

**Assessment of Demand Response Potential
of
Heat Pump Water Heaters
Final Report**

**Bonneville Power Administration
Technology Innovation Project 302**

Organization

**Washington State University –
WSU Energy Program in Olympia, WA**

Co-Sponsors

**Northwest Energy Efficiency Alliance
Pacific Northwest National Laboratory
Sanden International
Western Area Power Administration**

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Publication Date: September 30, 2015

WSUEEP15-021

Contents

Executive Summary	1
Introduction	2
Research Objectives	3
CO₂ Refrigerant System Operation	4
Unitary System	5
Split System.....	6
Controlled Field Study	7
Protocol Development	7
Controlled Field Study Tests	8
Data Collection.....	8
Control of the HPWHs.....	8
Baseline Tests.....	8
Oversupply Mitigation	10
Balancing INC	12
Comparison to ER Water Heater DR Performance	14
ER Baseline Test	14
ER Oversupply Results.....	15
ER Balancing INC Results.....	16
Energy Use	18
Lab Tests	19
Protocol Development	19
Lab Tests.....	20
COP Mapping Tests	20
Demand Response Profiles and Tests.....	22
Measured Energy Use and Efficiency	25
Measured Storage Capacity	25
Circulation Line Temperature Experiments	26
Simulation	27
Efficiency Impact	28
Conclusions	30
Recommendations	34
References	35
Appendix A: PNNL Lab Homes Test Report	36
Appendix B: Ecotope Report on Cascade Engineering Services Lab Test	37

Tables

Table 1. Oversupply Mitigation Test Results for an Oversupply Duration of 6 hours	12
Table 2. Measured Load Reduction.....	13
Table 3. Comparison of ERHW Oversupply and Balancing INC Performance to HPWH	17
Table 4. Test Conditions During Controlled Field Study	18
Table 5. Energy Use During Tests.....	18
Table 6. Minimum and Mean Outlet Temperatures.....	24
Table 7. Draw Profile and DR Test Summary Results.....	25
Table 8. Estimated Freezing Times at Ambient Temperatures.....	26
Table 9. Comparison of Energy Storage in the PNNL and Ecotope Tests	30
Table 10. Oversupply Mitigation and Balancing INC Summary	31
Table 11. Comparison of Water Heater Efficiencies	32

Figures

Figure 1. Comparison of CO ₂ and Standard Refrigerant Operation.....	4
Figure 2. Impact of Operating at Optimum Temperature	4
Figure 3. Unitary HPWH System	5
Figure 4. Split HPWH System Components –.....	6
Figure 5. Compressor On and Energy Consumed: 40-gallon Unitary System.....	9
Figure 6. Baseline Power Draw: 80-gallon Split System.....	10
Figure 7. Unitary System Shut-off Schedule and Variation in Water Temperature	11
Figure 8. Unitary System Water Temperature Fluctuations after Additional 1-hour Shut Off (at 5 p.m.)..	11
Figure 9. Results of the Three-Hour Test – Unitary System.....	13
Figure 10. Results of the Three-Hour Test – Split System.....	13
Figure 11. ERWH Baseline Power Profile, June 3, 2013	14
Figure 12. GE ERWH Baseline Delivered Water Temperature Profile, June 3, 2013	15
Figure 13. ERWH Oversupply Power Profile: 2:00 p.m. to 5:00 p.m. Powered-down Protocol	15
Figure 14. ERWH Oversupply Delivered Water Temperature Profile: 2:00 p.m. to 5:00 p.m. Powered-down Protocol, June 13, 2013	16
Figure 15. ERWH Balancing INC Power Profile 8:00 a.m. and 8:00 p.m. (1 hour powered-down).....	16
Figure 16. GE ERWH Balancing INC Delivered Water Temperature Profile: 8:00 a.m. and 8:00 p.m.....	17
Figure 17. COP Test at 67°F Ambient – Split System	20
Figure 18. COP Map for Sanden GES 40-gallon Tank – Unitary System.....	21
Figure 19. COP Map for Sanden GAU 80-gallon Tank – Split System	21
Figure 20. Hot Water Draw Profile.....	22
Figure 21. Lab Test Draw and DR Schedule	23
Figure 22. GES 40-Gallon Tank DR Profile Test at 35°F – Unitary System.....	23
Figure 23. DR Profile Test at 35°F – Split System	24
Figure 24. GAU Split-System Water Transfer Line Temperature Profile.....	26
Figure 25. Simulated Outlet Temperature, Oversupply Event, 3-Person Draw in Spokane – Split System	27
Figure 26. Simulated Outlet Temperature, Oversupply Event, 4-Person Draw in Spokane – Split System	28
Figure 27. System Annual COP in Oversupply vs. Number of Occupants in Portland, OR	29
Figure 28. System Annual COP in Oversupply vs. Number of Occupants in Spokane, WA.....	29

Abbreviations

AC	alternating current
BA HSP	Building America House Simulation Protocol
Balancing DEC	decreases the ratio of generation to load
Balancing INC	increases the ratio of generation to load
BPA	Bonneville Power Administration
CDD	Cooling Degree Days
CO ₂	carbon dioxide
COP	coefficient of performance
DOE	U.S. Department of Energy
DR	demand response
EF	energy factor
EPRI	Electric Power Research Institute
ER	electric resistance
ERWH	electric resistance water heater
FEF	Field Energy Factor
GE	General Electric
GPD	gallons per day
GWP	Global Warming Potential
HDD	Heating Degree Days
HFC	hydrofluorocarbons
HPWH	heat pump water heater
NEEA	Northwest Energy Efficiency Agency
OSA	outside air
PNNL	Pacific Northwest National Laboratory
PSI	pound per square inch
RTF	Regional Technical Forum
TRC	Total Resource Cost
UL	Underwriters Laboratory
WAPA	Western Area Power Administration
WSU	Washington State University

Executive Summary

This report is for Technology Innovation Project 302 conducted by Washington State University (WSU) and funded by Bonneville Power Administration (BPA) with support from the Northwest Energy Efficiency Alliance (NEEA), Pacific Northwest National Laboratory (PNNL), Sanden International USA (Sanden) and Western Area Power Administration (WAPA). The project conducted controlled field studies and lab tests of the Sanden model # GAU-A45HPA (split system) and model # GES-15QTA (unitary system) heat pump water heaters (HPWH) for demand response (DR) service potential.

The equipment studied both use CO₂ as a refrigerant. The split system has a separate outdoor unit and an 84-gallon water storage tank. The unitary system combines the compressor, heat exchangers, and 40-gallon tank in a unit designed for indoor installation with ducted supply and exhaust. The project began in October 2013 and ended in September 2015.

The controlled field study was conducted at the Lab Homes Test Center in Richland, Washington. The lab test took place at Cascade Engineering Services in Redmond, Washington, under the direction of Ecotope, Seattle. The controlled field study at PNNL was the first of the two studies conducted, and it informed the development of the test protocol for the lab test.

This report combines, summarizes, and discusses the implications of separate reports from each of the studies that make up this research. Each report is included as a digital appendix that can be accessed in full form.

The controlled field study found that:

- Both units tested were capable of providing the base daily draw amount of 130 gallons at 120°F.
- Both units could provide balancing INC services without difficulty.
- The split system could be off for 12 hours to create capacity for oversupply mitigation and still meet the total daily draw pattern at 120°F while the unitary system with its smaller tank had more limited storage capacity.

The lab study found that:

- The temperature of the water entering the heat exchange impacted system efficiency.
- The 40-gallon unitary system could provide an average family of three with hot water and still perform DR services, including oversupply mitigation.
- Efficiency was enhanced by operating the system exclusively off peak, which provided balancing INC and oversupply mitigation services.

The studies found the dispatchable power of both systems ranges from 1.2 to 1.7 kW, and the energy storage depends on temperature and ranges from 2.29 kWh at 50°F to 3.09 kWh at 35°F.

It is recommended that BPA take the lead in developing a regional DR communication protocol; that DR and capacity savings be added to efficiency value in benefit-to-cost analysis; that utilities with large renewable portfolios invest in DR-enabled CO₂ HPWH to mitigate oversupply and achieve efficiency at the same time; and that the manufacturer is encouraged to enhance freeze protection, sophisticated controls that enhance DR value, and additional tank insulation to increase overall efficiency.

Introduction

This project is a controlled field study and lab test that assessed the demand response (DR) potential of split system and unitary heat pump water heaters (HPWHs) manufactured by Sanden that use carbon dioxide (CO₂) refrigerant. The researchers included Washington State University (WSU), Pacific Northwest National Laboratory (PNNL), Efficiency Solutions, and Ecotope working with Cascade Engineering Services.

The controlled field test took place at PNNL's Lab Homes Test Center in Richland, Washington. The configuration of the Lab Homes allowed simultaneous testing of the water heaters under the same weather, interior temperature, and loads. The draw amount and patterns were determined through consensus by Bonneville Power Administration (BPA), Ecotope, PNNL and WSU, and the demand patterns were informed by demand response experts at BPA.

The draw amount during all baseline and DR tests was 130 gallons per day (GPD), which is more than three times the regional daily average (Ecotope and NEEA, 2015). This volume was the same as previous testing done by PNNL on GE HPWHs operating in electric resistance (ER) mode (Widder et al., 2013). The controlled field test project also had the advantage of testing the equipment under extreme conditions. The tests conducted were:

- Baseline measurement;
- Balancing INC, which tests the response of hourly or sub-hourly changes in demand and the available dispatchable power/energy shift associated with it; and
- Oversupply mitigation, which identifies the total dispatchable power, and resulting energy shift, that a noncritical load like water heating can provide during a 3- to 12-hour window.

The Lab Homes tests reveal that both the unitary system and the split system HPWHs could provide water at the required temperature at the 130 GPD draw, and could perform balancing INC consisting of three 1-hour periods without a loss of delivery performance. Both HPWHs could also deliver setpoint hot water after being shut down for six hours for oversupply mitigation. The split system could continue delivery for a full 12 hours of shutdown, while the unitary system with its 40-gallon tank failed to provide setpoint temperature water after the sixth hour.

Ecotope developed the lab test protocol within the context of the controlled field study test protocol. With the PNNL Lab Homes program exploring the extreme ends of the draw spectrum, the draw pattern selected for the lab tests was based on the regional average hot water use of approximately 15 gallons per person per day and with an average home occupancy of three. This added a broader range to the tests done at PNNL and produced an assessment of the units more closely tied to actual use. The goal of the lab tests was to identify the impact of DR on hot water delivery, HPWH performance, the dynamic energy storage potential, and controls needed for optimum DR implementation.

The protocols developed are not customized for these specific water heaters; they can be used to test any HPWH or ER water heater for DR purposes. This report contains an overview of what was learned in developing and implementing these tests.

Research Objectives

The goal of the research was to assess the potential for using CO₂ refrigerant HPWHs of two different configurations to provide dispatchable DR services including load balancing and oversupply mitigation. To achieve this goal, tests were developed and conducted in a controlled field study at the PNNL Lab Homes facility and a lab at Cascade Engineering Services under the direction of Ecotope, Inc.

Specific research questions were proposed:

1. What is the energy storage capacity in long-term field use subject to typical hot water system end use and dispatch driven by actual events?
2. What is the impact on system efficiency of oversupply, load shifting, and load balancing operation over the long term? What is the impact on HPWH 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 is due to differing outside air (OSA) temperatures?
3. What is the impact on performance of increased tank loss, if any, due to increasing temperatures for energy storage?
4. How do DR-enabled HPWHs interact with conditioned space and overall whole-house power consumption?
5. How does the DR performance of the HPWH compare to a similar, baseline ER water heater?
6. How are the impacts of dispatchable load following or balancing reserves and inherent efficiency combined and valued to determine the overall capacity reduction potential of HPWHs?
7. 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?
8. What are the DR benefits and issues of the tested technology, and how might the tested technology be redesigned to further improve its DR function, marketability, and cost-effectiveness while retaining efficiency?

These questions were originally targeted at either the controlled field study or lab tests, but in practice the answers emerged during the entire research project. The overarching question is: what is the potential of these systems to provide DR services? The generic answer is that it is significant. This report will provide details and answer the specific questions.

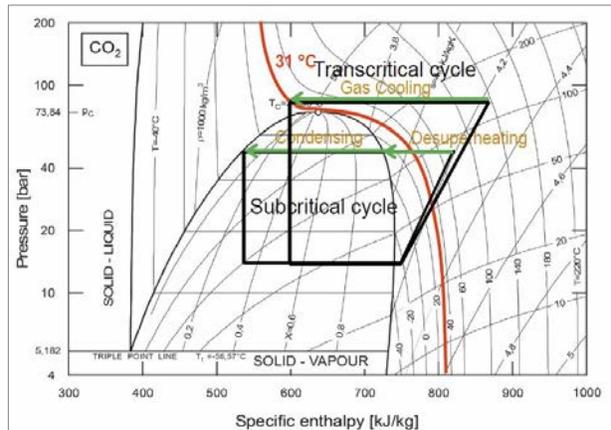
CO₂ refrigerant operates differently than standard hydrofluorocarbons (HFCs). The next section describes CO₂ refrigerant operating systems and the two different configurations – unitary and split systems – studied in this research.

