic Energy Storage and Capacity Reduction Potential

In the context of the scenarios simulated, the energy storage most directly applies to the oversupply mitigation and the capacity reduction applies to the peak shift. After the first day in an oversupply situation, the energy storage capacity on all subsequent days is strictly limited by the amount of hot water the house uses. If the water heater makes enough hot water overnight to coast through the day without running, it has maximized the amount of storage "space" available. The lab test profiles showed that the electric storage capacity of the Sanden HPWHs could range from 1.8-3.1kWh for outside temperatures from 67°F to 35°F. That was for a single day, 3-person draw profile. The simulation can be used to explore myriad other draw profiles and control strategies. This is important because, for a given amount of cold water in the tank, the amount of electric energy the tank can soak up varies with season (outdoor temperature).

Likewise, the capacity reduction potential also depends on the current operating conditions of each individual water heater. Table 3 showed the Sanden HPWH power can range from 1-1.8 kW depending on outdoor temperatures. Consequently, to shed the same total load in the summer time, the utility would need to turn off approximately twice as many water heaters as in the winter. Although this specifically applies to the Sanden units, a similar trend is expected for al HPWHs. The simulations confirms this and could expand on the findings if run with a full distribution of draw profiles found in the housing population not just the typical draws used in this project.

4.4 Control Characteristics for DR Implementation

In working with the Sanden water heaters in the lab and the simulation, it became clear that certain operating controls would make the equipment more desirable for DR use. As mentioned in section 1.2, the equipment tested did not have onboard DR controls – all such testing was done with secondary switches. Fundamentally, for DR use, there needs to be two-way communication between the HPWH and electric utility. Additionally, the water heater should have an adjustable set point. This would allow for increased storage in times of excess capacity or in anticipation of greater demand by "overheating" the stored water. It would further allow for more gradual recovery from load shedding DR event.

For the two-way communications, the water heater needs to accept a set of commands from the utility briefly summarized as: status query, operation enable, force off, force on. On the water heater side, it needs to be able to provide the following minimal information to a status query: operating status, if on, current and voltage measurements, tank temperature, user setpoint, and quantity of hot water in the tank.

An adjustable setpoint for the water heater will allow a wider range of possibilities. Ideally, the range should be from as low as the user wants to 190°F+. The extra hot setting enables a larger storage capacity. Along with the adjustable tank setpoint, the unit should have an integrated mixing valve which is adjustable to the user setpoint. Both the tank setpoint and the user setpoint need to be communicated to the utility with control of the tank setpoint given over to the utility. The difference in temperature, above the user setpoint, determines the amount of energy stored (or available) to the utility.

5 Conclusions

This project explored the demand response potential of advanced HPWHs in a closely controlled lab setting and beyond in a calibrated simulation. The project found the HWPHs are suitable for a variety of DR scenarios. The transcritical CO_2 refrigerant cycle provides an even greater potential because it is inherently suited to heating the water to higher temperatures than other refrigerants giving program operators even more flexibility. The conclusions are grouped in topic areas below:

Lab Findings

The lab tests successfully mapped the HPWH coefficient of performance from 17°F to 95°F ambient air and water from 50°F to 140°F for both products. This is critical information which shows how much power and energy is used during a given set of conditions. The lab tests also observed a DR scenario interacting with a 3-person, 46 gpd draw profile. In that case, either tank handily provides enough hot water. Those tests demonstrated the energy storage "space" at the end of the day is only a function of the amount of hot water used during that day. They further revealed that the electric storage space and equipment power, for a given amount of cold water in the tank, are not constant. Rather, they are strong functions of outdoor temperature. Consequently, the COP map is needed to predict capacity reductions and energy shifts for any given scenario.

A series of lab measurements, of particular interest to DR, where the water heater is forced off for extended periods, quantified the heat loss rate of the external water circulation lines. The data show that for installation locations where the outdoor temperature drops below freezing, the water lines need to be well insulated and either heated with a supplementary source or circulated periodically. The experiments suggest additional controls to operate the circulation pump could prevent freezing but that these controls would need to remain active under any DR scenario.

