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Demand-Response Performance of Sanden Unitary/Split-System Heat Pump Water Heaters

GP Sullivan
JP Petersen

July 2015

WASHINGTON STATE UNIVERSITY

Prepared for Washington State University
under a Commercial Work for Others Agreement
with the U.S. Department of Energy
Contract DE-AC05-76RL01830

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Richland, Washington 99352

[1] Principal, Efficiency Solutions, LLC, Richland, Washington. Mr. Sullivan was involved in this project under a subcontract with Washington State University.

Summary

Increasing penetration of heat pump water heaters (HPWH) in the residential sector will offer an important opportunity for energy savings, with a theoretical energy savings of up to 63% per water heater[1] and up to 11% of residential energy use.[2] However, significant barriers must be overcome before this technology will reach widespread adoption in the Pacific Northwest region and nationwide. One barrier is that the demand-response (DR) performance and characteristics of HPWHs is unknown. Previous research has demonstrated the potential of electric resistance water heaters (ERWH) to provide significant grid stability and control benefits through demand-side management, or DR, strategies.[3] However, if ERWHs are to be replaced with HPWHs to improve residential energy efficiency, it is important to understand the DR characteristics of HPWHs and how these characteristics will impact DR programs and overall grid stability now and in the future.

This project evaluates and documents the DR performance of two Sanden CO_2 HPWHs for two primary types of DR events: peak curtailments and balancing reserves. The experiments were conducted in the Pacific Northwest National Laboratory (PNNL) Lab Homes[4] using a Sanden Split-System 83-gallon GAUS-315 EQTA HPWH and a Sanden Unitary 40-gallon GES-15QTA HPWH.

Three tests were conducted for each of the three water heaters: 1) a Baseline test, 2) an Oversupply test (peak curtailment), and 3) a Balancing INC test (balancing reserves). The purpose of the Baseline test was to understand the normal operation of each unit before initial testing began and quantify the energy use, captured as kWh/day, of each of the water heaters. The Oversupply test was conducted to identify the total Dispatchable Power, and resulting energy shift, that the noncritical load can provide during a 3 to 12 hour window. The Balancing INC test provides results that show the response of sub-hourly changes in demand and the available Dispatchable Power/energy shift associated. More details about these DR events and their effect on delivered water temperature can be found in Sections 3.5 and 3.6.

The water heaters in the PNNL Lab Homes were operated under near-identical simulated occupancy conditions and 130 gallons/day draw profile for all the tests. Testing was conducted over two different experimental periods. Testing of the Sanden HPWHs took place from August to November 2014.

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[1] Based on the DOE test procedure (10 CFR 430.32(d)) and comparison of an ERWH (energy factor, EF = 0.90) versus a HPWH (EF = 2.4)

[2] U.S. Energy Information Administration. 2009. *Residential Energy Consumption Survey*. Accessed August 6, 2013, at http://www.eia.gov/consumption/residential/.

[3] Diao R, S Lu, M Elizondo, E Mayhorn, Y Zhang, and N Samaan. 2012. *Electric Water Heater Modeling and Control Strategies for Demand Response.* IEEE Power and Energy Society General Meeting, 2012, pp.1–8, July 22–26 2012. DOI: 10.1109/PESGM.2012.6345632. Accessed August 6, 2013, at http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6345632

[4] http://labhomes.pnnl.gov/

The Oversupply DR reduction of noncritical loads for a period of 3 to 12 hours during times when power use is the highest were imposed on the two HPWHs. The DR schedules for the Sanden Unitary and Split-System HPWH Oversupply testing began with the water heaters powered-down at 6:00 PM, and then, for the next 7 days, this period was increased by 1 hour per day. The last day of the protocol has the HPWH powered-down for a full 12 hours from 12:00 PM to 12:00 AM. The delivered water temperature to the homes during the Sanden DR experiments was set to a nominal 120°F. This temperature was determined to be appropriate and representative of recommended residential delivery temperatures.

Balancing reserves respond to hourly changes in generation capacity because of either 1) inherent variability in the generation resource or 2) large disturbances in the grid. The balancing reserves for the Sanden Unitary and Split systems involved two different protocols: 1) singular DR balancing reserve periods lasting 1 hour per day and 2) an extended protocol that implemented three 1-hour DR events per 24 hours for the experimental period. Balancing INC is used when generation and load are mismatched because the load is higher than the generated power.

Table S.1 details the peak demand shift (dispatchable watts) and the resulting Recovery Energy Shift (shifted kWh) of each water heater. The increase in dispatchable watts for the HPWHs between the two experiments is attributed to the cooler source air and supply water encountered during the Balancing INC experiments that were conducted during the heating season.

Table S.1. Peak Demand and Recovery Energy Shift Summary

Experiment Metric	Unitary System HPWH	Split-System HPWH
Oversupply Experiment		
Dispatchable Power (kW)	1.3	1.2
Recovery Energy Shift (kWh)[a]	2.65	2.95
Oversupply Duration (hours)	6	6
Maximum Off Period while Delivered Temperature Met (hours)	6	12
Balancing INC Experiment		
Dispatchable Power (kW)[b]	1.7	1.6
Recovery Energy Shift (kWh)[c]	1.7	1.6
Balancing INC Duration (hours)	1	1

[a] The Oversupply Recovery Energy Shift is the water heater energy use at the conclusion of the Oversupply period.
[b] The increase in HPWH Dispatchable Power for the Balancing INC experiments results from the cooler source air and supply water during this period.
[c] The Balancing INC Recovery Energy Shift is reported assuming the protocol period aligns with a water heater activation event. Assuming alignment and the 1-hour event, the values listed are the maximum possible energy shifts.

Results from the Oversupply and Balancing INC tests show the magnitude of the peak demand and resulting Recovery Energy Shift of the Sanden water heaters. It is important to note that, by virtue of the higher water generation temperature (149°F), the HPWH power activation profile is not as regular as a standard electric resistance water heater. The HPWH tends to stay on for longer periods an off for longer periods resulting in fewer activation events over the course of a day. This operational characteristic can be important when developing DR impacts, particularly with a system that has less frequent and/or less predictable activation events.

Regardless of the protocol implemented, a key finding of this research is that alignment of the water heater power profiles, and the ability to have them coincide with enacted DR protocols, is an important consideration. Furthermore, because the Sanden HPWHs operate at temperatures of 149°F (and the Split-System has a larger tank capacity), the standard power draw profile is predictable (based on the enacted water draw profile); however, the activation events are less frequent than an ERWH.

After implementing a draw profile of at least 130 gal/day, the Sanden Unitary System was able to maintain the delivered water temperature while powered-down for 6 hours, and the Split System was able to maintain the delivered temperature while powered-down for a total of 12 hours.

Acknowledgments

The authors acknowledge Mark Jerome of CLEAResult for his expertise in the installation and commissioning of the Sanden water heaters. The assistance of John Miles of Sanden International, U.S.A in initial installation and troubleshooting various operational issues was greatly appreciated. The efforts of Sarah Widder of Pacific Northwest National Laboratory (PNNL) in initial project organization as well as the technical insights provided by Ben Larson of Ecotope were most helpful. The authors could not have done this project without the management and coordination efforts of Graham Parker between Washington State University (WSU) and PNNL. Finally, the authors acknowledge the dedication, leadership, and support of the WSU Principal Investigator, Ken Eklund.

Acronyms and Abbreviations

Balancing INC	demand-response action to reduce load when generation is insufficient to meet it
BPA	Bonneville Power Administration
CSA	Canadian Standards Association
DOE	U.S. Department of Energy
DR	demand-response
ERWH	electric resistance water heaters
EF	Energy Factor
gal/day	gallons per day
HPWH	heat pump water heater
INC	decrease load (increase in generation capacity is needed)
kW	kilowatt
PNNL	Pacific Northwest National Laboratory
W	watt
Wh	watt-hour
WSU	Washington State University Energy Program

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1.0 Introduction

Water heating represents ~18% of residential energy consumption, amounting to 1.8 Quads annually (EIA 2009), and efficient water heater options are needed to achieve significant energy savings in the residential sector. Heat pump water heaters (HPWH) with a theoretical energy savings of up to 63%, offer a significant efficient option for the 41% of homes with electrically heated water heaters.[1]

However, some barriers must be overcome before this technology will reach widespread adoption in the Pacific Northwest and nationwide. One barrier noted by the Northwest Energy Efficiency Alliance is that HPWH products are not ideal for northern climates, especially when installed in or in communication with conditioned spaces, as there may be complex interactions with the home space conditioning (Kresta 2012). One way to address this issue would be to duct the supply and exhaust air to and from the exterior; another solution would be to use a Split-System HPWH with the compressor and heat collection coil in an outdoor unit (Larson 2013, Eklund and Banks 2014). Both of these solutions were used in the HPWHs tested in this study.