CO₂ Refrigerant System Operation

The systems used in the field study heat water from the cold water supply temperature to 149°F in a single pass. This thermal lift is a characteristic of CO₂ systems that results from the heat capacity of CO₂ at a specific operating pressure, and is an important contributor to the efficiency of these systems and their ability to extract heat from OSA at low temperatures.

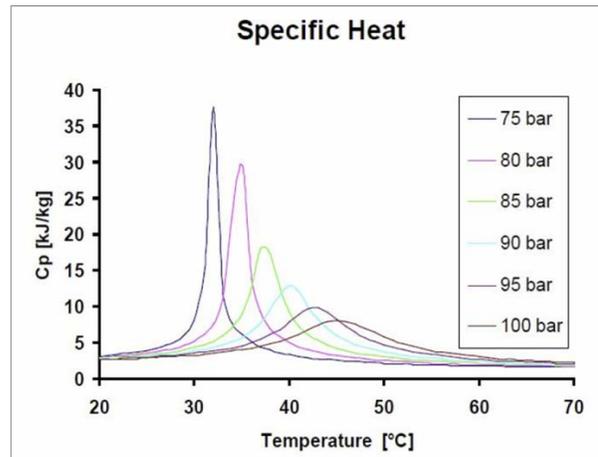
Figure 1 compares the operation of CO₂ and standard refrigerants in terms of their state, pressure, and energy-holding capacity (specific heat). CO₂ operates in a transcritical cycle at a pressure of ≈75 bar or 1,087 pounds per square inch (PSI) on the high-pressure side. The CO₂ is in the transcritical phase at the refrigerant-to-water heat exchanger. This phase is called gas cooling and the CO₂ is not discernably in either a liquid or vapor phase – it has attributes of both. After it leaves the gas cooler, it drops into the evaporator at a lower pressure and temperature, where it absorbs heat from the ambient air as it changes state from a liquid/vapor mixture to a gas. The compressor then lifts the CO₂ back to the transcritical zone where it transfers heat to the colder water.

Figure 1. Comparison of CO₂ and Standard Refrigerant Operation



The impact of operating at the optimum temperature and pressure at the evaporator is shown in **Figure 2**.¹ The specific heat at 75 bar is significantly greater than that of CO₂ gas at other pressures. This allows the CO₂ to absorb more heat at low temperatures, and requires great engineering skill in system design to maintain.

Figure 2. Impact of Operating at Optimum Temperature



Every CO₂ system must work with pressures higher than those for conventional refrigerants. In the systems used for this research project, the manufacturer has isolated the CO₂-charged components, and the charged system is serviced only by the manufacturer.

This design is approved in Japan, China, Australia, and Europe. UL listing for the U.S. is currently in process. The manufacturer, which builds one-third of the world's vending machines and most automotive compressors, already has UL listing for a vending machine cooling compressor using CO₂ refrigerant, and Coca Cola is currently changing all of its vending machines worldwide to use CO₂ refrigerant.

¹ Figures 1 and 2 are from Rolf Christensen at Alfa Laval, a manufacturer of advanced heat exchangers used with CO₂ and other heat exchange fluids, and are used with permission. The terms used are metric, but are shown here for the relative and relational aspects they reveal about the physics of CO₂ refrigerant.

Two systems were used in this research: a unitary HPWH (Model GES-15QTA) and a split system HPWH (Model GAUS-315 EQTA). Both are manufactured by Sanden International – the unitary system in France and the split system in Australia. Both use the same compressor and are designed to lift the temperature of supply water that is between 50°F and 60°F to 149°F in a single pass through the heat exchanger. Neither system has a backup ER element.

Both systems were installed and removed by Mark Jerome of CLEAResult under agreement with WSU. Mr. Jerome provides installation guidance and expertise to all of the research sites where this technology has been monitored.

Unitary System

The unitary system, shown in **Figure 3**, is designed to keep the tank and compressor unit together in a unit that can be installed inside conditioned space or a buffer area. Air is brought to the unit from – and exhausted to – outside the conditioned space through 8-inch ducts.

The system is built in two containers that may be installed vertically or horizontally. The hot water tank is 40 gallons. The vertical configuration used at the Lab Homes installation is located on the bottom. The compressor, heat exchanger, fan, and pump are housed in the other container and connected by hoses to the tank. The system is plumbed like a regular water heater with the exception that a tempering valve is needed to bring the temperature down to safe levels. A tempering valve was used in the controlled field study but was not necessary in the lab tests.

Like the split system, this unitary water heater was tested according to U.S. Department of Energy (DOE) and Advanced Water Heater Specification 6.0 (AWHS) (formerly Northern Climate Specification) standards (Larson and Logsdon, 2013). In terms of efficiency, the unit is comparable to the split system. It is, however, constrained in terms of delivery of hot showers because of its smaller hot water tank. During the controlled field testing, a major delay was caused by a switch malfunction and condensate issue in this system. The issues were diagnosed and solved by Greg Sullivan of Efficiency Solutions, a contractor to WSU, and Sanden.

At the PNNL Lab Homes installation, the unitary system was installed in the water heater closet that opens to the outside of the home. Supply air was ducted from the crawl space beneath the home, and exhaust air was taken through the roof. Taking supply air from underneath the home provided some energy from the ground and the floor heat loss, making the air slightly warmer than that used by the split system during cold weather conditions.

Figure 3. Unitary HPWH System



Split System

The split system functions are separated into two different parts:

- The compressor, air-to-CO₂ and CO₂-to-water heat exchangers, control system, and circulation pump are all located in the outdoor unit.
- The heat storage is an insulated water tank that is located inside conditioned space.

The tank has a sensor that measures the tank temperature at a height about two-thirds from the bottom of the tank. When the water temperature at that location drops to 113°F, the outside unit activates.

The two components are connected by hot and cold water lines and a sensor wire. Cold water is pumped from the bottom of the tank into a heat exchanger at the base of the outdoor unit, where heat is transferred from the high-temperature/high-pressure CO₂ gas in the transcritical phase. On the low-temperature/low-pressure side of the water exchanger, the CO₂ pulls its heat from OSA through an exchanger in the face of the outdoor unit, where a fan circulates air from front to back. **Figure 4** illustrates the system components. The heated water returns to the top of the tank.

The sensor wire connects the tank temperature sensor to the control system in the outdoor unit. The controls turn the system on and off for water heating, operate the defrost cycle to prevent icing in cold weather, and circulate hot water to prevent freezing of the lines and heat exchanger during long periods of system inactivity in cold weather.

The water lines are equipped with heat tape by the system installer. Installation also requires providing power to the outdoor unit, running water and sensor lines between the outdoor unit and tank, insulating the water lines, and connecting the tank to the household water supply and distribution piping.

Figure 4. Split HPWH System Components – Outdoor Unit and Insulated Water Tank



Controlled Field Study

The PNNL Lab Homes are two identical manufactured homes located at the PNNL main campus in Richland, Washington. The homes are set up in parallel but at sufficient distance to be unshaded from any direction, thereby experiencing similar solar and wind conditions at all times. They are fully instrumented and have the ability to program loads including electric load operation and water and appliance use.

Richland is in the Northwest Power and Conservation Council's heating zone 1 with 4,828 heating degree days (HDD) and cooling zone 3 with 881 cooling degree days (CDD),² making it one of the more extreme climates in the region. The testing began in August 2014 and ended in November 2014. Due to equipment issues, the testing was delayed and the final test was done under different temperature conditions than the beginning tests.

Protocol Development

The tests done at the PNNL Lab Homes were the product of a long protocol development process beginning with the first draft delivered on January 29, 2014. Development continued through February and March 2014, and the protocol was reviewed with PNNL by BPA, Ecotope, Sanden, and WSU. BPA DR experts were key to designing the DR protocols used. The final protocol submitted to BPA on June 3, 2014 represents a consensus of the entire project team and is attached as Appendix A.

The protocol specified three tests:

- 1) Baseline tests to establish ability to meet the daily draw of 130 GPD and the energy needed by the system to meet that demand,
- 2) Oversupply mitigation tests to measure the capacity of the HPWHs to store energy at times of excess generation, and
- 3) Balancing INC tests that evaluate the potential of the system to provide dispatchable load reduction in an hourly or sub-hourly time frame. All of these tests were done while the systems met the 130 GPD hot water draws.

The draw profile and total daily amount drawn comprised a foundational decision in designing the tests. In the written protocol, the 130 GPD draw amount is designated as the Building America House Simulation Protocol (BA HSP) Extreme (BA HSP Extreme) profile. It was chosen by consensus after a discussion where the regional average of 42 GPD per household was advocated as the minimum and the BA HSP Extreme as the maximum with several mid-range points. It was agreed to use the BA HSP Extreme for the controlled field study for several reasons:

- 1) It represents use by a large household at the high end range of actual use;
- 2) It tests the equipment at the limits it is likely to see;
- 3) In controlled situations, most is learned by stressing systems; and
- 4) Previous testing of HPWH acting in both heat pump and ER modes at the PNNL Lab Homes was done at the BA HSP Extreme profile, allowing direct comparison to those results (Widder et al., 2013). This project resulted in two test protocols for assessing water heater DR potential. Both this protocol used at the PNNL Lab Homes and the protocol developed for the lab test are

² Both HDD and CDD are based on 65°F interior setpoint. Source: Western Regional Climate Center.

valuable additions to the toolkit for making these assessments and bracket the approaches as necessary to provide comprehensive insights.

Controlled Field Study Tests

The PNNL Lab Home configuration allowed each system to be installed in a separate home and be subjected to the same conditions. A complete description of the test equipment and system installation is found in the final PNNL report (Sullivan et al., 2015).

Data Collection

Data was taken at one-minute intervals. The test points included:

- Water flow time and volume through the hot water tank measured at the hot water outlet
- Water temperatures
 - Cold water supply
 - Hot water to tempering valve
 - Tempered water to house
- Air temperatures
 - Air temperature to the heat exchange coil
 - Air temperature near the hot water tank in the water heating closet where the entire unitary system (Lab Home A) and tank of the split system (Lab Home B) were located
- Power measurements
 - Time and amperage of compressor electricity use
 - Time and amperage of outdoor pipe freeze protection (heat tape) electricity use

Control of the HPWHs

Both HPWHs were controlled for DR dispatch. It was proposed that they have onboard controls using CEA 2045 communication protocols. The manufacturer made a good faith effort to obtain control devices using this software, but the devices were not available for these tests. The manufacturer also looked into programming its own controller, but the protocol was not developed enough to allow this. BPA agreed that the testing would have to proceed with local controls, but that the overall project should examine the best type of control to optimize the DR potential of the water heaters. This analysis is included in the last section of this report.

For these experiments, both water heaters were dispatched according to the test protocols by programmable breakers that switched power to the water heaters. This simulated the simplest type of control and allowed the tests to proceed.

Baseline Tests

The units were installed at the Lab Homes in June 2014 and baseline testing started in late June. The testing was interrupted by a malfunction that prevented the unitary system from staying in “comfort” mode, which utilizes the full output of the compressor. Instead, the unit was defaulting to “eco” mode, which operates the system at two-thirds power. It took approximately 12 weeks to solve these problems.

When testing resumed, the first issue encountered was failure to properly remove condensate from the compressor housing. This repair was identified and completed by Greg Sullivan.

The second problem was the switch that governed system mode. The system only worked in full capacity in comfort mode, but kept reverting to eco mode. The manufacturer, who had representatives in the technical group that met weekly during the tests, identified the issue and provided a replacement part. Proper function was restored on October 1, 2014 and baseline testing resumed. All tests on the unitary system were performed in comfort mode after this repair.

The baseline tests demonstrated that both the unitary and split systems could provide 120°F water while meeting the prescribed draw pattern and amount. That the unitary system with its 40-gallon tank could meet this demand was somewhat surprising to the project team because it required the heat pump to produce over three tankful of hot water during the day. **Figure 5** shows the time the compressor was on and the power consumed to achieve this (Sullivan et al., 2015, p. 3.4). The graph also demonstrates the tempering impact of the crawspace air supply used by the unitary system.