Simulation Findings

The project exercised the simulation with two DR scenarios: oversupply and peak shifting. The simulation proved especially useful in demonstrating hot water availability (or lack thereof), calculating the shift in operating hours/temperatures, and calculating efficiency changes. Surprisingly, in the oversupply case, even though operation was shifted to colder temperatures, the DR scenario was more efficient than the base case. The simulation shows this is because the DR case delays operation, storing more cold water in the tank, reducing standby losses, and increasing recovery efficiency by sending relatively colder water to the compressor unit. The findings are for the Spokane and Portland climates, for a particular set of draw profiles, and so should be explored further in different scenarios.

Desired Controls for Demand Response

After observing and simulating the Sanden HPWHs, a clear set of desired controls emerged. In short, to be the most useful and versatile, the HPWH should have two-way communications and a variable tank setpoint. The two-way communications needs to support four basic commands: status query, operation enable, force off, force on. To support the status query, the HPWH needs to be able to report its current power draw and tank temperatures. To provide maximum flexibility, the tank setpoint should be adjustable and settable remotely. To keep final control with the user, the tank should have an integrated tempering valve where the user determines the outlet water setpoint.

Future Work and Simulation Improvements

In sum, the Sanden HPWHs are promising for DR applications. Once equipment is available with onboard communications and the ability to heat water to very hot settings, those specific aspects should be investigated and used to augment the current body of work.

Although already calibrated to lab data, to further validate the simulation, it should be compared to the PNNL controlled field test data. That dataset contains a wider range of operating conditions and DR profiles. Such work was beyond the scope and time constraints of this project. Doing so in the future should add to the veracity of the simulation.

The DR simulation should also be updated with more features in order to cover more scenarios and extend beyond this project's scope. First, the DR schedule should be upgraded to allow a "force on" setting in addition to the power enabled and power disabled currently available. Second, the setpoint schedule should be upgraded so it may be varied in time allowing the water heater to be "overheated" and then cool off. Third, another set of schedules should be introduced to provide ancillary services like voltage control and frequency regulation. Finally, and most importantly, work should be initiated to introduce arbitrary hot water draw profiles to the simulation. To more accurately simulate the entire water heater population, the simulation needs to run with the population's hot water draw distribution and not just the thirty-five typical days used as examples in this project. The simulation could allow a unique draw at every minute of the year (for 525,600 data input points in all). These could be based on actual, field-observed draw patterns. In this way, even more DR scenarios could be tested out before being implemented in the field. The simulations would show which scenarios limited hot water availability and how much power and energy could be added or dropped.

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Appendix A: Lab Test Protocol

Measurement set up

Attributes to be measured are listed below.

- Temperature:
    - Ambient Air in the Walk-in Chamber
    - Compressor outlet air
    - Inlet water
    - Outlet water
    - Water inside Water Heater tank at six levels
    - Water temperature in circulation line between indoor tank and outdoor unit (both supply and return lines)
- Humidity:
    - Ambient air in Walk-in chamber
- Electrical Power:
    - Total system power
- Flow:
    - Inlet/Outlet Water

Test Matrix

Test Name	**Ambient Air Conditions**					**Inlet Water**		**Outlet Water**		**Operating Mode**
	Dry-Bulb		Wet-Bulb							
	F	C	F	C	RH	F	C	F	C	
Draw Profiles Tests										
DP-3p-35	35	2	33	1	50%	50	10	149	65	Comfort
DP-3p-50	50	10	44	7	50%	50	10	149	65	Comfort
DP-3p-67	67.5	20	57	14	50%	50	10	149	65	Comfort
COP Measurements - Baseline Development - Performance Mapping										
COP-17	17	-8	15	-9	70%	50	10	149	65	Comfort
COP-35	35	2	33	1	80%	50	10	149	65	Comfort
COP-95	95	35	75	24	40%	50	10	149	65	Comfort

DP tests should start once the water in the unit is fully heated; if the water is not heated, a pre-draw should be initiated to allow the water heater to initiate a heating cycle. The test may begin, starting at minute 0, when the unit has ceased running.

Draw profiles are provided given the "minute of test", where the 0'th minute marks the start of the test. The Draw Schedule table gives the number of gallons to be drawn with the minute the draw should begin. Draws may last as long as needed to provide the specified gallons. The flow rate should be approximately 1.7 gpm, though the exact value is not vital as long as it is not changed throughout the test.