Another potential barrier is the impact of HPWHs on demand-response (DR) programs because HPWH DR characteristics are currently unknown. Many utilities currently employ electric resistance water heaters (ERWHs) to reduce peak load by turning off the water heater during times of peak demand. Some utilities also are demonstrating the potential of using HPWHs to increase load for areas with high renewable energy penetration and to provide additional balancing and ancillary (voltage regulation) services.

1.1 Project Scope

The focus of this activity is to develop a better understanding of HPWH functionality while subject to real-world conditions/loads and imposed DR protocols. The key research questions include:

- What is the dispatchability of the HPWHs using the standard utility protocol?
- What is the energy-storage capacity in field use subject to typical hot-water draw patterns and dispatch driven by actual events?
- What is the impact on system efficiency of oversupply, load shifting, and load-balancing operation?

To help answer these questions, a set of controlled experiments were undertaken in a matched pair of unoccupied laboratory homes (Lab Home A and Lab Home B) located on the campus of Pacific Northwest National Laboratory (PNNL) in Richland, Washington.

The DR experiments were conducted with Sanden carbon dioxide (CO_2) refrigerant HPWHs that are new to the U.S. market. The two units evaluated included a fully ducted 40-gallon integrated HPWH installed in the water heater closet of Lab Home A and a Split-System HPWH with an outdoor compressor/evaporator and an 83-gallon indoor water tank located in the Lab Home B water heater closet.

[1] Based on U.S. Department of Energy (DOE) test procedure (10 CFR 430.32(d)) and comparison of an ERWH (energy factor, EF = 0.90) versus a HPWH (EF = 2.4).

1.2 Background

Traditionally, the electric power grid has been operated such that generation resources are controlled to match the variable demand of residential, commercial, and industrial loads on continuous basis. This includes services such as meeting peak demand, regulation and contingency services for providing consistent and reliable power, and frequency response to make sure the frequency of supplied power remains within a tight tolerance band around 60 Hz. However, with the increased communication and control capabilities inherent in the smart grid, it is now possible to dynamically modulate loads to match supply more conveniently and cost effectively than could be accomplished with the previously used generation-side control. Such a strategy, of controlling demand rather than supply (Lu et al. 2011), is referred to as demand-response (previously defined as DR).

The benefits of DR include increased system reliability, defrayed cost of new infrastructure investment, improved system efficiency, and decreased carbon emissions through increased penetration of intermittent renewable resources (Lu et al. 2011).

When considering grid stability, reliability, and economics, two types of DR are of particular interest and are evaluated in these experiments: oversupply mitigation and balancing reserves. These types of DR are briefly described below:

- *Oversupply mitigation* is used in the Pacific Northwest during spring runoff when wind energy is frequently available at night. The hydroelectric system is constrained to use large river flows for generation, thereby leaving no load for wind-generated power. Shifting of load to the hours when wind-generated electricity is available allows capture and storage of this energy for use during peak load hours. In preparation for storage, the water heater being used as a storage device may be turned off to create future capacity for storing energy as hot water. Once heated with oversupply energy, this hot water is then delivered at a time when it has value the following day.
- *Balancing reserves* are used to respond to hourly or sub-hourly changes in generation capacity either because of 1) inherent variability in the generation resource or 2) large disturbances in the grid (e.g., transmission fault) (Diao et al. 2012). As increasing amounts of power from wind and solar resources are introduced on the grid, the need for balancing reserves to respond to fluctuations in wind speed or insolation will be needed (Konodoh et al. 2011). Using DR for balancing reserves also can increase overall grid efficiency and decrease stress on mechanical generators from frequent ramping (Konodoh et al. 2011). Balancing INC DR events evaluate the potential of an HPWH to provide balancing reserves of dispatchable kW load shed as compared to the baseline.

In a residential environment, inertial loads such as water heaters, air conditioners, and refrigerators, accommodate DR most easily because their electrical energy input can be changed with minimal impact on the customer or the utility of the appliance (Saker et al. 2011). Specifically, residential ERWHs have been identified as ideal candidates for DR for the following reasons:

- They contain significant thermal storage.
- They contribute a significant amount of the residential load in the Pacific Northwest.
- They have relatively high power consumption and a large installed base in the Pacific Northwest.
- They follow a consistent load pattern that is often coincident with utility peak power periods (Sepulveda et al. 2010; Diao et al. 2012).

Also, an ERWH is essentially a resistor, which is not affected by frequent switching and does not require reactive power support to operate (Diao et al. 2012).

Several modeling studies previously evaluated the potential of ERWHs to provide peak curtailment and load following, and these studies identified significant potential and benefits for ERWH to perform these grid functions (Mathieu et al. 2012; Sepulveda et al. 2010; Konodoh et al. 2011; Diao et al. 2012; Saker et al. 2011; Lu et al. 2011). New HPWH technology has the potential to dramatically decrease electricity use for residential water heating. However, this technology, with its inherent energy efficiency may impact the potential of water heaters to perform DR types of grid services. While utilities and efficiency advocates have significant interest in encouraging the adoption of HPWHs, no modeling or field studies were identified that evaluated the DR potential and characteristics of HPWHs in comparison to ERWHs. If ERWHs are to be replaced with HPWHs to improve residential energy efficiency, it is important to understand how such a change will impact the use of ERWH in DR programs and overall grid stability now and in the future.

2.0 Water Heater Experimental Plan

Given the need to understand both the DR characteristics and capabilities of water heaters, a set of experiments were designed and conducted in the PNNL Lab Homes. These experiments are described in this chapter.

2.1 PNNL Lab Homes

The PNNL Lab Homes are unique platforms in the Pacific Northwest region for conducting experiments on residential sector technologies. These electrically heated and cooled 1500 square-foot homes are sited next to each other on the PNNL campus in Richland, Washington. They are fully instrumented with end-use metering (via a 42-circuit panel), indoor and outdoor environmental sensors, and remote data collection. The homes can be operated to simulate occupancy (via PowerLink® controllable breaker panels) and, thus, any occupant effects on equipment performance can be evaluated and managed using the control features in the homes. The unique nature of this side-by-side siting means the homes experience the same weather at any given time. This allows comparisons over the same time period of energy efficiency measures in the experimental home with baseline measures in the baseline home under identical environmental (indoor and outdoor) conditions and water supply temperatures. In addition to providing accurate information about energy consumption and savings associated with a specific technology, the independence of the data from weather allows weather-related factors, such as outdoor air temperature and wind speed and their effects on savings, to be evaluated as independent variables rather than confounding variables.

2.1.1 Monitoring Approach

The monitoring approach included metering and system-control activities taking place at both the electrical panel and at the hot-water generation point. Monitored metrics were electricity use, temperature, and flow. Table 2.1 highlights the performance metrics (the equipment/systems being monitored), the monitoring methods and/or points, the monitored variables, and the data application.

All metering was done using Campbell® Scientific data loggers at 1-minute, 15-minute, and hourly intervals. Metering points in the PNNL Lab Homes not relevant to the HPWH DR experiments and further technical specifications on the controllable breaker panel, data acquisition system, and relevant sensors are described in detail in a previous report (Widder et al. 2013).

2.1.1.1 Electrical Measurements

The PowerLink controllable electrical panels allow accurate time cycling of the breakers throughout the experimental period. In each home, all 42 of these electrical breakers were monitored for amperage and voltage. The resulting data were used to calculate apparent and real power (kVA/kW). All data were captured at 1-minute intervals by the Campbell Scientific data logger.

Table 2.1. PNNL Lab Homes Metering Strategy and Equipment

Monitored Parameter	Monitoring Method/Points	Monitored Variables	Data Application
Electrical Power Measurements			
Whole House Electrical Power and Circuit Level Power	One Campbell data acquisition system with 42 current transducers at electrical power mains and panel	kW, amps, volts	Comparison and difference calculations between homes of • power profiles • time-series energy use • differences and savings
HPWH Electrical Power			
Electric Power for HPWH Fan			
Power for Electric Heaters			
Temperature Measurements			
Inlet Water Temperature	Insertion thermocouple	Temperature, °F	Characterize impact of incoming water temperature on HPWH performance
Outlet Water Temperature	Insertion thermocouple	Temperature, °F	Monitor outlet water temperature as proxy for tank temperature
Flow Rate Measurements			
Outlet Water Flow Rate	Turbine flow meter, in line with hot-water outlet prior to mixing valve	Flow rate, gallons per minute	Verify water draws are in accordance with specified profile
Thermostatic Mixing Valve	Mixing valve in line with hot water and tempered with cold supply water	Temperature, °F	Tempering supply water to the required delivered water temperature

2.1.1.2 Temperature and Environmental Sensors

Water temperatures were recorded for the water input to the tank (i.e., city water) and the hot water delivered to the fixture. All temperature measurements were taken with T-type thermocouples at1-minute intervals by the Campbell data logger. The inlet water temperature thermocouple is located on the cold water supply immediately upstream of the water heater and the outlet water temperature thermocouple is located at the hot-water outlet. A thermostatic mixing valve installed between the tank and the outlet to regulate the temperature of the HPWH-delivered water to a nominal 120°F. The delivered water temperature was measured at the outlet of the mixing valve.