Figure 5. Compressor On and Energy Consumed: 40-gallon Unitary System

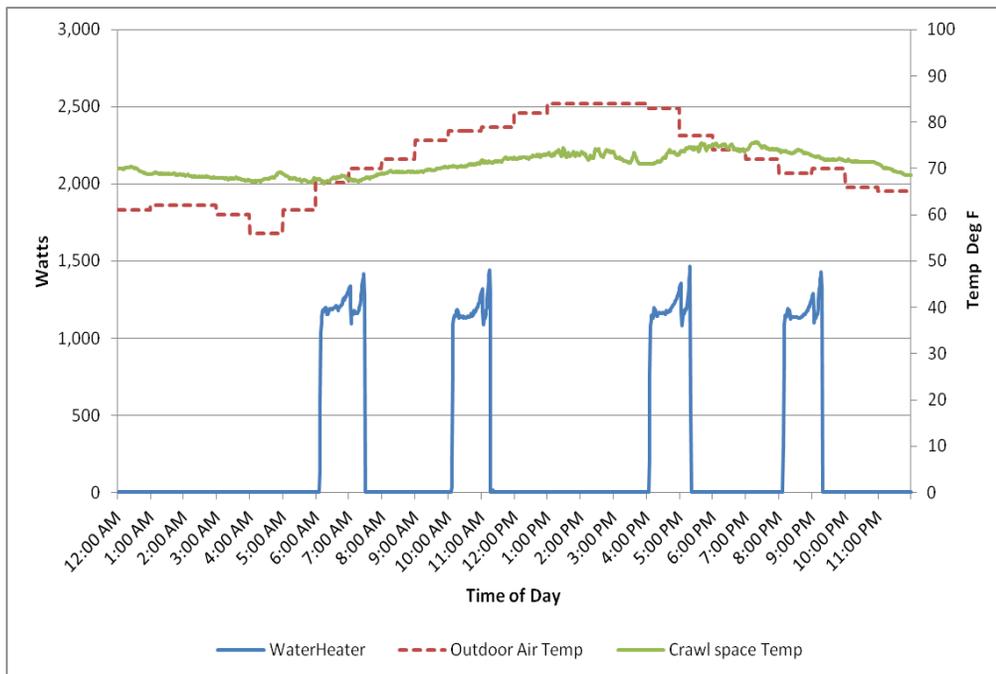
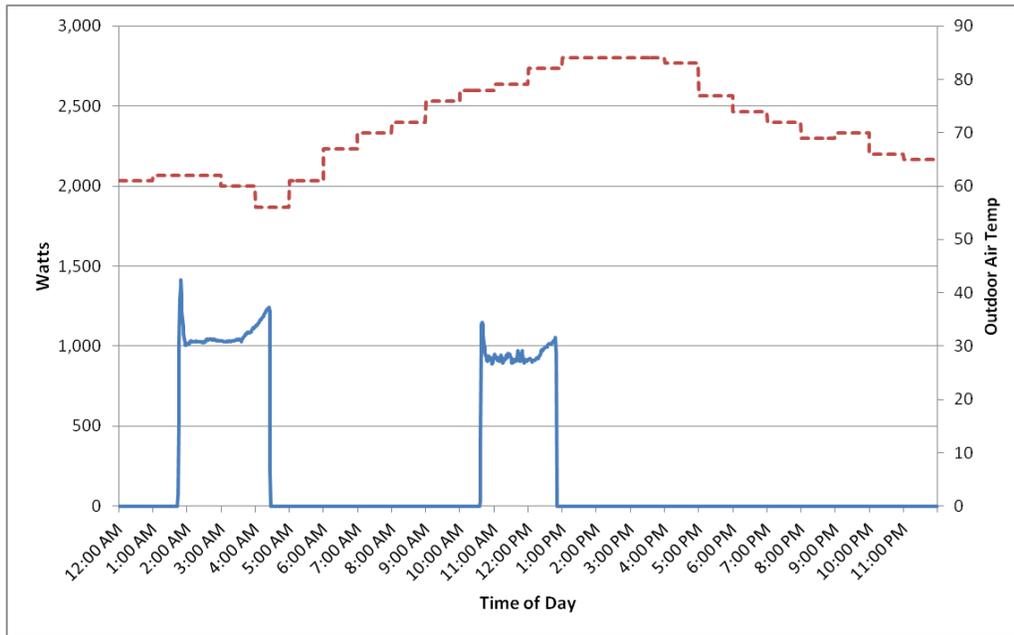


Figure 6 shows the baseline power draw for the 80-gallon split system tank. Note that the system comes on for half the number of times, stays on longer, and has a slightly lower power draw than the unitary system. This is probably because the split system tank is larger, has a greater hot water reserve and, because of stratification, has cooler water supply to the outside unit, which increases efficiency of the heat exchange.

Figure 6. Baseline Power Draw: 80-gallon Split System



Oversupply Mitigation

When generation exceeds demand for electricity for a number of hours, the situation is called oversupply. Absorbing that extra electricity and applying it to a useful purpose is called oversupply mitigation. Water heaters with ER heating elements generally accomplish this by raising the water temperature. This can be done by these CO₂ HPWHs without ER coils in two steps:

- They stay off to create a storage space of cool water because hot water demand is filled without heating incoming cold water, and
- During the oversupply period, energy is stored by heating the cold water in the tank.

With the proper controls, HPWHs could perform these functions as directed by the utility system.

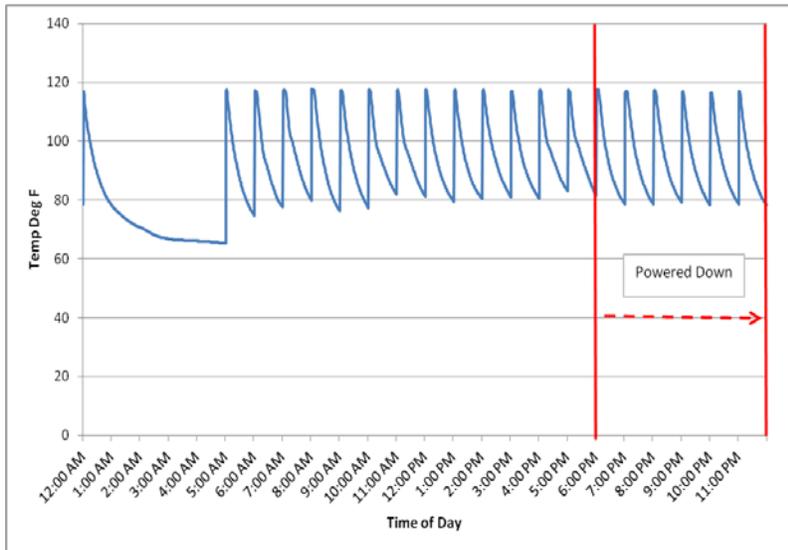
Oversupply in the Pacific Northwest typically occurs when spring runoff water must go through turbines to benefit migrating salmon and/or by excess wind power generation – often at night when loads are reduced.

In this experiment, the HPWHs could not be set up to produce temperatures higher than 149°F.³ Instead, the protocol was designed to turn the systems off to create space for later energy storage as hot water. The test began with a minimum 6-hour shut off followed the next day by an additional 1-hour shut off, up to a maximum of 12 hours shut off during a 24-hour period.

Tank size proved to be the determining factor in how long the system could be turned off and still meet the 130 GPD draw. As shown in **Figure 7**, the unitary system could be turned off for 6 hours and still deliver water at the setpoint (Sullivan et al., 2015, p. 3.7).

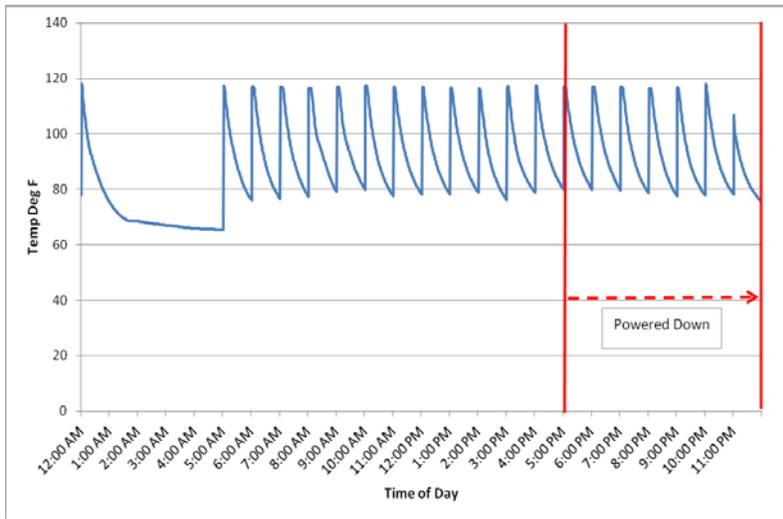
³ Other CO₂ HPWH equipment manufactured by Sanden for the Japanese market routinely heats water to 194°F.

Figure 7. Unitary System Shut-off Schedule and Variation in Water Temperature



But the addition of one more hour to the shutdown caused the unitary system to deliver colder water in the last draw of the day, as shown in Figure 8 (Sullivan et al., p. 3.8). The split system with its 80-gallon tank provided setpoint hot water after being shut down for 12 hours.

Figure 8. Unitary System Water Temperature Fluctuations after Additional 1-hour Shut Off (at 5 p.m.)



The results of the oversupply mitigation tests, shown in **Table 1** (Sullivan et al., 2015, p. 3.12), indicate that the tested units do provide measurable DR benefit with a demonstrated ability to maintain storage and absorb energy during an oversupply period. They also show the ability to shut down for extended periods of time and still provide hot water, which may also be useful.

Keep in mind what this could mean from a utility or power system manager’s perspective. If thousands of these units with dispatchable controls are available, the DR potential is significant. For example, a thousand split system units would provide energy storage of almost 3 MWh with the amount of storage created by the draw amount used in the experiment.

In addition, with sophisticated controls, the manufacturer could easily add temperature increase to the DR services provided by this water heater. The manufacturer of these systems already produces a remote-controlled HPWH capable of producing water from 149°F to 194°F. In either case, a tempering valve is used to reduce the temperature to safe operating temperatures.

Table 1. Oversupply Mitigation Test Results for an Oversupply Duration of 6 hours

Experiment Metric	Unitary System HPWH	Split-System HPWH
Oversupply Experiment		
Dispatchable power (kW)	1.3	1.2
Energy Storage (kWh) ^a	2.65	2.95
Oversupply preparation duration (hours) ^b	6	6
Maximum off period while delivered temperature met (hours)	6	12

^a The oversupply energy storage is the water heater energy use at the conclusion of the oversupply period to bring the tank temperature bank to setpoint.

^b The oversupply duration of the split-system presented was for the 6-hour interval and provided for comparison to the unitary system. The 12 hour energy storage for the split system is estimated at 3.9 kWh.

Balancing INC

Electricity distribution is a dynamic enterprise. From moment to moment, utilities and power generators face a generation/load balancing act. If a utility does not have enough power, it could turn up generation for a short time or it could shed load. Load shedding is called balancing INC because it increases the ratio of generation to load.

If the overall load falls off, the options are to turn off generation or to increase load, called balancing DEC because it decreases the ratio of generation to load. The test protocol specified balancing INC tests, which also provide insight into how well the equipment might serve for balancing DEC.

The protocol specified two different tests. The first specified an off period of 1 hour at 2 p.m. The second specified three, 1-hour off periods at 2 a.m., 8 a.m., and 8 p.m. Both HPWHs continued to maintain the 130 GPD draw throughout these tests. There was no doubt that the split system could manage these interruptions in water heating, but the unitary system performance was carefully watched. A reason for this concern was that this testing occurred during a cold period in November 2014 when nighttime OSA temperatures dropped to 20°F, and the average incoming water temperature was 57.9°F (Sullivan et al., 2015, p. 3.13).

Throughout this testing and despite the colder air and water temperatures, both systems maintained hot water output at setpoint temperatures. **Figure 9** shows the 3-hour test for the unitary system. It demonstrates an increase in recovery power use from 1.3 kW in the oversupply mitigation tests to 1.7 kW for the unitary system, and from 1.2 kW to 1.6 kW for the split system. This is caused by the need to operate the heat pump in colder supply air and water temperature conditions. Both the OSA and crawl space temperatures are shown, indicating the advantage of drawing supply air for the heat pump from beneath the home.

Figure 9. Results of the Three-Hour Test – Unitary System



Figure 10 shows the split system performance during the 3-hour test. The operation of the heat pump is actually interrupted during this test, resulting in clear load reduction. The power use periods are longer than those of the unitary system, but they are fewer and at generally lower wattage.

Figure 10. Results of the Three-Hour Test – Split System

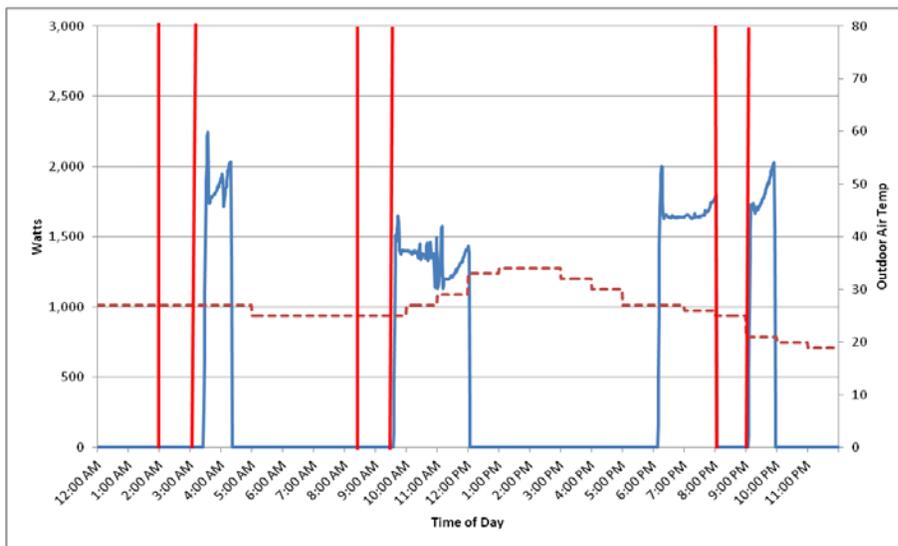


Table 2 shows the measured load reduction from the HPWH during the tests described above. (Sullivan et al., 2015, p. 3.16).