The schedule for supplying power to the unit is specified in the Demand Response Schedule table. Times are given in hours, with the test starting at time 0. A value of 1 indicates that the power to the unit should be enabled. A value of 0 indicates power to the unit should be disabled.

Draw Schedule	
Minute of Test	Gallons to Draw:
178	1.61
187	7.245
363	4.025
374	1.61
390	1.61
679	1.61
685	2.415
694	1.61
901	1.61
903	1.61
911	5.635
922	1.61
1093	3.22
1103	1.61

Demand Response Schedule	
Hour of Test	State of Unit
0	1
1	1
2	0
3	0
4	0
5	0
6	0
7	0
8	1
9	1
10	0
11	0
12	0
13	0
14	0
15	0
16	0
17	0
18	0
19	0
20	1
21	1
22	1
23	1

COP Tests

COP tests need not be done as independent tests. The COP test can be run, and once the water is heated and the ambient temperature stabilizes, a draw profile test can be started. The COP test in this case provides the same benefit as a “pre-draw” and will suffice for heating the water prior to a draw profile test.

The COP measurement is made by observing the rate at which the compressor heats water. The COP varies according to the water temperature and the ambient temperature; typically the ambient temperature is held constant while the water is heated. Since the water must be preheated for all other tests, this provides an opportunity to measure the COP. After installation of the unit, the ambient temperature is allowed to stabilize at the indicated setpoint and the unit will be filled with water at the specified inlet temperature. Data recording should begin and continue throughout the heating process. When the tank has finished heating, this terminates the COP test and other tests, such as the draw profiles, may commence.

Water Line Test

The Water Line Test is not an independent test as much as a measurement to be taken during the testing period. The purpose of the Water Line Test is to determine the susceptibility to freezing of the lines which carry water from the tank to the compressor and back. A separate run sequence for this test is unnecessary; the data needed to calculate the rate of heat loss will be acquired during all other tests. Additional thermocouples will be needed. Thermocouples should be placed in contact with the water lines, underneath the insulation. Thermocouples should be located halfway between the wall of the chamber and the compressor unit, on each water line.

Appendix B: Measurement Instrumentation List

Equipment	Make and Model	Function	Accuracy	Calibration Expiration Date
Walk-in Chamber	Make : ESPEC, Model No.: EWSX499-30CA	Test environment temperature and relative humidity control	±1 °C	8/11/2015
Data Acquisition System	Make : Agilent Technologies, Model No : Agilent 34970A	Log temperature, power and flow rate data	Voltage: 0.005% of reading + 0.004% of range Temperature: (Type T):1.5°C	9/9/2015
Thermocouple	OMEGA, T type	Temperature measurement	0.8 °C	Note 1
Power Meter	Acuvim II – Multifunction Power Meter with AXM-I02 I/O Module	Continuous power measurement as necessary (system, heater and heat pump)	Main Unit: 0.2% full scale for voltage and current AXM-I02 Analog Output: 0.5% full scale + 1% resistor tolerance	Note 2
Ammeter	LH41	One-time fan power measurement	1mA in 4A range 10mA in 40A range	Note 2
Flow Control	Control: Systems Interface Inc. Flow meter: Signet 2537 paddlewheel	Water draw rate and amount control	Note 3	Note 3
Electronic Scale	OXO "Good Grips" Scale	Measurement of water mass	5.0 Kg full scale with 1 g increment	6/9/2015
Hand-held Temperature and Humidity Meter	Omega RH820W	Lab environment temperature and humidity measurement	± 0.5° C	Note 5
Electronic Scale	Dymo Pelouze Model: 4040 Range 180 Kg	Measurement of water mass	± 0.2 Kg	Note 5
Inlet Water Conditioning System	Temp control: TCS-4010	Conditioning of unit under test inlet water temperature	± 1 °C	Note 4

Notes:

1. Thermocouples are calibrated using Omega CL1500 system.
2. Each Acuvim II along with current transformer and LH41 Clamp-on Ammeter are checked against a calibrated power/current meter.
3. Flow control is checked by actual collected water weight measurement at required GPM.
4. This is not used for inlet water temp data used in calculations.
5. Checked against calibrated instrument/device.