Water flow rates were measured using low-flow, impeller-type flow meters installed on the inlets to the water heaters. The water draw schedule implemented in both homes was identical; there were some challenges with day-to-day consistency of total volumes drawn resulting from difficulties with the thermostatic mixing valve operation. Figure 2.1 shows the flow rate and duration of each Lab Home over the duration of the experiment.

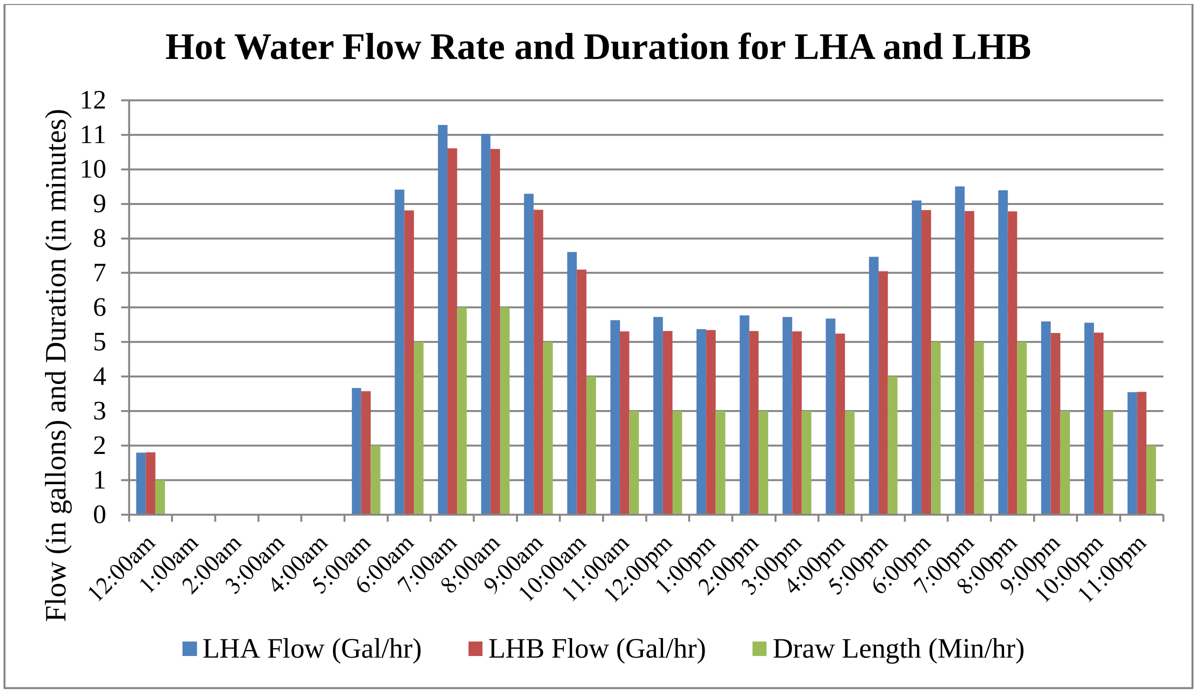

Figure 2.1. PNNL Lab Homes Water Draw Profile for the Sanden HPWH Experiment

2.1.2 Water Heater Control Approach

The DR schedules for the Sanden HPWHs were implemented through the use of the PowerLink controllable electrical panels installed in each home. These panels, which are commercial lighting panels by design, use motorized electrical breakers to activate or deactivate circuits based on a pre-programmed schedule. The pre-defined DR schedules were programmed into the panels and used to activate and deactivate the HPWHs as required. The use of CEA 2045[1] was rigorously explored by Sanden International as integrated control software for the water heaters in these experiments, but it was not developed as a workable protocol in time. The units have no factory-installed DR control at this time. Nonetheless, the company is committed to developing a state-of-the-art integrated DR control strategy in the second generation of its U.S. product line.

2.1.3 Occupancy Simulation and Water Draw

To simulate occupancy for the experiments, hot-water draw profiles were implemented identically in both homes. The hot-water draws used a modulating solenoid valve at the kitchen sink hot-water supply and were controlled via the Campbell data acquisition system. Other occupancy loads in the homes were simulated via the PowerLink breaker panel to simulate sensible loads associated with occupancy, lighting, equipment, and appliance loads. More detailed information on the electrical loads used to simulate occupancy and the relevant schedules is provided by Widder et al. (2013).

[1] CEA-2045 specifies a modular communications interface to facilitate communications with residential devices for applications such as energy management.

The PNNL research team reviewed hot-water draw profiles that were representative of a typical daily draw pattern for a population of homes, rather than a single home. The selected draw profile was based on U.S. Department of Energy (DOE) Building America House Simulation Protocols, which specify typical daily draw volumes for different appliances based on the number of bedrooms, and an hourly draw pattern based on the fraction of total daily load (Hendron and Engebrecht 2010). For a three-bedroom, two-bathroom Lab Home, the Building America House Simulation Protocol recommended a total hot-water use of 78.51 gallons per day (gal/day). While the recommended draw profile for a home of this size is 78.51 gal/day, a higher draw volume was chosen for these experiments to create a "worst-case" scenario for evaluating the maximum impact to the water heaters. As such, the hot-water flow rate was set to 2.0 gallons per minute, for a total draw volume of roughly 130 gal/day in Lab Homes A and B. Because of imprecision of the thermostatic mixing valve, this draw pattern fluctuated, up to 140 gal/day on some days, during the experiment.

2.2 Water Heater Experiments

The two types of water heaters tested were a Sanden Split-System HPWH and a Sanden Unitary System HPWH. Each of these systems is described below.

2.2.1 Sanden Split-System HPWH

The Sanden Split System (model GAUS-315 EQTA) installed in Lab Home B had two main components: the storage tank and the outdoor unit. The storage tank was an insulated, 83-gallon tank designed for operation within the conditioned or semi-conditioned (e.g., garage) envelope of a home. The outdoor unit includes the compressor, heat exchange coil, and associated controls. The Split-System design allows the source of heat to be the outside air as opposed to air within the comfort envelope of the home, thus negating any interactive effects between water heating and comfort heating and cooling. A circulation pump takes cooler water from the bottom of the tank to the outdoor unit where it is heated and returned to the top of the tank. The heat pump uses CO_2 refrigerant because of its higher performance (i.e., better efficiency over a larger outdoor air temperature range) and low environmental impact. This unit also uses an inverter-driven compressor and variable frequency evaporator fan to achieve even higher efficiencies, and no backup resistance heating elements are employed.

A thermostat located about one-third of the way from the bottom of the storage tank monitors the temperature within the tank. As the temperature begins to fall below 113°F, the compressor cycles on, and the heat exchange process begins. Fan and compressor speeds are dictated by control logic within the heat pump. The compressors constantly attempts to maintain the rated 4.5-kW heating output regardless of outdoor temperature, and it has been documented that as the outdoor temperature decreases, the compressor power draw increases (Larson 2013). During the Lab Home testing, the delivered water was tempered through the use of a thermostatic mixing valve from the output temperature of 149°F to a delivered nominal temperature of 120°F. Figure 2.2 shows the Sanden Split System as installed in PNNL Lab Home B.