Table 2. Measured Load Reduction

Experiment Metric	Unitary System HPWH	Split System HPWH
Dispatchable Power (kW) ^a	1.7	1.6
Energy Storage (kWh) ^b	1.7	1.6
Balancing INC Duration (hours)	1	1

Comparison to ER Water Heater DR Performance

In addition to conducting the controlled field study with the Sanden HPWH, PNNL also conducted tests at the Lab Homes comparing DR performance of the General Electric Geospring™ HWPH in ER mode and HPWH mode. These tests were conducted in 2013 (Widder et al., 2013). The ER water heater (ERWH) tests from this study provide the ER comparison for the Sanden HPWH studied in this research.

ER Baseline Test

The baseline period for the ERWH was June 2013. A series of data collected over five days was analyzed and compared for proper baseline operation. **Figure 11** presents the power profile of the GE ERWH (blue line), along with the hourly average OSA temperature (red dashed line). The ERWH has a very consistent wattage profile, and the peaks generally align with the automated hot-water draws. Across the daily draw pattern, the average energy use per water heater power draw event was 0.89 kWh.

Figure 11. ERWH Baseline Power Profile, June 3, 2013

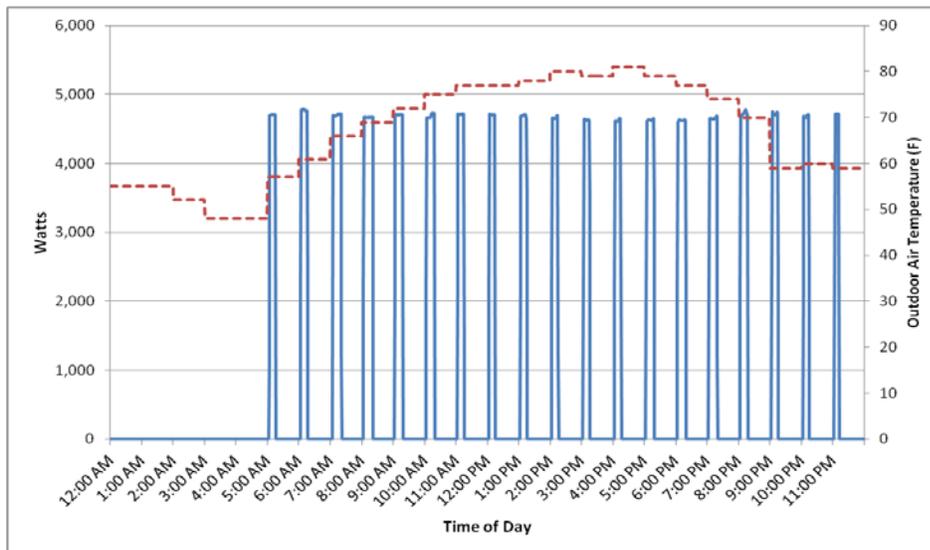
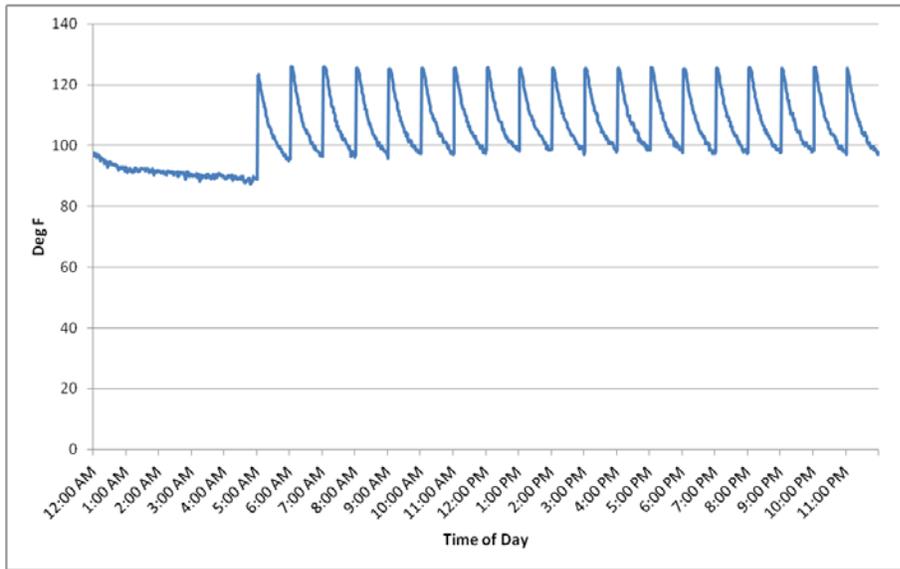


Figure 12 shows the temperature profile of delivered water measured after the thermostatic mixing valve. The delivered water set point was fixed at a nominal 120°F, though inaccuracy in the thermostatic mixing valve allowed this to rise to 125°F, and the total draw was approximately 130 GPD. Evident from the graph, the water heater was able to deliver water at the requisite temperature throughout the high draw pattern; that is, at no time during the day did the temperature on any of the draws go below the 125°F set point.

Figure 12. GE ERWH Baseline Delivered Water Temperature Profile, June 3, 2013



ER Oversupply Results

The schedule for the ERWH oversupply testing included off periods of three hours. **Figure 13** presents the power profile with the OSA temperature shown as a dashed red line. **Figure 14** highlights the resulting temperature profile for this DR schedule. The vertical red bars indicate when the DR schedule was implemented (i.e., when the water heater was powered-down) to create storage for the mitigation.

Figure 13. ERWH Oversupply Power Profile: 2:00 p.m. to 5:00 p.m. Powered-down Protocol

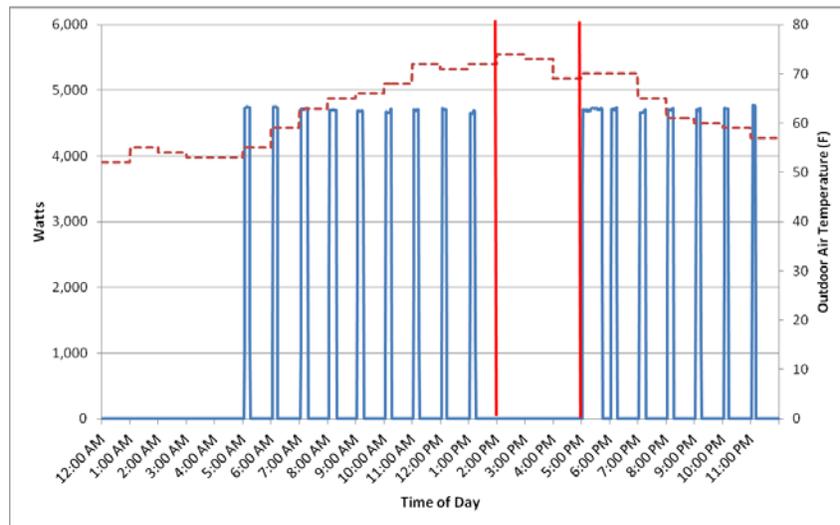
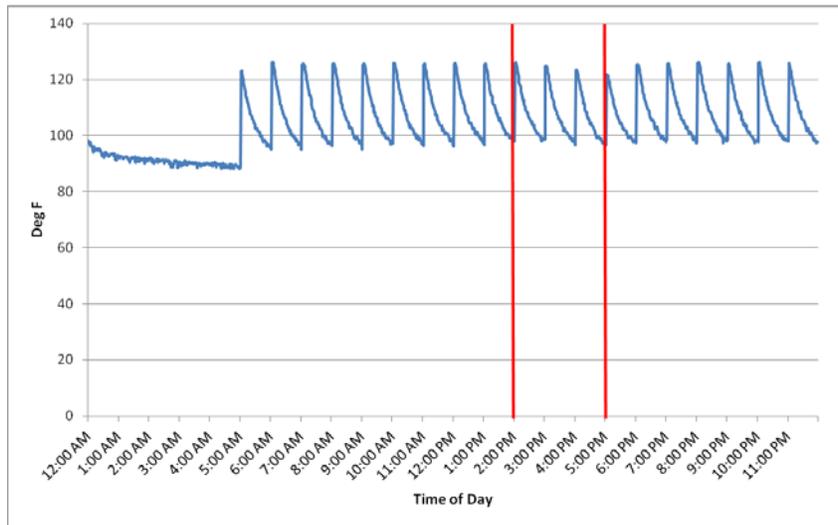


Figure 14. ERWH Oversupply Delivered Water Temperature Profile: 2:00 p.m. to 5:00 p.m. Powered-down Protocol, June 13, 2013



It is evident from Figure 14 that the temperature dropped below setpoint after two hours of the shutdown, and dropped a full 5°F by the end of the power-down cycle of three hours. In comparison with the ERHW baseline, the oversupply DR profile created a demand shift of four 4.6 kW events during the oversupply period. This shift is evident in the graph, where at 5:00 p.m., the ERWH went into recovery mode during which it drew the same 4.6 kW of power but over a longer duration.

ER Balancing INC Results

The schedule for the ERWH balancing INC testing included off periods of one hour each. **Figure 15** presents the power profile with OSA temperature for one of the days when the 8:00 a.m. and 8:00 p.m. schedules were implemented. **Figure 16** highlights the resulting temperature profile for this DR schedule.

Figure 15. ERWH Balancing INC Power Profile 8:00 a.m. and 8:00 p.m. (1 hour powered-down)

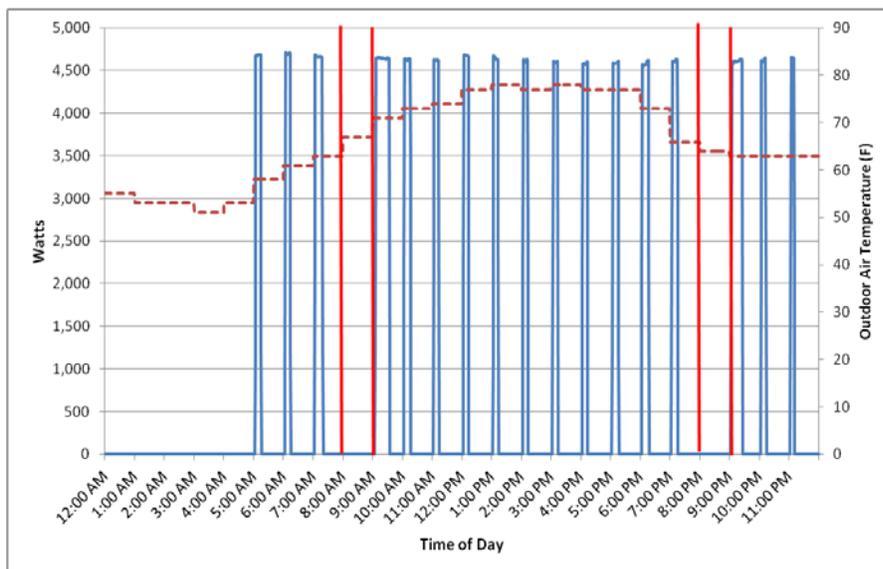
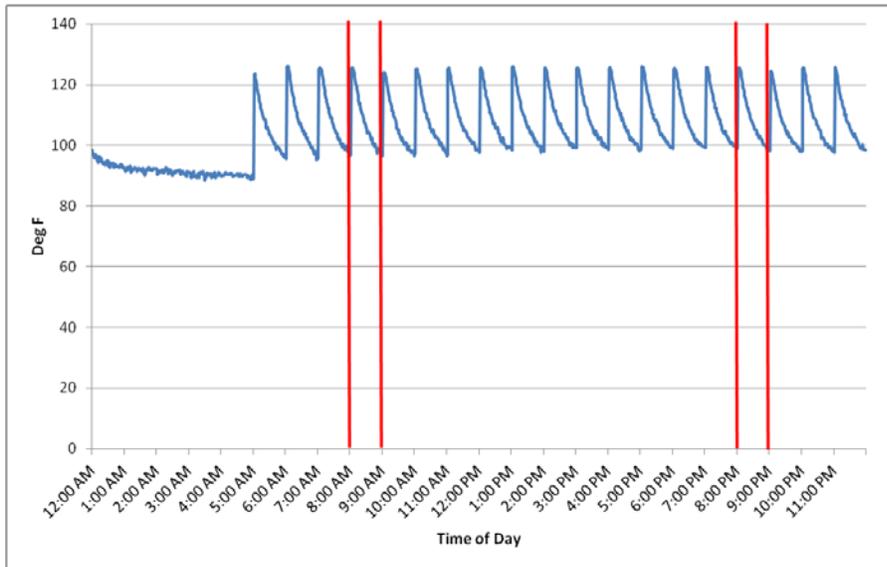


Figure 16. GE ERWH Balancing INC Delivered Water Temperature Profile: 8:00 a.m. and 8:00 p.m.



In comparison with the ERWH baseline, the ERWH balancing INC DR profile highlights a demand shift of 4.6 kW for each of the two displaced water heater activation events. This shift is evident in the graph, where at 9:00 a.m. and 9:00 p.m., the ERWH goes into recovery mode in which it draws the same 4.6 kW of power but over a longer duration. No impact on delivered water temperature was evident.