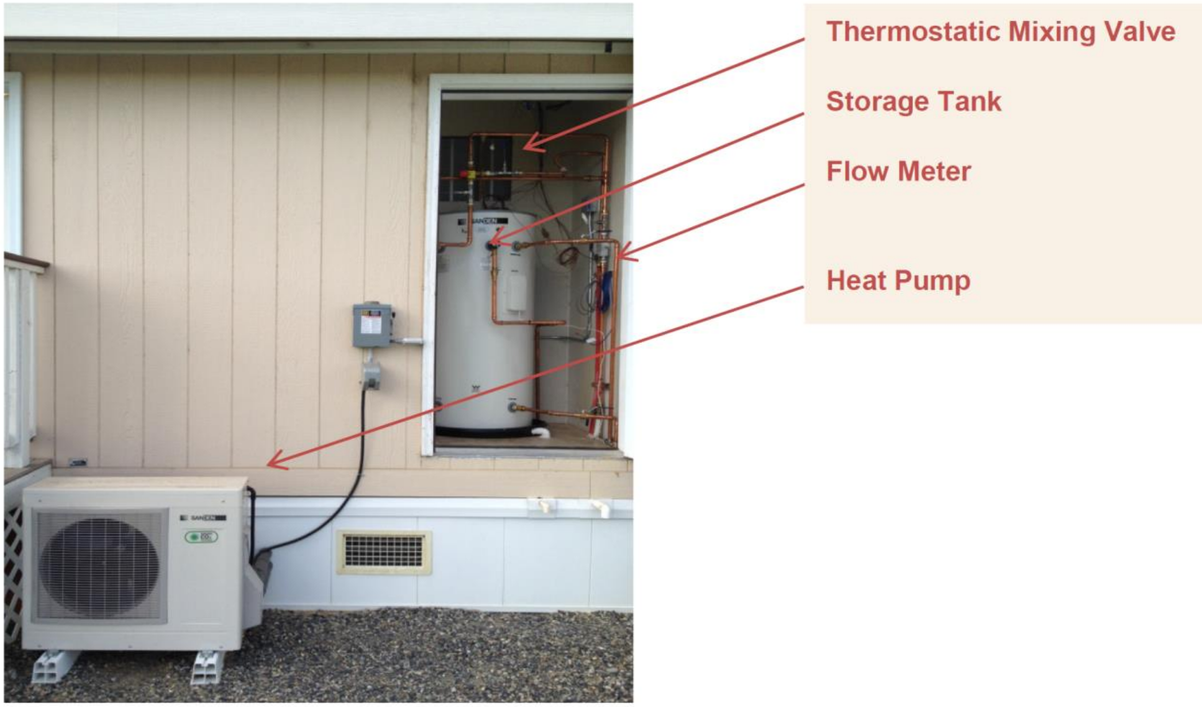

Figure 2.2. Sanden Split-System Heat Pump Water Heater as Installed in PNNL Lab Home B

2.2.2 Sanden Unitary HPWH

Similar to the Sanden Split System, the Unitary System (Model GES-15QTA) has two main components: the storage tank and the compressor/heat exchange/control system. As with the Split System, no backup resistance heating elements are employed in the Unitary System. The heat pump extracts heat from the ambient air because both the supply air inlet and exhaust outlet of the water heater are ducted; the inlet duct draws become the main source of heat. Supply air was drawn from beneath the home (the home has a roughly 3-foot crawlspace) by a variable speed centrifugal fan and an 8-inch ducted intake. This air then is passed over a coil where the heat exchange from the supply air to CO_2 gas occurs. After heat exchange, the air is discharged through the outlet duct outside of the home. The CO_2 gas transfers heat to the lower temperature water from the bottom of the storage tank. The heated water then is pumped back to the top of the storage tank to maintain stratification (Larson 2013). The storage tank is an insulated 39.7-gallon tank that can be either attached or separated from the compressor/heat exchanger section. In the Lab Home A installation, the two sections were attached in a stacked arrangement as shown in Figure 2.3. Evident in the picture are the two sections, the top being the compressor and heat exchanger and the bottom being the tank assembly.

As with the Split System, hot water was delivered from the water heater at the factory preset temperature of 149°F. This hot water then was tempered through a thermostatic mixing valve. The mixing valve in Lab Home A also was set to a nominal 120°F, though the in-field measured temperature varied between 118°F and 120°F.

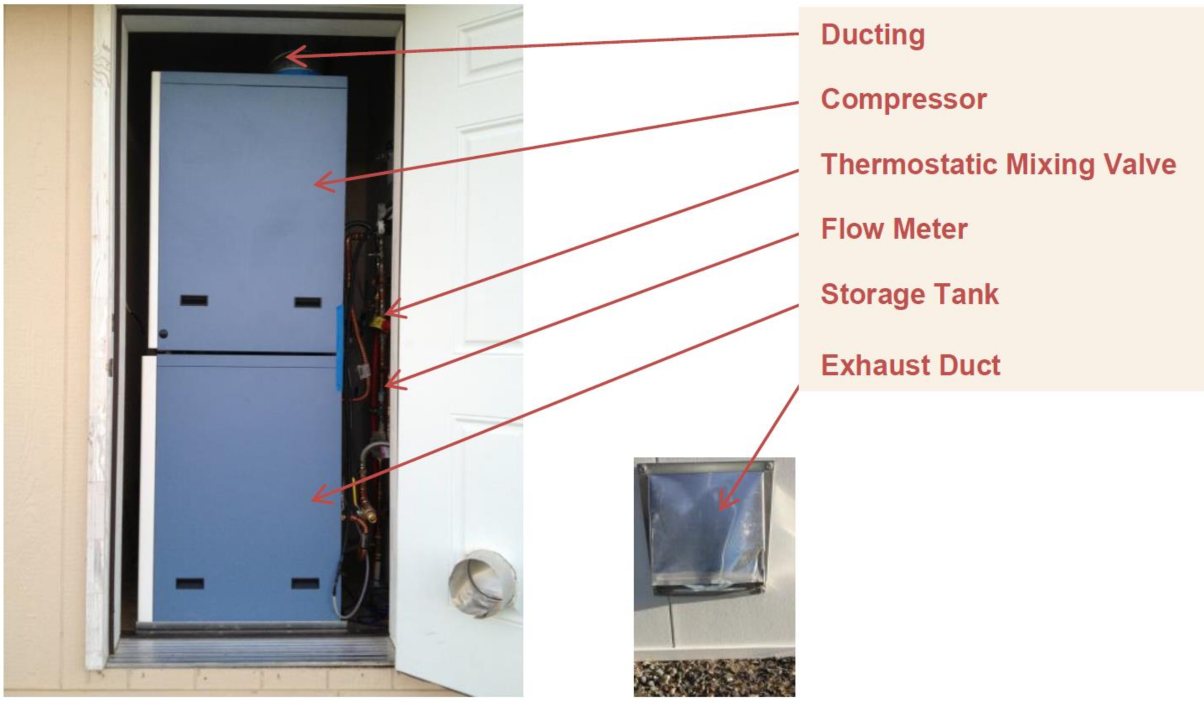

Figure 2.3. Sanden Unitary Heat Pump Water Heater as Installed in PNNL Lab Home A

3.0 Experimental Protocols

The primary goal of this experiment is to understand the DR characteristics of the two Sanden HPWHs. With the input of Bonneville Power Administration (BPA), Washington State University, Ecotope,[1] and PNNL, two DR protocol schedules—an Oversupply protocol and a Balancing INC protocol—were developed for the Sanden HPWHs. These schedules were developed to test the performance of the water heaters and demonstrate the load shifting capability associated with each.

3.1 Oversupply Protocol

A DR schedule to simulate the oversupply condition was generated to demonstrate the peak shift or reduction associated with each experiment. The schedule for the Sanden HPWHs was implemented over 7 days and consisted of increasing the time step that the unit is off, beginning at 6 hours, to a total of 12 hours by the seventh day. This increased daily strain on the water heater was imposed to determine at which hour the system could not meet the delivered water temperature during the daily draw schedule. The experiment also was designed to determine the load impact from the shift in the HPWH operation and quantify the recovery energy use after the HPWH was again energized. The oversupply schedules are shown in Table 3.1 for the Sanden HPWHs.

Table 3.1. Sanden HPWHs Oversupply DR Schedule

Day	Start Time	End Time	Oversupply Event Duration
1	6:00 PM	12:00 AM	6 hours
2	5:00 PM	12:00 AM	7 hours
3	4:00 PM	12:00 AM	8 hours
4	3:00 PM	12:00 AM	9 hours
5	2:00 PM	12:00 AM	10 hours
6	1:00 PM	12:00 AM	11 hours
7	12:00 PM	12:00 AM	12 hours

3.2 Balancing INC Protocol

The Balancing INC protocol was applied to determine the ability of the water heaters to respond to a balancing reserve call, while not adversely affecting the occupants. By its nature, Balancing INC calls can come at typical or random times during a day depending on grid resources and utility operating characteristics. As such, the Balancing INC schedule was spread over the day with relatively short 1-hour requirements. The Balancing INC protocol was applied to the Sanden HPWHs during identical time periods of a 24-hour period.

[1] Ecotope, 4056 9th Avenue NE, Seattle, WA 98105

Table 3.2. Sanden HPWHs Balancing INC DR Schedule

Day	Start Time	End Time	Balancing INC Event Duration
1	2:00 PM	3:00 PM	1 hour
2	2:00 PM	3:00 PM	1 hour
3	2:00 PM	3:00 PM	1 hour
4	8:00 AM 2:00 PM 8:00 PM	9:00 AM 3:00 PM 9:00 PM	1 hour 1 hour 1 hour
5	8:00 AM 2:00 PM 8:00 PM	9:00 AM 3:00 PM 9:00 PM	1 hour 1 hour 1 hour
6	8:00 AM 2:00 PM 8:00 PM	9:00 AM 3:00 PM 9:00 PM	1 hour 1 hour 1 hour

3.3 Experiments and Schedules

The two styles of water heaters studied (HPWH Unitary and HPWH Split-System) were installed and operated over three different experimental periods. Table 3.3 provides a summary of the water heater experiments in the Lab Homes.

Table 3.3. Summary of Water Heater Experiments in the Lab Homes

Experiment	Equipment	Experiment Description	Experimental Period
1	Sanden HPWHs: Baseline	Baseline operating metrics of Sanden HPWHs	August 2014
2	Sanden HPWHs: Oversupply	DR characteristics (Oversupply) of Sanden HPWHs	October 2014
3	Sanden HPWHs: Balancing INC	DR characteristics (Balancing INC) of Sanden HPWHs	November 2014

While not part of the original experimental design, it is important to note that seasonal temperature variations occurred over the Sanden HPWHs experimental schedule. Technical issues encountered with one of the HPWHs required extended investigation into the causes of the malfunction, procurement, and installation of a new controller and wiring and modification of a problematic condensate removal system. These unplanned events resulted in a protracted experimental schedule and significant seasonal changes in outdoor air and cold water supply temperatures over the experimental schedule from warmer to colder temperatures.

Table 3.4 presents the average temperatures (source air and supply water) over the experimental periods. The largest seasonal changes took place between the Oversupply and Balancing INC periods during which both the outdoor air temperatures and supply water temperatures decreased significantly.

Table 3.4. Experimental Periods and Relevant Temperatures

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

[a] Air is sourced from the crawlspace beneath Lab Home A and rejected outside through a vent in the water heater closet door.
[b] Air is sourced at the Split-System evaporator adjacent to Lab Home B (i.e., outdoor air).

3.4 Baseline Operation

Baseline functional tests of the two water heater types were conducted to determine standard operation with no interruption of power, operational efficiencies, and to benchmark operation. These baseline tests were completed in August 2014. In each case, a standard series of water draws were completed, and the metrics of supply, delivery temperatures, and power draws were recorded.

Graphs presented in the following sections show the baseline performance for each water heater. In each case the first graph provides the power profile (in watts [W]) over the course of a day [24 hours]). The second graph presents the output temperature of water supplied to the home on the same day.

3.4.1 Sanden Unitary HPWH Baseline

The baseline period for the Sanden Unitary HPWH DR experiment in the PNNL Lab Homes was during August 2014. Figure 3.1 shows data for one day of the baseline power profile and the accompanying outdoor air and crawlspace temperatures. Evident in this graph is the relative consistency of power profile, both in magnitude and duration, in responding to the hot-water draw profile. Because this HPWH sources air from beneath the home, the effect of outdoor air temperature on system energy use is somewhat dampened by the crawlspace temperatures. This effect will become more noticeable as these temperatures change. Of interest are the few, but longer, water heating events associated with the water draws. This has to do with the higher set-point temperatures of the HPWH. The alignment of these events and the ability to have them coincide with future DR protocols is an important consideration. Across the daily draw pattern and for the ambient conditions during the period shown, the average energy use per power draw event was 1.46 kWh.

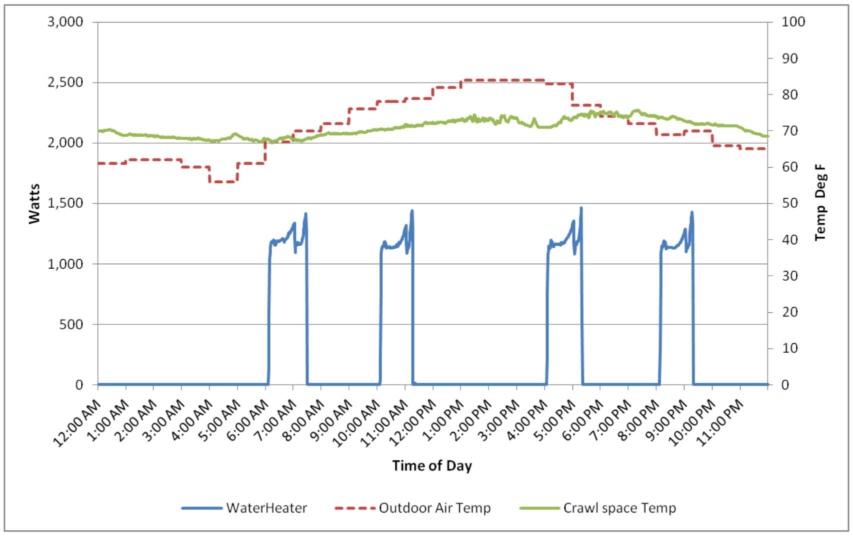

Figure 3.1. Sanden Unitary HPWH Baseline Power Profile, August 22, 2014

Figure 3.2 presents the resulting temperature profile of delivered water measured after the thermostatic mixing valve. The delivered water set point was nominally 120°F (though operational difficulties with the mixing valve during the experiments allowed the temperature to drop to 118°F), and the total draw was approximately 140 gal/day. The lower temperature and the higher total draw were functions of inaccuacy of the metering element in the mixing valve.

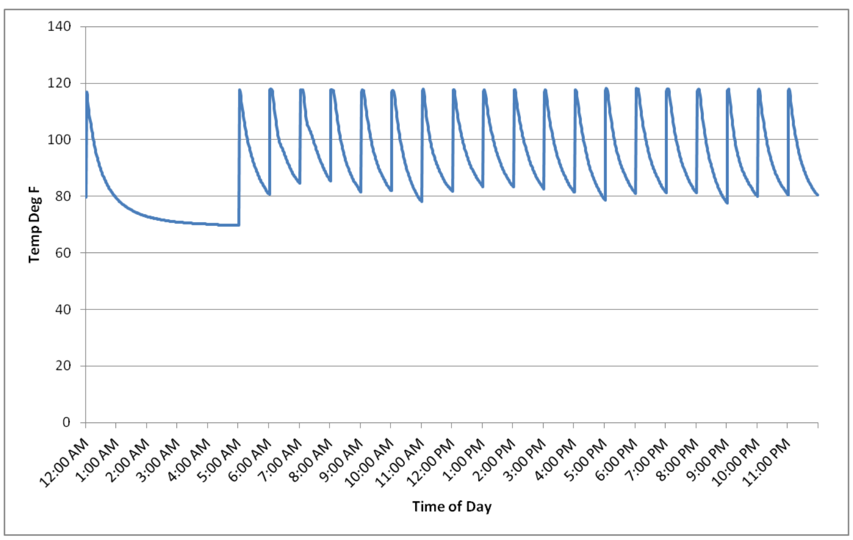

Figure 3.2. Sanden Unitary HPWH-Delivered Water Temperature Profile, August 22, 2014

The sawtooth pattern shown in Figure 3.2 is a result of the temperature monitoring via an insertion thermocouple in a thermowell at the outlet of the mixing valve. As water is drawn, the temperature peaks to the set delivery temperature, a nominal 120°F, followed by the temperature decay after the draw is concluded. This decay approached ambient temperature (i.e., temperature of the water heater closet) until the next draw occurs at which time the cycel begins again. Evident from the graph, the water heater was able to deliver water at the requisite temperature throughout the high water draw.

3.4.2 Sanden Split-System HPWH Baseline

The baseline period for the Sanden Split-System HPWH DR experiment in the Lab Homes also was during August 2014. Figure 3.3 highlights one day of the baseline power profile and the accompanying average hourly outdoor air temperature.

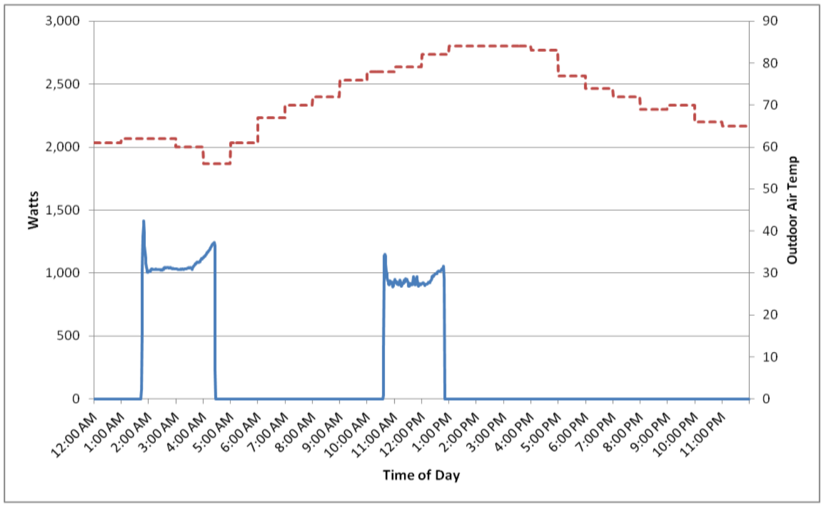

Figure 3.3. Sanden Split-System HPWH Baseline Power Profile, August 22, 2014

Like the Unitary HPWH, the Split System delivered a relatively consistent power profile across the week, both in magnitude and duration, in responding to the hot-water draw. As with the Unitary HPWH, there are the fewer, but longer, electric load events associated with the water draws. This has to do with the higher set-point temperature and the large tank capacity (85 gallons). Across the daily draw pattern, and for the ambient conditions during the period shown, the average energy use per power draw event was 2.50 kWh. While this energy use is larger than the Unitary System, there are fewer of these events across the day; the magnitude is related to the larger tank volume of the Split System.