Table 3 summarizes the oversupply capability of the water heaters tested at the PNNL Lab Homes – the 60-gallon ERWH, 40-gallon Sanden unitary HPWH, and 80-gallon split system HPWH. Note that the measured oversupply mitigation storage is comparable among the systems, while the dispatchable power of the ERWH is approximately 3.5 times greater than that of the HPWH, requiring the HPWH to operate longer to fill the storage created during the down time.

The table also highlights the capacity savings of the HPWH compared to the ERWH. The high capacity may appear to be an advantage of the ERWH in DR potential, but in overall operation it contributes to the problem of high-capacity use compared to the HPWH performing the same task.

Table 3. Comparison of ERWH Oversupply and Balancing INC Performance to HPWH

Experiment Metric	ERWH	Unitary System HPWH	Split-System HPWH
Oversupply Experiment			
Dispatchable Power (kW)	4.6	1.3	1.2
Energy Storage (kWh)	2.69	2.65	2.95
Oversupply Duration (hours)	3	6	6
Max Off for Storage (hours)	3	6	12
Balancing INC Experiment			
Dispatchable Power (kW)	4.6	1.7	1.6
Energy Storage (kWh)	0.86	1.7	1.6
Balancing INC Duration (hours)	1	1	1

Energy Use

The original question posed concerning energy was: What is the impact of DR on system efficiency? Because the period during which testing occurred at the Lab Homes included dynamic changes in weather, it was not possible to determine the impact the DR measures had on system performance. If all the testing could have been done in summer, the conditions might have allowed meaningful observations related to this issue. Instead, the question is addressed in the controlled environment of the lab, which is the next section of this report. The actual test conditions during the controlled field study are show in **Table 4** (Sullivan et al., 2015, p. 4.1).

Table 4. Test Conditions During Controlled Field Study

Water Heater/Metric	Baseline	Oversupply	Balancing INC
Sanden Unitary HPWH: dates of experiment	August 2014	October 2014	November 2014
Average source air temperature ^a	71.2°F	59.6°F	46.8°F
Average supply water temperature	70.4°F	63.5°F	59.7°F
Sanden split-system HPWH: dates of experiment	August 2014	October 2014	November 2014
Average source air temperature ^b	72.0°F	53.7°F	23.7°F
Average supply water temperature	70.4°F	63.5°F	59.7°F

^aAir is taken from the crawlspace beneath Lab Home A and exhausted outside through a vent in the water heater closet door.

^bAir is sourced at the split-system evaporator adjacent to Lab Home B (i.e., outdoor air).

The energy use in watt hours per gallon for the various tests is shown in **Table 5** (Sullivan et al., 2015, p. 4.1). The most interesting finding is the low energy use per gallon at the 70°F and 50°F temperatures (baseline and oversupply testing, respectively) and the increase during November with the 20°F to 40°F air source temperatures (balancing INC testing). The air supply to the unitary HPWH was warmer than the OSA temperature used by the split system during the DR tests because it came from the crawl space of the home. The result is less energy used by the unitary system. When the ERWH is compared to the HPWH, the efficiency of the HPWH is highlighted.

Table 5. Energy Use During Tests

System	Baseline (Wh/gal)	Oversupply (Wh/gal)	Balancing INC (Wh/gal)
Unitary System – Lab Homes Test	41.5	43.7	67.7
Split System – Lab Homes Test	36.0	44.3	76.1
ERWH – Lab Homes Test	153.7	151.0	148.5

Lab Tests

The lab tests were designed to explore issues identified by the controlled field study protocol and results, and to delve into questions uniquely addressable in the controlled lab environment. The two complementary sets of experiments allowed the project to look at the impacts of an extreme draw amount in a situation governed by actual weather at the PNNL Lab Homes, while the lab focused on average daily draw volumes at set temperatures and issues such as freezing caused by shutting the system down for extended periods. One of the unique tests conducted at the lab was to map the Coefficient of Performance (COP) to measure DR impact on efficiency and performance.

The HPWHs tested in the Lab Homes were also tested in the Cascade Engineering lab, and were subjected to similar tests. The split system was set up with only the outdoor unit in the climate-controlled chamber, while the entire unitary system was placed inside. In this case, both compressor units experienced exactly the same conditions, while at the Lab Homes the unitary system supply air was taken from the crawl space beneath the home and was somewhat warmer than the OSA that the split system was subjected to.

Protocol Development

The lab test protocol was developed by Ecotope within the context of the controlled field study. The first draft lab test protocol was delivered by Ecotope on October 29, 2014 and was revised in light of information provided by PNNL from the controlled field study. The revised draft was discussed in a conference call with BPA and PNNL on December 2, 2014, and the final protocol was delivered on January 20, 2015.

The lab test protocol specified COP mapping tests, draw profile and demand response tests, and water circulation line temperature tests. The COP mapping is necessary to understand the impact on energy use as the season and time of day change for implementing DR measures, and to provide data for simulation. These experiments increased the number of temperatures at which COP was tested compared to the Lab Homes tests (Larson, 2013, p. 20).

The draw profile tests were the direct DR experiments. The key difference from the controlled field study DR tests was the amount of the daily draw. In the lab tests, the daily draw was 46 GPD based on average use rather than the large draw amount of 130 GPD at the Lab Homes. The tests conducted were oversupply mitigation and load shedding, also known as balancing INC.

The water circulation line temperature tests measured the rate of heat loss of the water lines connecting the split system outdoor unit to the tank during periods when the system was not operating due to DR testing. Based on these tests, the time to freezing at specified outdoor temperatures was calculated.

Lab Tests

The lab tests were conducted at Cascade Engineering Services in Redmond, Washington, in February and March 2015. Analysis took place during spring and summer of 2015. The lab test report is electronically attached to this report as Appendix B.

COP Mapping Tests

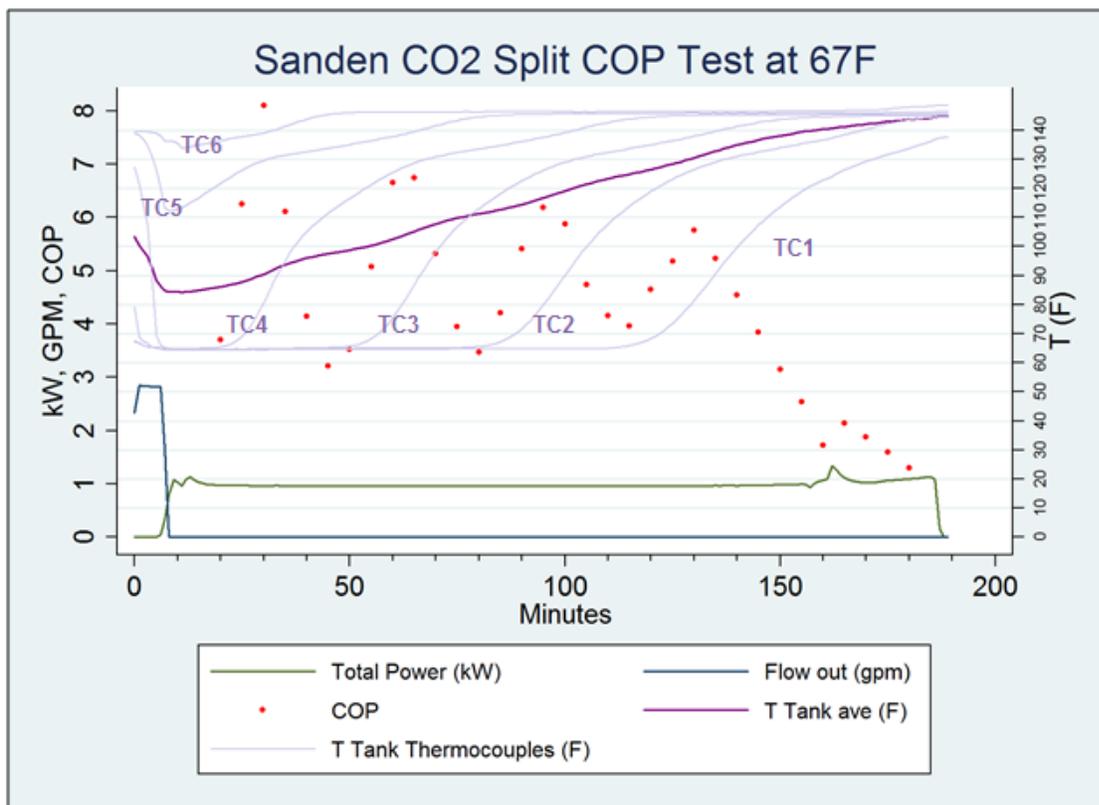
The COP is the change of energy in the water caused by the heat pump divided by the energy used to operate the heat pump. Equipment efficiency must be known to determine the impact of DR services on energy use and changes in performance as time of day and seasons change. Performance testing in the lab previously determined COP at 50°F and 67.5°F for both units; these tests added COP measurements for 17°F, 35°F, and 95°F.

The COP tests start with a tank at the cold water temperature (55°F to 65°F) and measure the energy needed to heat the water to near setpoint temperature. The tank has a string of sensors to measure the temperature at six different levels from which the energy introduced into the tank can be calculated.

Figure 17, taken from the original lab test report by Ecotope, shows the COP test at 67.5°F (Larson, 2013, p. 20).

The COP declines as all of the tank temperature levels approach setpoint. This is because there is little temperature difference to drive heat exchange from the refrigerant to water.

Figure 17. COP Test at 67°F Ambient – Split System



Figures 18 and 19 show the COP maps for the unitary and split systems. 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. Moreover, the COP mapping showed the strong dependence of efficiency on the water temperature entering the heat exchanger in the base of the outdoor unit. The hotter the water, the worse the relative heat transfer and the lower the COP. For example, the split system GAU graph shows that at 35°F ambient air (green points), the COP is 3 if the water being heated enters the heat exchanger 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.

Figure 18. COP Map for Sanden GES 40-gallon Tank – Unitary System

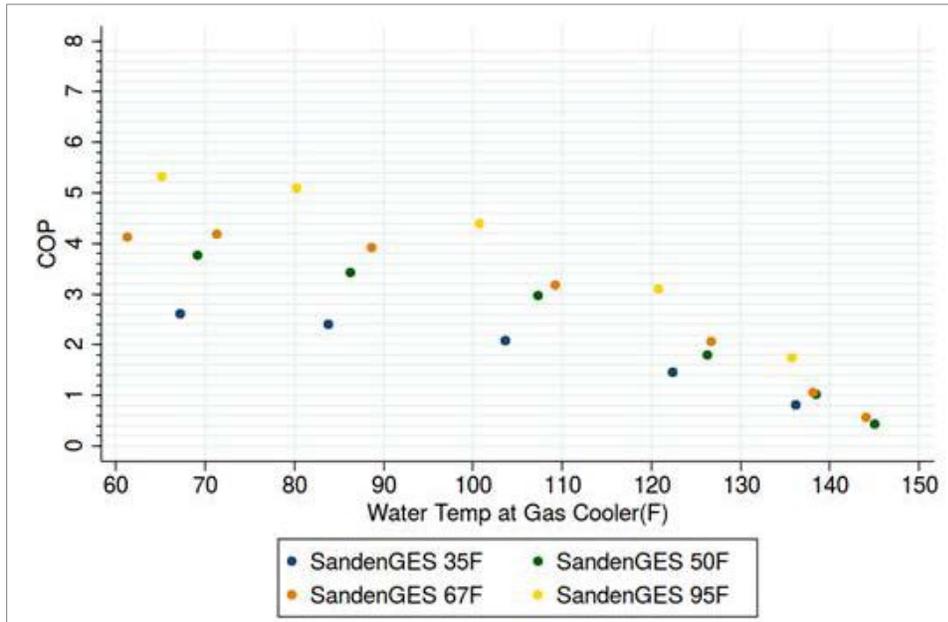
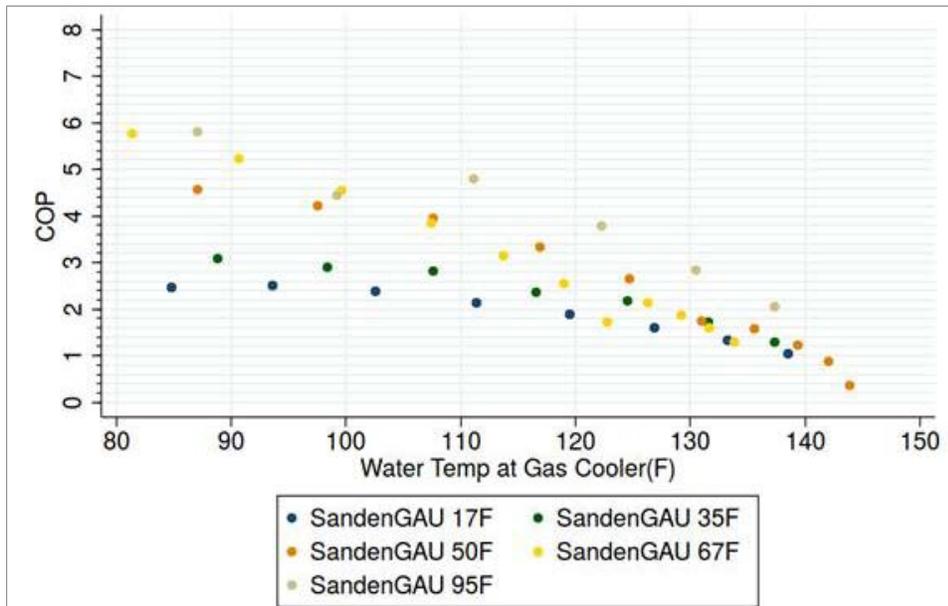