Regardless of the protocol enacted, a key finding of this research is that the alignment of the water heater power profiles and the ability to have these coincide with enacted DR protocols is an important consideration.

Figure 3.4 presents the resulting temperature profile of delivered water. The delivered water set point was fixed at ~120°F and the total draw was ~139 gal/day. As expected, the water heater was able to deliver water at the requisite temperature throughout the draw pattern.

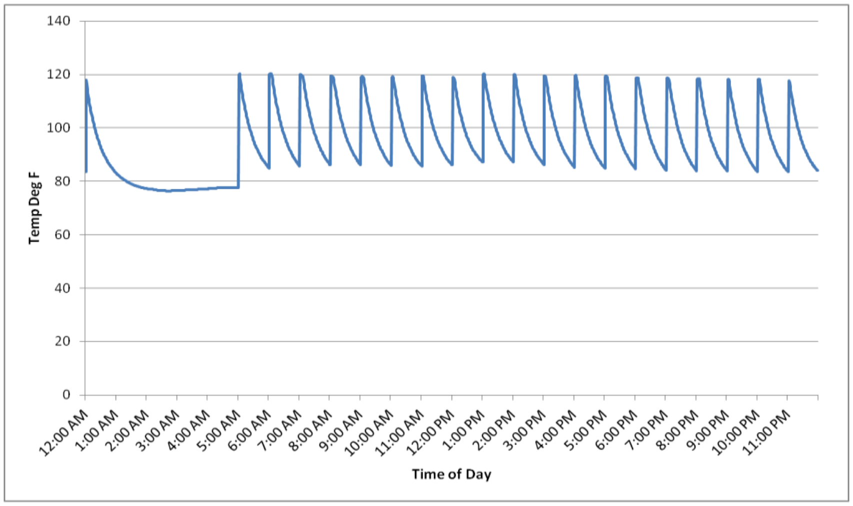

Figure 3.4. Sanden Split-System HPWH-Delivered Water Temperature Profile, August 22, 2014

The power profiles of the two water heaters highlight the operational differences between each HPWH. As can be seen in Figure 3.1 and Figure 3.3, the capacity of the storage tank effects the total amount of power draws that can be seen throughout the experimental period. Because the Unitary System has a much smaller tank, the frequency of the water draws will be higher than for the Split System.

3.5 Oversupply DR Protocol

The oversupply schedules presented in Section 3.1 were implemented across both water heater types.

3.5.1 Sanden Unitary HPWH Oversupply Results

The DR schedule for the Sanden Unitary HPWH Oversupply testing began with the water heater powered-down at 6:00 PM., and then, for the next 7 days, this period was increased by 1 hour per day. The last day of the protocol has the HPWH powered-down from 12:00 PM to 12:00 AM, a full 12 hours. **Error! Reference source not found.** presents the power profile for the first day of DR implementation when the water heater was powered-down for 6 hours. This is followed in Figure 3.6 by the corresponding temperature profile for the same DR schedule.

Evident in this first Oversupply DR schedule (6 hours powered-down) is the demand shift by eliminating one of the four activation events noted in the Sanden Unitary baseline graph (Figure 3.1). Because this initial oversupply event powered-down the water heater between the hours of 6:00 PM and 12:00 AM, the regular demand activation (water heater cycling on) at approximately 8:00 PM (seen in Figure 3.1) did not take place. The resulting demand impact was ~1.3 kW. This demand was not eliminated but simply shifted, in this case to when the water heater was allowed to cycle back on at 12:00 PM. The recovery energy use for the 6-hour DR event was 2.35 kWh. This recovery energy represents the amount of future energy able to be stored by implementing this DR protocol.

Based on the DR event (6-hour oversupply), the ambient conditions present, and the assumed draw pattern, this protocol yields a demand reduction of roughly 1.3 kW and a storage capacity of 2.35 kWh. This event was shown to have minimal impact on the residential water heating end-use and likely could be enacted without affecting the end-users.

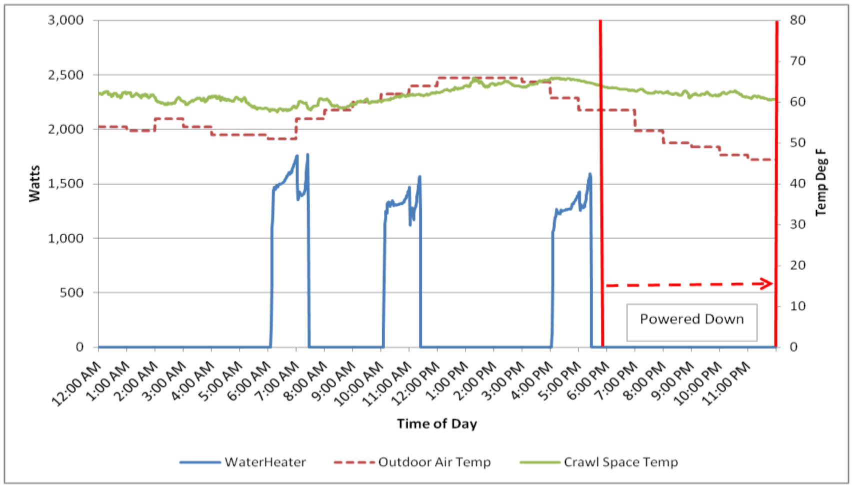

Figure 3.5. Sanden Unitary Oversupply Power Profile: First DR Event (6 hours powered-down), October 21, 2014

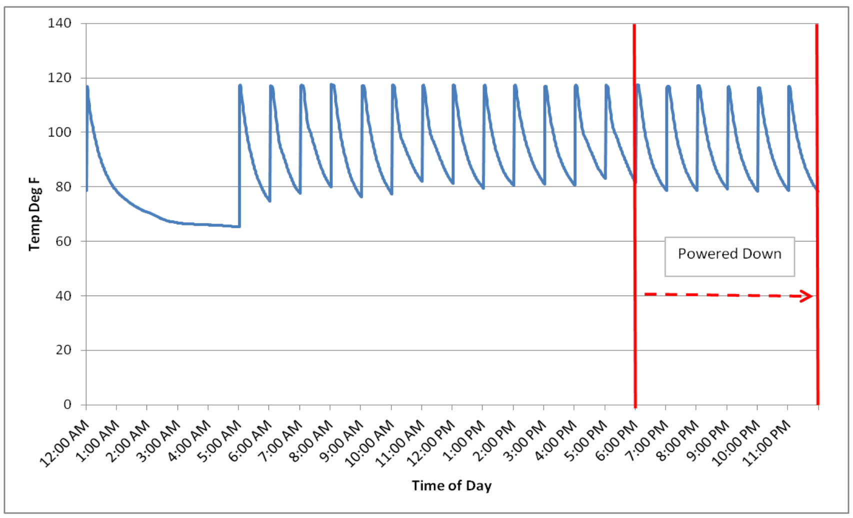

Figure 3.6. Sanden Unitary HPWH Oversupply Delivered Water Temperature Profile: First DR Event (6 hours powered-down), October 21, 2014

Figure 3.6 shows the delivered temperature response to this oversupply event. As shown, there is no reduction in delivered water temperature across the oversupply event; the water heater maintains its 118°F temperature output. Figure 3.7 and Figure 3.8 present the next DR event in the series—the powered-down period extended to 5:00 PM. As shown, the same demand shifting occurs; however, the water temperature does drop below the set point to about 115°F after 6 hours, thus making this demand event (powered-down duration at 7 hours) unavailable for residential applications with the Sanden Unitary HPWH.