Figure 19. COP Map for Sanden GAU 80-gallon Tank – Split System

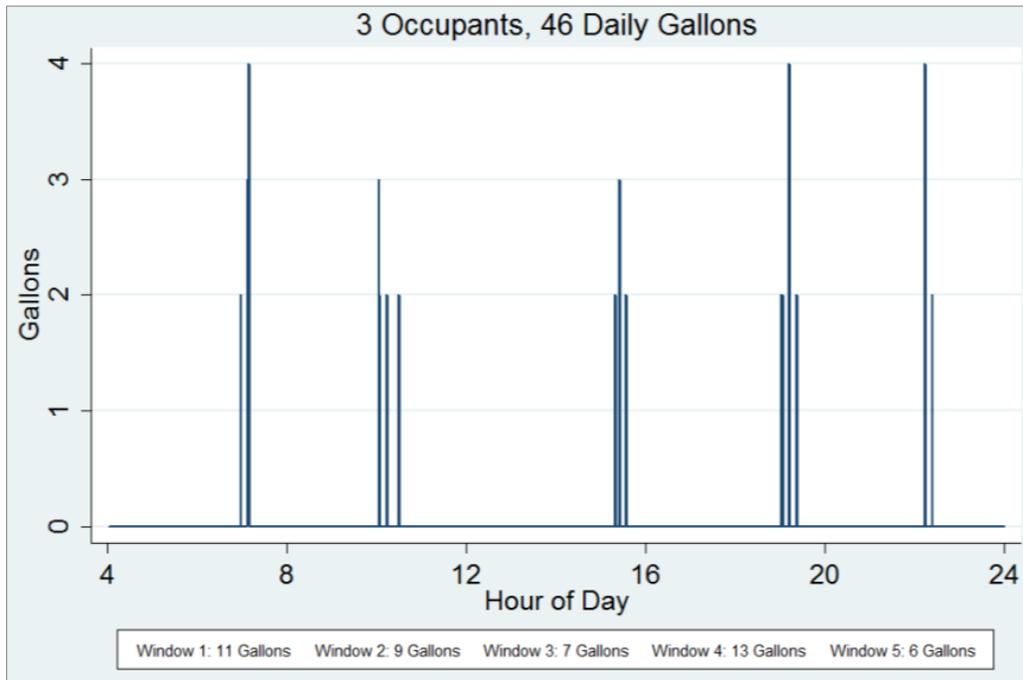


Demand Response Profiles and Tests

The DR tests consist of two patterns that take place on a 24-hour schedule: a water draw pattern and DR scenarios overlain on the draws that shut the heat pump down while the draws continue.

The lab test draw pattern in **Figure 20** is a representative three-person draw profile based on field study measurements in the Pacific Northwest (Ecotope and NEEA, 2015). The schedule is 24 hours with five clusters of water use throughout the day.

Figure 20. Hot Water Draw Profile



The second pattern is the DR scenarios overlain on the draw pattern. The lab test included the same DR tests as those done at the PNNL Lab Homes – oversupply mitigation and balancing INC – but they were combined into a daily pattern. This was possible because the amount of the daily draw was reduced from 130 to 46 GPD. **Figure 21** shows the DR scenarios and their relationship to the draw profile. The red blocks show when the heat pumps were allowed to operate.

The tests were aimed at the peak power demand periods with a shutdown for balancing INC from 6 a.m. to noon and a longer shutoff from 2 p.m. to midnight to create a demand reserve for oversupply mitigation.

DR tests were conducted at 35°F, 50°F, and 67.5°F ambient. The unitary system performed predictably with heat pump operation at the beginning of each period of allowed operation. As the supply air temperature increased, the power used by the system decreased. The test at 35°F is shown in **Figure 22**.

Figure 21. Lab Test Draw and DR Schedule

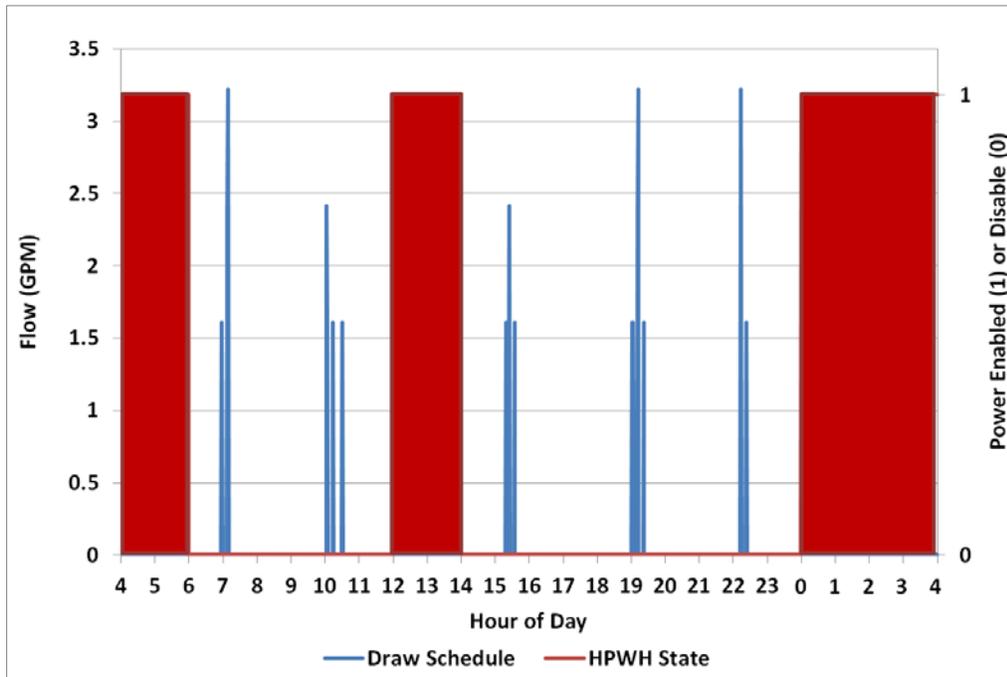
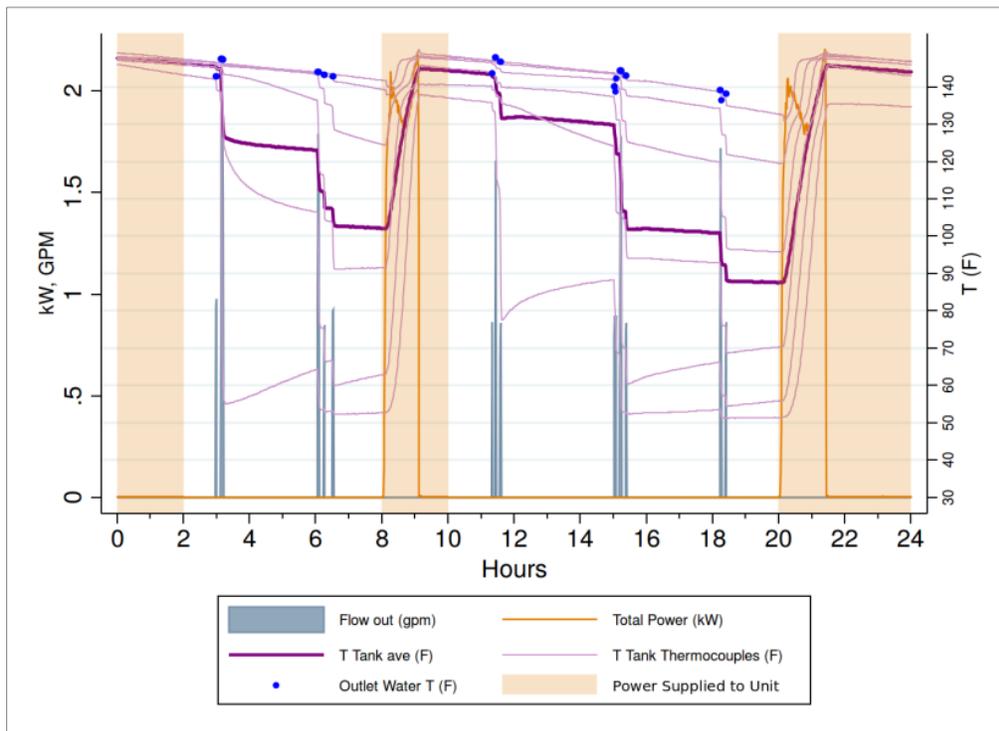
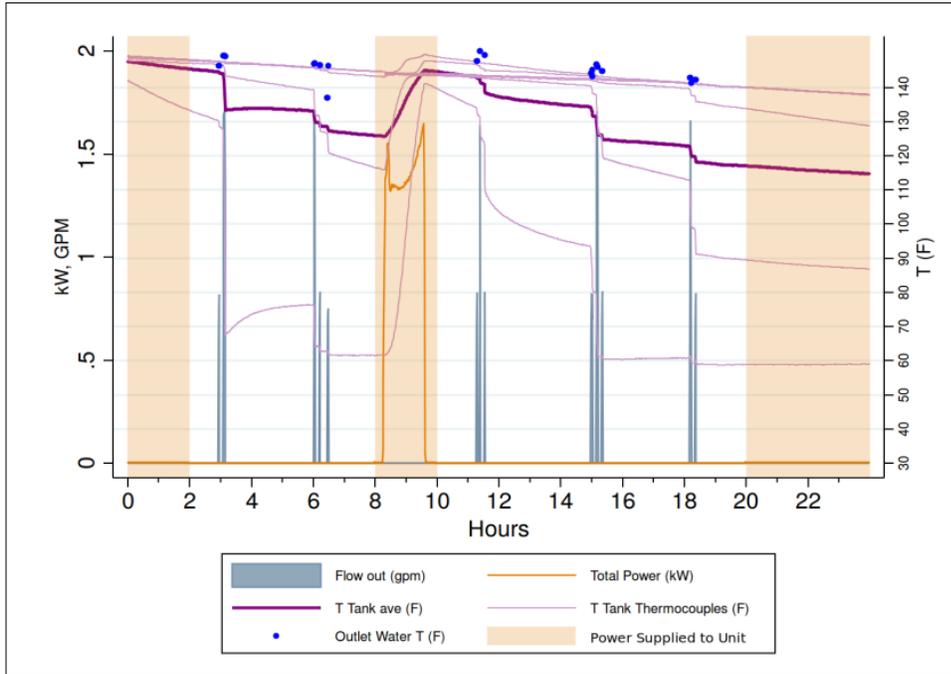


Figure 22. GES 40-Gallon Tank DR Profile Test at 35°F – Unitary System



The split system operated only once during the midday ON period at 35°F, but operated at the start of the midday and midnight power-on periods at 50°F and only at midnight during the 67.5°F test. Like the unitary system, the split system used less electricity and lower power capacity as the supply air temperature increased. In the Ecotope report, graphs for both systems at all temperatures are shown. **Figure 23** shows the split system operation.

Figure 23. DR Profile Test at 35°F – Split System



At no time were the outlet water temperatures below temperatures usable by typical households.

Table 6 shows the minimum and mean outlet temperatures produced during the tests.

Table 6. Minimum and Mean Outlet Temperatures

Ambient Temperature (°F)	GAU 80-gallon (Split System)		GES 40-gallon (Unitary System)	
	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

Measured Energy Use and Efficiency

The measured energy use and efficiency during the DR tests confirmed what was found in both the PNNL controlled field study and the lab COP mapping – that the energy use increases as the supply air temperature drops and COP decreases. The energy increase is caused by the increase in power needed to operate the compressor, pump, and fan faster to maintain heat output at colder temperatures.

- The energy use of the unitary system increased from 2.82 kWh at 67.5°F to 4.55 kWh at 35°F.
- The energy use of the split system was similar, though the 35°F test was reduced because the tank did not fully recover its temperature to setpoint by the end of the test and only 1.9 kWh was measured, as shown in **Table 7**.

Table 7. Draw Profile and DR Test Summary Results

Supply Air 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)
GAU 80-Gallon Tank (Split System)							
35	2.1	23,365	3.09	1.9	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	1.0
GES 40-Gallon Tank (Unitary System)							
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	1.80	2.82	29,577	2.8	1.3

Measured Storage Capacity

Effective oversupply mitigation requires knowing the amount of energy storage space available in the water heater tank at the end of the day – it is the amount of energy required to heat the water in the tank from its temperature at the end of the storage period to setpoint. **Table 7** also shows the energy storage capacity for oversupply mitigation for the unitary and split system HPWHs.

Supply air temperature impacts the amount of energy storage because the lower the temperature of the source air, the more heat pump energy is needed to bring the stored water to setpoint. For example, the unitary system can store 2.8 kWh at 35°F, but only 1.8 kWh at 67.5°F. Both energy storage and system power are impacted by supply air temperature.

The main factor that determines oversupply capacity is how much hot water was used before the event. As long as the water heater can provide this capacity, the size of the tank is irrelevant. However, as was shown by the PNNL controlled field study, a smaller-capacity water heater may not be able to meet load as demand increases. In that case, only a larger tank size unit will serve to provide effective DR service.

It is possible to increase capacity by raising the heated water temperature. This increases DR potential in two ways:

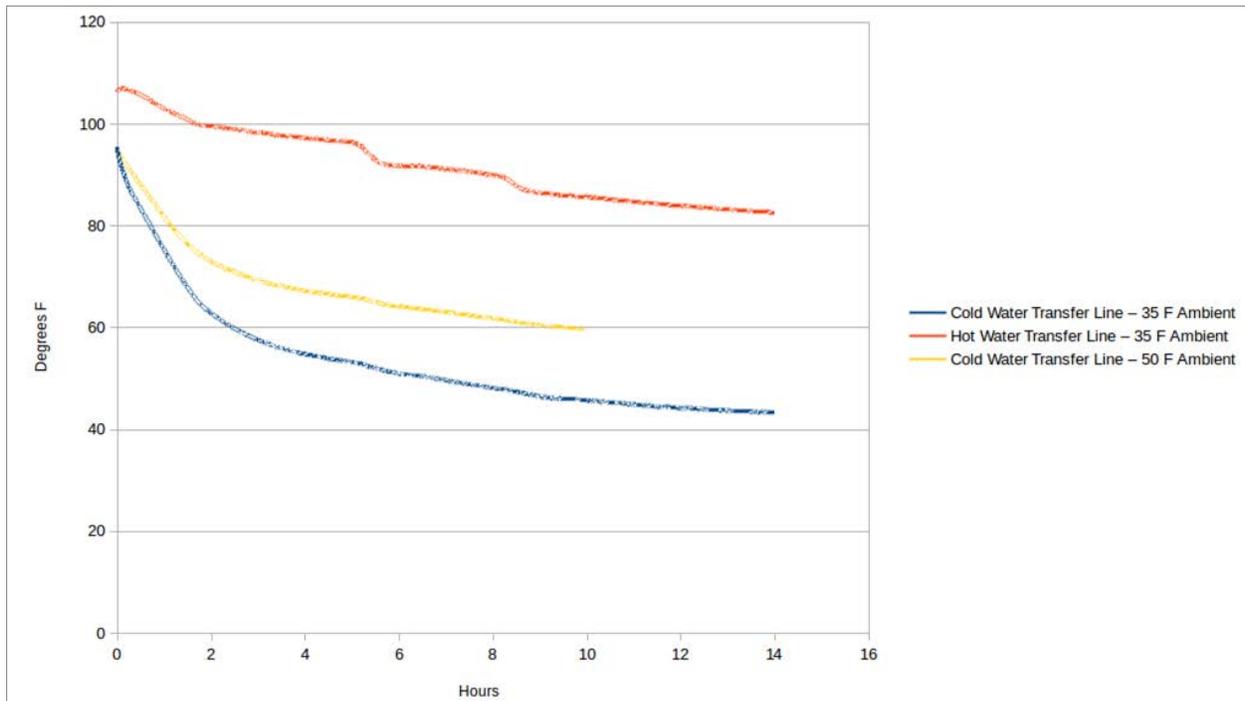
- First, it increases the storage capacity of the tank by absorbing more energy.
- Second, it increases the energy demand when the system is activated because delivering hotter water requires more energy. This could be an asset in oversupply mitigation, though it will reduce system efficiency by lowering COP and increasing tank losses. It will also increase heat stored beyond daily household demand and make the system less available for immediate future use.

Circulation Line Temperature Experiments

The split system has water lines that move water between the storage tank and the outdoor unit. Though they are insulated and protected with circulation routines built into the system control, the systems are vulnerable when turned off for a substantial period of time without heat tape, or when the power fails and all protection is disabled.

Ecotope researched the temperatures of the water lines in the thermal chamber as the air temperatures were chilled for the low-temperature COP mapping and DR tests. **Figure 24** shows the temperature measurements in the lines as the temperature dropped.

Figure 24. GAU Split-System Water Transfer Line Temperature Profile



By subtracting the ambient temperature, the data follows an exponential fit that matches the actual decay after the initial temperature drop. This is described in detail in the lab test report (Ecotope and NEEA, 2015). The summary estimates of freezing times at various temperatures based on this analysis are shown in **Table 8**.

Table 8. Estimated Freezing Times at Ambient Temperatures

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

The split system already has automatic water circulation to prevent freezing when the system is on. The risk of freezing occurs when the system is turned off for oversupply mitigation and the heat tape on the

pipes is not functioning, or the power goes off for extended periods of time during freezing conditions. The solution for DR setup is to keep the system on so it can operate anti-freezing and defrost protection, but with DR controls so the system can stay off for purposes of heating when thermal storage or load balancing is taking place. The manufacturer is already designing automatic protection against system freezing when the power is off for long periods.

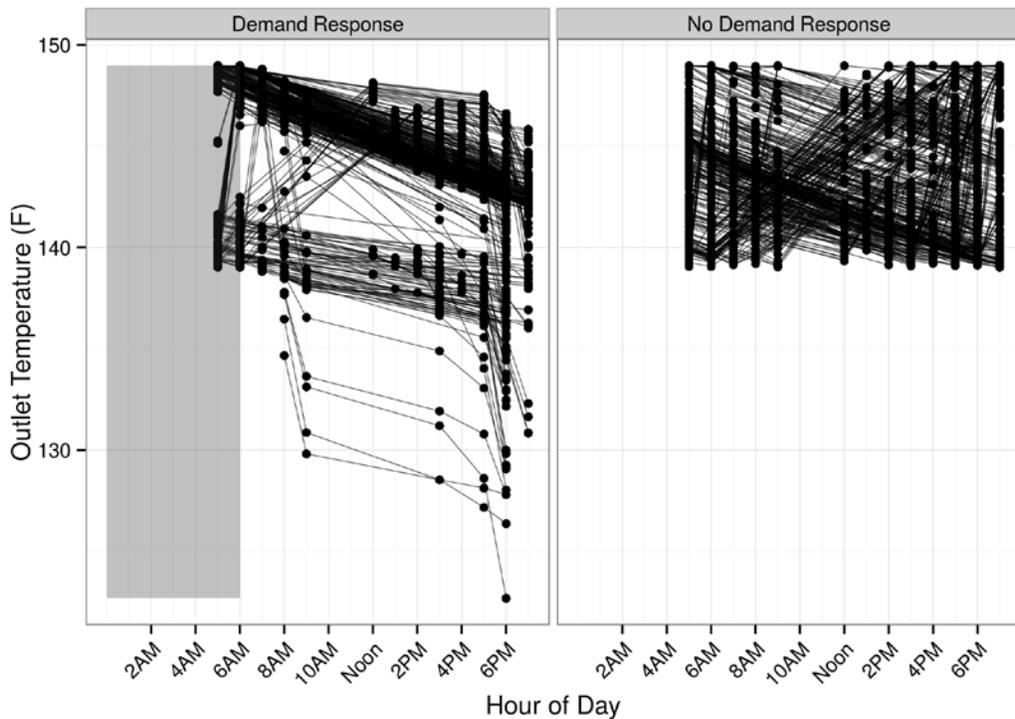
Simulation

The lab tests provide a wealth of information. With simulation, that information can be used to explore unlimited DR situations. It is also the best way to answer the research questions, particularly the impact of DR on system efficiency when it requires operation at nighttime or during off-peak hours.

Ecotope created a simulation for HPWH performance for its earlier work analyzing field study results of HPWH performance and normalizing those results for standard weather conditions. With modification, Ecotope used this tool to analyze DR scenarios using Typical Meteorological Year data for Portland, OR and Spokane, WA in households with one to five members using 23 to 72 GPD. The simulation included seven unique draw days per week to reflect variability based on actual data from large-scale field monitoring. The simulations allowed the researchers to view daily operation and annual performance.

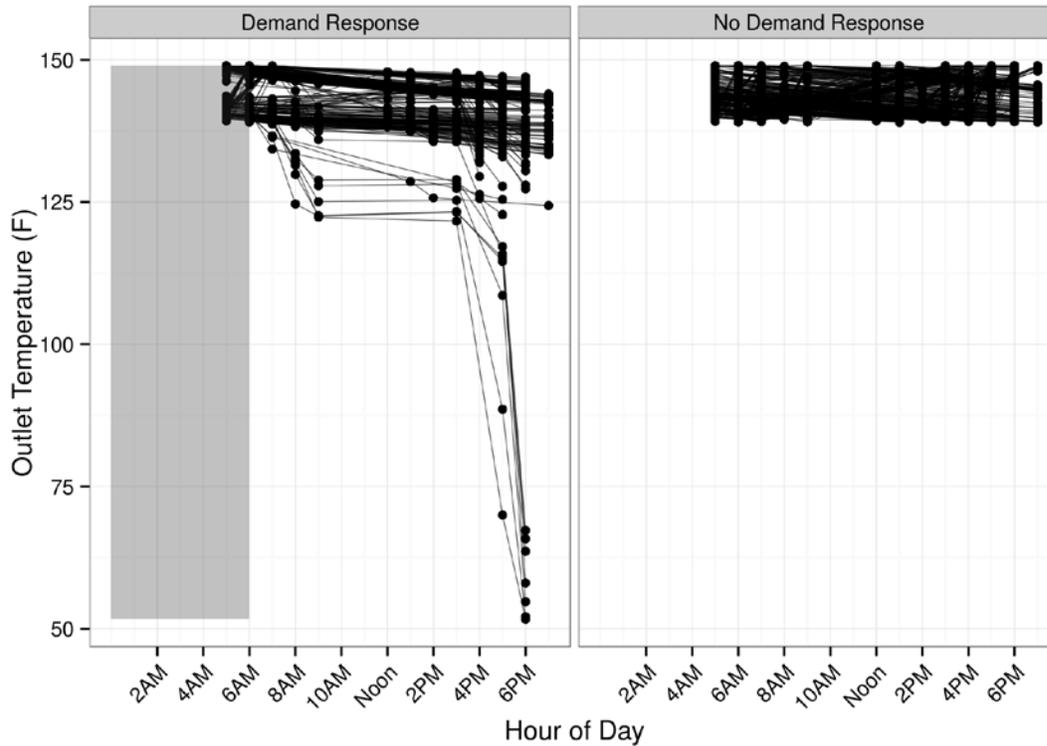
Figure 25 shows the outlet water temperature before tempering for each hot water use during a simulated year in Spokane in a household of three people with an 80 gallon system doing oversupply mitigation. In the three-person household, the water temperature never went below 120°F, resulting in no usability failures in the DR case shown on the left. With DR, there is no risk of cold showers.

Figure 25. Simulated Outlet Temperature, Oversupply Event, 3-Person Draw in Spokane – Split System



The situation is different in the four-person household. **Figure 26** shows the same Spokane system doing oversupply mitigation DR with one more water user. Note that there are seven days where the output water temperature drops below 105°F in the afternoon and 12 days where the water temperature dropped below 120°F. Modeling further indicates that the number of hot water usability failures increase with five water users and with the smaller tank of the unitary system.

Figure 26. Simulated Outlet Temperature, Oversupply Event, 4-Person Draw in Spokane – Split System



Efficiency Impact

Simulation can reveal surprising results. Ecotope simulated the annual COP including tank losses for the unitary and split systems, and compared the efficiencies of systems doing no DR and those doing oversupply mitigation. The results are shown in **Figure 27** for Portland and **Figure 28** for Spokane.

The main finding here is that DR does not necessarily reduce system efficiency. The solid lines show that the annual simulated system efficiency is higher for both the unitary and split systems with DR than without it. The conclusion is that the tanks operate colder when the system is subjected to DR, which reduces tank losses and significantly improves performance.