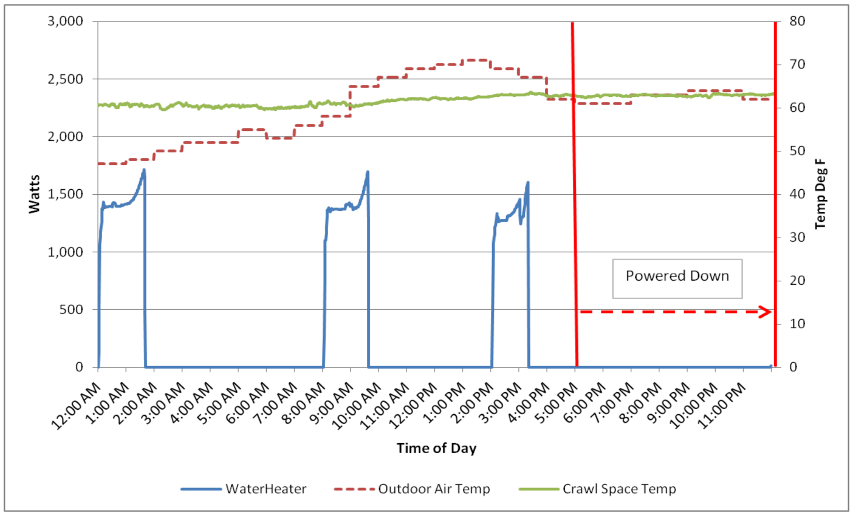

Figure 3.7. Sanden Unitary Oversupply Power Profile: Second DR event (7 hours powered-down), October 22, 2014

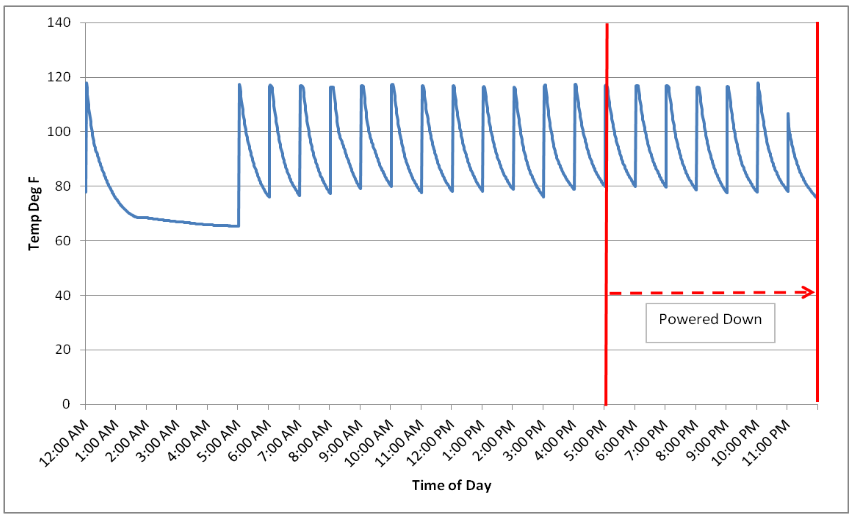

Figure 3.8. Sanden Unitary HPWH Oversupply Delivered Water Temperature Profile: Second DR Event (7 hours powered-down), October 22, 2014

The final series of Sanden Unitary HPWH Oversupply graphs are presented in Figure 3.9 and Figure 3.10, which highlight the longest DR event at 12 hours and the resulting implications. On the demand shifting side, two of the baseline activation events (i.e., the 8:00 PM and 4:00 PM events) are now displaced. The resulting temperature profile (Figure 3.10) shows that, after about 6:00 PM, the delivered water temperature has dropped below 115°F.

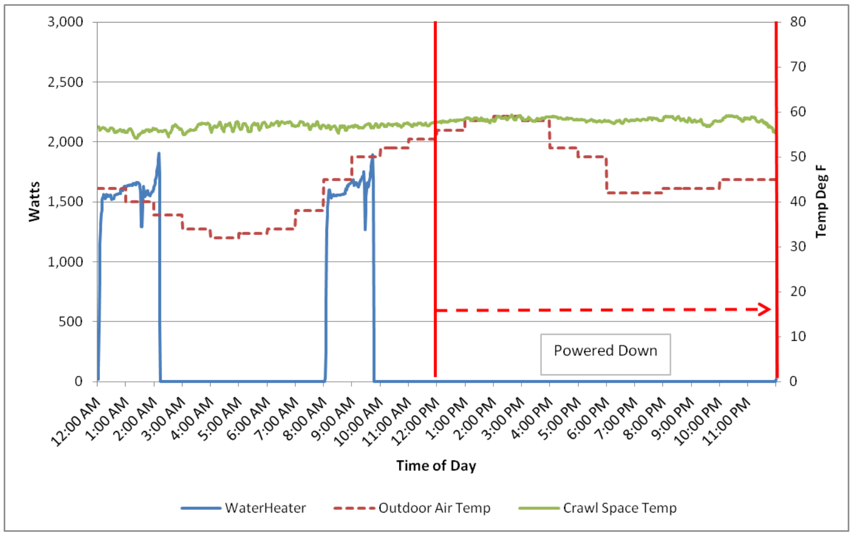

Figure 3.9. Sanden Unitary Oversupply Power Profile: Seventh DR Event (12 hours powered-down), October 27, 2014

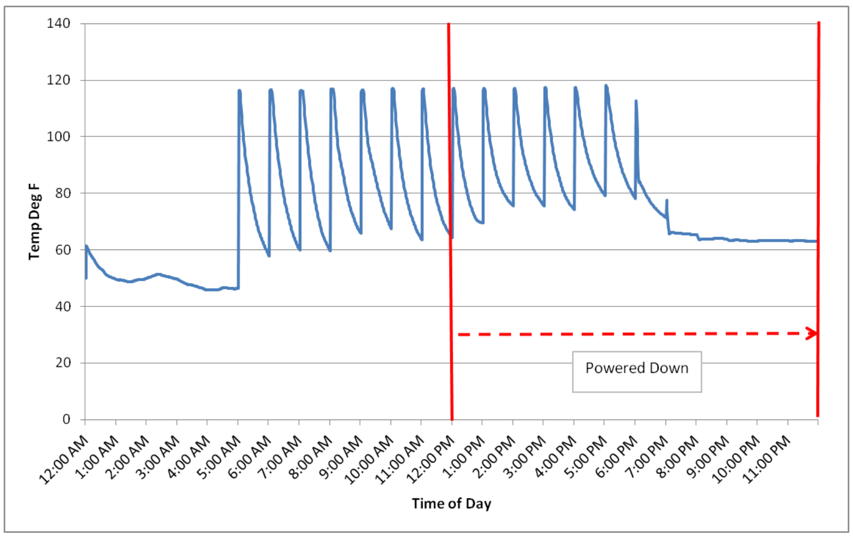

Figure 3.10. Sanden Unitary HPWH Oversupply Delivered Water Temperature Profile: Seventh DR Event (12 hours powered-down), October 27, 2014

In comparison with the Sanden Unitary HPWH baseline, the Oversupply DR power profile highlights a wattage reduction of about 1.3 kW. The operational temperature and tank capacity of the water heater becomes important when attempting to assure a demand event is "highly likely" for implementing an Oversupply protocol. If a demand event is expected during an oversupply call, but that event does not take place because of the technology's profile does not align, then the protocol may not be completely successful. However, for long-term load shifting, it does not matter when the load activates, just that service (i.e., occupant-acceptable hot water availability) can be provided for the duration and then use off-peak power to heat and store water for use at a later time.

Assuming there is alignment between the event and the Oversupply call, and for the conditions examined, the Sanden Unitary HPWH results in a demand shift of about 1.3 kW with a resulting energy recovery of 2.35 kWh. Because the Sanden units are HPWHs, the wattage of the demand shift and the resulting recovery energy, are a function of the HPWH source temperature. When the source air temperature or supply water temperature is colder, the demand value is larger. Regardless of alignment and depending on the duration of the DR event, the protocol will shift load to the period after which the protocol has ended regardless of the time of day.

The Sanden Unitary HPWH temperature profiles show that this water heater and water draw profile can accommodate an oversupply event of up to 6 hours in duration, creating a storage capacity of 2.35 kWh by the draws during this period. However, due mostly to the smaller tank capacity (39.7 gallons), after 6 hours the delivered water temperature drops below 115°F.

3.5.2 Sanden Split-System HPWH Oversupply Results

The DR schedule for the Sanden Split-System HPWH Oversupply testing was identical to that of the Unitary System. Figure 3.11 presents the power profile for the first day of DR implementation when the water heater was powered-down for 6 hours. This is followed in Figure 3.12 by the corresponding temperature profile for the same DR schedule.