Figure 27. System Annual COP in Oversupply vs. Number of Occupants in Portland, OR

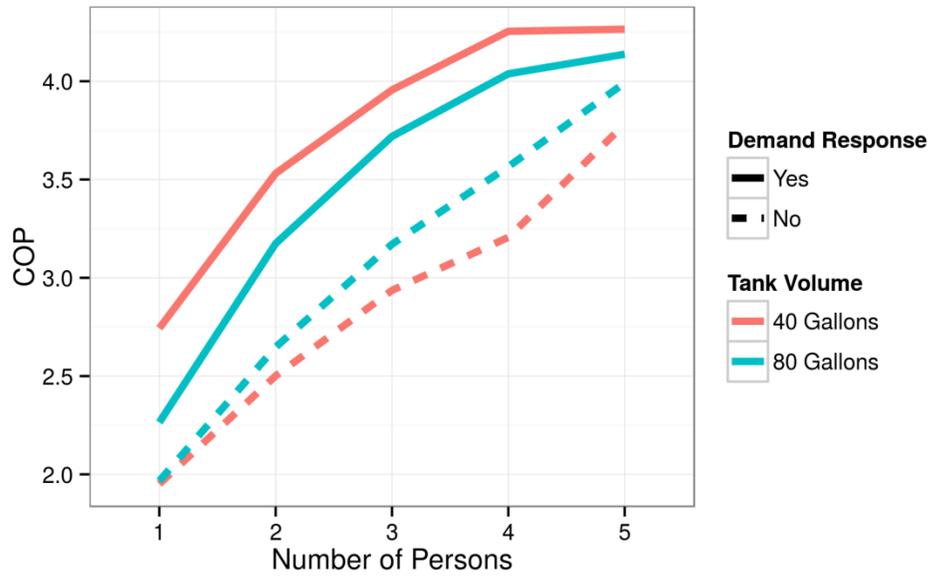
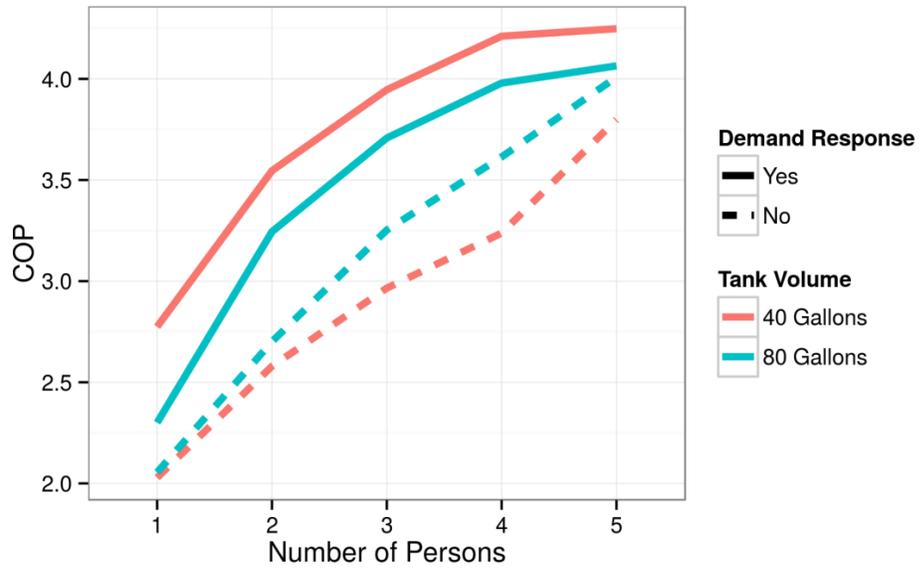


Figure 28. System Annual COP in Oversupply vs. Number of Occupants in Spokane, WA



Conclusions

The conclusions are designed to address the specific research questions stated on page 2 of this report within the larger context of this study and, where relevant, the broader body of research and policy surrounding these topics.

1. Both the 40-gallon unitary and 80-gallon split system HPWHs are capable of implementing DR in both balancing INC and oversupply mitigation modes. Table 9 compares PNNL’s measurements for energy storage capacity, which segregated the DR experiments, to Ecotope’s measurements, which combined balancing INC and oversupply mitigation tests. The PNNL results are impacted significantly by the 130 GDP draw amount, and it is demand that establishes the storage capacity. However, PNNL’s results show the upper limit at the fixed temperature setpoint of both systems.

Ecotope’s test results reflect the split system operation, which operated only once at 35°F and 50°F, but twice during the 67.5°F test, resulting in more storage capacity at 67.5°F than at 50°F. Although the draw was 46 GPD, the total energy storage measured by Ecotope’s combined test across all temperature ranges is roughly comparable to the PNNL results for both systems.

Table 9. Comparison of Energy Storage in the PNNL and Ecotope Tests

Tester	System	Supply Air T	Oversupply	Supply Air T	Balance INC
PNNL	Split	53.7°F	2.95 kWh	23.7°F	1.6 kWh
	Unitary	59.6°F	2.65 kWh	46.8°F	1.7 kWh
Tester	System	Supply Air T	Combined Storage Capacity		
Ecotope	Split	35°F	3.09 kWh		
		50°F	2.55 kWh		
		67.5°F	2.75 kWh		
	Unitary	35°F	2.79 kWh		
		50°F	2.29 kWh		
		67.5°F	1.80 kWh		

In terms of actual application, a thousand split systems with average water use during a spring oversupply situation would provide approximately 2.5 MWh of storage. At an average power draw of 1.35 kW (average of PNNL and Ecotope measurements), they would exert 1.35 MW of demand. These estimates are based on average water use and weather and will be influenced by diversity in these factors.

These systems provide constant kW capacity reduction by using one-fourth the energy to heat water that is used by ER heaters. Their DR potential is icing on the cake.

2. According to the Ecotope simulation results, DR services enhance system efficiency because they lower tank temperature and reduce heat loss. Given that the CO₂ refrigerant systems operate at higher temperatures than most water heaters, this effect will not be as significant in other systems, though it will be present.

This may be the most important finding of this research. It removes a key barrier to DR with HPWHs, which was the notion that pushing operation into colder times of the day would cost the homeowner significantly more in operational energy. This is not the case, at least with CO₂ HPWHs that operate well in cold weather.

3. Another DR strategy is to increase hot water temperature and use the delta as thermal storage. It is a possibility with CO₂ technology. Sanden already produces a model that has settable temperatures from 149°F to 194°F. It appears that it would negate the advantage that DR gains from reducing tank temperature over regular operation. Simulations could easily answer how much impact this type of storage would have on efficiency.

4. Split systems have no impact on conditioned space. When the unitary system is ducted, it also has no impact because its supply air comes from outside. In addition, they are extremely quiet.

DR increases power draw in cold weather. The coldest test in this research project was PNNL’s balancing INC test on the split system, which took place at 23.7°F and created a power draw of 1.6 kW. Compare this to Ecotope’s measured power draw of 1.0 kW at 67.5°F, and the impact of cold weather operation on power use is clear. The magnitude of the simulation finding that DR enhances annual efficiency is made more remarkable by this fact of increased power use in cold weather.

5. How do CO₂ HPWHs compare to ERWHs? **Table 10** shows results on both efficiency and DR, drawing on other research on these systems by WSU and PNNL.

Table 10. Oversupply Mitigation and Balancing INC Summary

Experiment Metric	GE ERWH	Unitary System HPWH	Split-System HPWH
Oversupply Experiment			
Dispatchable Power (kW)	4.6	1.3	1.2
Energy Storage (kWh)	2.69	2.65	2.95
Oversupply Duration (hours)	3	6	6
Max Off for Storage (hours)	3	6	12
Balancing INC Experiment			
Dispatchable Power (kW)	4.6	1.7	1.6
Energy Storage (kWh)	0.86	1.7	1.6
Balancing INC Duration (hours)	1	1	1

This table is taken directly from the section comparing PNNL research in the controlled field study to previous research on ERWHs subjected to the same high-demand profile. Note that both CO₂ HPWH systems could meet setpoint temperatures far longer than the ER system when turned off. This is probably the result of higher water temperatures. In addition, the stored energy capacity is comparable. The power draw for the HPWH, labeled dispatchable power, is approximately one-third that of the ER heater, meaning the HPWHs will operate three times longer when they are put into oversupply mitigation mode to fill the stored energy capacity created by the power shut off.

The HPWHs also provide significant capacity reduction in normal operation compared to ERWHs through reduced power needed to perform the same task. With the ability to heat water with only one-quarter the power use, CO₂ HPWHs avoid creating capacity issues.

Table 11 compares the efficiencies and performance of ERWHs, standard HPWHs, and CO₂ HPWHs. In terms of performance, CO₂ HPWHs heat water more efficiently than either ER or standard HPWHs. The split system also provides more than twice the number of energy efficient showers (the Northern Climate Delivery Rating) than the average HPWH, due primarily to tank size. This means that investment in this technology is an all-round winner from a DR, efficiency, and performance perspective.

Table 11. Comparison of Water Heater Efficiencies

Standard	ERWH	Std. HPWH	CO ₂ HPWH
First Hour Rating (gal)	58	58	97.8
Energy Factor (DOE)	0.93	2.0	3.4
Northern Climate EF (NEEA)		2.0	3.2
Delivery Rating		2.5	7.5
kWh per Gallon	0.23	0.11	0.05

6. Where a technology provides both efficiency and DR services, it should be valued for each and the values should be additive. It is easy to overlook this because we take for granted the capacity reduction created by most efficiency technologies. This is about to change with the 7th Power Plan, which will value capacity. Where a technology also performs DR services like balancing and oversupply mitigation, these should be valued independently from capacity. In that way, it ensures the technologies will be properly evaluated and incented so they can be implemented. This is the second most important finding of this study. DR service is a legitimate value independent from efficiency. When the two are combined, the technology is more likely to be cost effective. Because the 7th Power Plan features both efficiency and DR, it is important that we use this new water heating technology as a case study to encourage the manufacturer to equip it for DR service.

7. The two systems tested by PNNL and Ecotope were not equipped for remote dispatch, though an effort was made to equip them with CEA 2045 communication. That effort failed because the 2045 protocol was not developed sufficiently to enable programming a control mechanism, though the manufacturer worked with EPRI to obtain a prototype. Therefore, the systems were controlled by exterior programmable switches that switched power to the heat pumps on and off according to DR schedules.

Many issues are created by this type of control, including:

- Turning off the unit also turns off the system’s defenses. Without power, the unit cannot defrost the outdoor unit or circulate tank water through the connecting pipes and heat exchanger to prevent freezing, or properly operate the automatic drain the manufacturer is developing.
- Turning off the unit creates the risk that it will run out of hot water when demand is high. If the system is powered, it can detect when it is out of hot water and operate the heat pump to avoid delivering cold water. This would allow larger households and sites in cold locations to participate in DR services.
- This blunt control strategy does not incorporate intelligent communication and dispatch where the system can assess its DR potential and communicate it to the DR command center, update the command center as the situation changes, and receive commands. It is this type of intelligence that will make equipment like this water heater part of a truly integrated power system.

8. The DR benefits revealed by these tests indicate that this is a highly efficient technology that can provide high-capacity storage for oversupply mitigation and can facilitate load balancing – in the same 24 hour period if necessary. This operation increases rather than decreases long-term efficiency. The equipment already has sophisticated controls, which can easily be adapted to DR communication once the region decides on a mature DR communication protocol and works with manufacturers to incorporate that ability into their products.

Because oversupply capacity depends on load, high loads provide greater storage potential and cold climates provide greater power demand. High-occupancy households, combined space and water heating systems, and sites in cold areas should be encouraged and enabled to participate.

Because this technology is expensive, the region will have to actively support it to ensure its implementation. A number of steps to accomplish this are described in the recommendations. Generally, a great deal must be done to prepare the way to integrate this great potential into the DR system.

Recommendations

The primary need for this technology is that it be properly valued in the regional system so that it can be broadly implemented by utilities throughout the region. This valuation will allow manufacturers to invest in the technology. A clear DR path for water heater manufacturers is also needed. Specific recommendations are designed to meet these needs:

1. BPA should lead in development of and support for a regional (and national) solution for DR communication and assist all HPWH manufacturers to implement it. This could include encouraging NEEA to incorporate a DR component into the AWHS.
2. BPA should advocate that normal operation capacity reduction capability be valued and included in the regional cost-effectiveness calculations for HPWHs. For example, the capacity reduction of the CO₂ HPWH studied in this project is 3 kW. Providing that capacity is a value that is in addition to efficiency value, and it should be credited in the Total Resource Cost analysis.
3. BPA should support valuation of DR as an incentive measure through the Regional Technical Forum (RTF). This value should be additive to efficiency and capacity values, and included in cost-effectiveness analysis for technologies that implement DR.
4. Utilities with high-capacity renewable energy portfolios should implement programs to encourage installation of DR-enabled CO₂ HPWH, especially in single-family homes with high hot-water loads, multi-family, and commercial/institutional settings.
5. Manufacturers of HPWHs should invest in intelligent DR with communication capability. Characteristics should include ability to:
 - Schedule oversupply mitigation,
 - Assess and report energy storage capacity,
 - Implement oversupply mitigation and balancing INC, and
 - Power on when dispatched.

The utilities will need to lead this effort. Until there is a clear agreement among utilities and power marketing entities (BPA and WAPA) for a specific, well-developed protocol and a commitment to invest in its implementation, manufacturers cannot move forward.

6. Manufacturers of split system HPWHs should invest in live DR controls that provide defrost and freeze protection during oversupply mitigation capacity building (power down) and can activate the heat pump if needed to provide hot water during this time rather than allow delivered water temperatures to fall below usable limits.
7. Manufacturers of high-temp CO₂ HPWHs should consider increasing tank insulation to enhance efficiency and performance in both normal and DR operation.

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NEEA HPWH Advance Water Heater Specification 6.0, May 10, 2016. This version contains a requirement that new, higher tiers have DR capability. It does not cover split system HPWH.

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Appendix A: PNNL Lab Homes Test Report

Please click this link to open the report.

http://www.energy.wsu.edu/documents/Sanden_HPWH_FINAL_rev_11-24-15.pdf

Appendix B: Ecotope Report on Cascade Engineering Services Lab Test

Please click this link to open the report.

http://www.energy.wsu.edu/documents/Sanden_CO2_HPWH_DR_lab_report_final.pdf