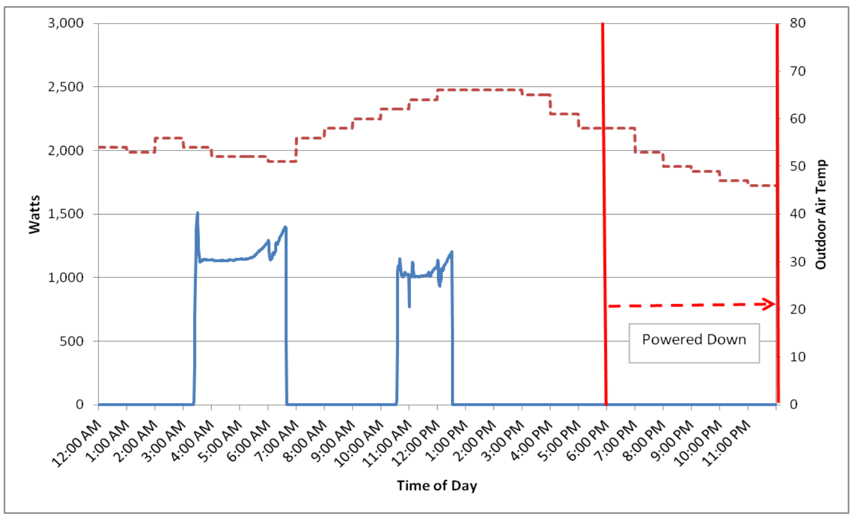

Figure 3.11. Sanden Split-System Oversupply Power Profile: First DR Event (6 hours powered-down), October 21, 2014

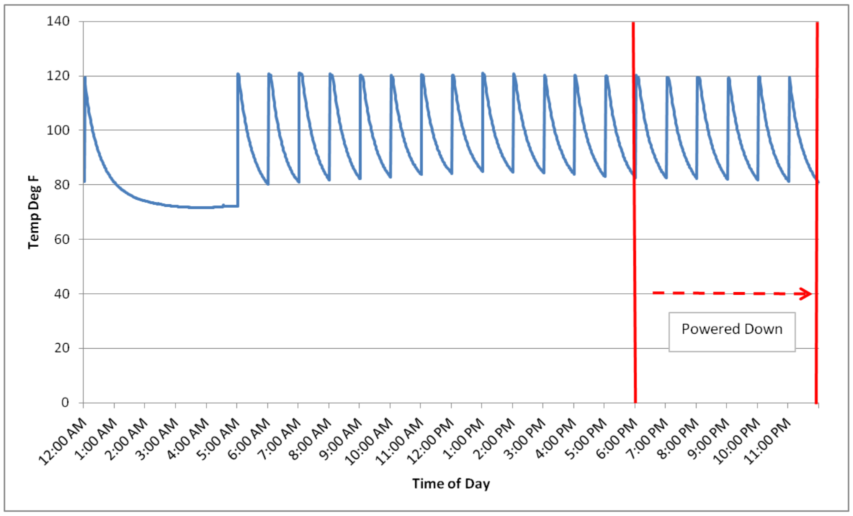

Figure 3.12. Sanden Split-System HPWH Oversupply Delivered Water Temperature Profile: First DR Event (6 hours powered-down), October 21, 2014

This test did not result in reducing demand during this off cycle because the water heater would normally have not operated. If the water heater had cycled on, the demand shift would be on the order of approximately 1.2 kW and would have resulted in additional demand (run time) at the next on-cycle event, after 12:00 AM, which achieves the oversupply goal of applying load to off-peak wind energy generation. If the water heater had cycled on, and given the ambient conditions during the test period, the energy-storage capacity created by the system being powered off for the 6 hours is calculated to be 2.95 kWh.

Based on the DR event enacted (6-hour oversupply), the ambient conditions present, and the assumed draw pattern, this protocol yields a demand reduction of roughly 1.2 kW and a calculated storage capacity of 2.95 kWh. This event was shown to have minimal impact on the residential water heating end-use and could be enacted without affecting the end-users.

Figure 3.12 highlights the temperature response to this oversupply event. Note that, in the graph, there is a not a decrease in delivered temperature with the outlet temperature remaining at 120°F because of both the high water temperature in the tank and the tank volume.

The final series of Sanden Split-System HPWH Oversupply graphs are presented in Figure 3.13 and Figure 3.14, which highlight the longest DR event at 12 hours and the resulting implications. For demand shifting, a portion of one of the typical baseline activation events was displaced, with the event normally beginning at about 11:00 AM. This demand shift, estimated to be between 1.1 kW and 1.2kW, also results in a longer event when the unit cycles back on after the DR event.

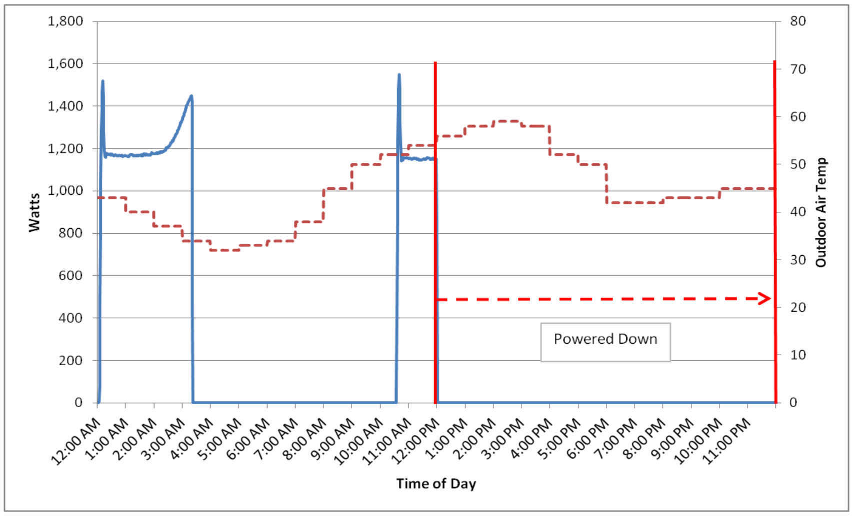

Figure 3.13. Sanden Split-System Oversupply Power Profile: Last DR Event (12 hours powered-down), October 27, 2014

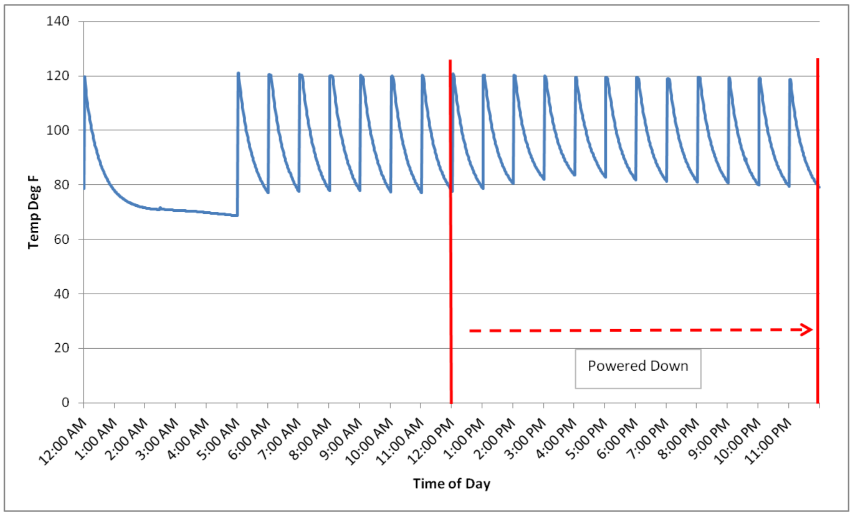

Figure 3.14. Sanden Split-System HPWH Oversupply Delivered Water Temperature Profile: Last DR Event (12 hours powered-down), October 27, 2014

The resulting temperature profile in Figure 3.14 shows that the delivered temperature still maintains the 120°F values across the DR period because of both the elevated set point and the larger tank capacity.

In comparison with the Sanden Split-System HPWH baseline, the Oversupply DR power profile highlights a wattage reduction of about 1.3 kW. Similar to the Unitary HPWH, the internal water temperature set point and the storage tank capacity become important factors when attempting to ensure a demand event is “highly likely” when implementing an Oversupply protocol. Assuming there is alignment between the event and the oversupply call, the Sanden Unitary HPWH results in a demand shift of about 1.3 kW. Regardless of alignment, the protocol will likely shift load to the period after which the protocol has ended (i.e., after 12:00 PM.).

The Sanden Unitary HPWH temperature profiles show that this water heater for the experimental water draw profile can accommodate an Oversupply call of 12 hours in duration while still delivering the requisite 120°F water to the resident.

Table 3.5 presents the DR summary findings for the Oversupply protocols enacted. The Dispatchable Power related to the peak watts available to be shifted through Oversupply implementation. The Recovery Energy Shift is the value of energy (kWh) that is shifted to the post-Oversupply period. The Oversupply Duration indicates the number of hours the protocol was enacted while still affording appropriate water heater delivery temperatures.

Table 3.5. Oversupply DR Protocol Summary Findings

Experiment Metric	Unitary System HPWH	Split-System HPWH
Oversupply Experiment		
Dispatchable Power (kW)	1.3	1.2
Recovery Energy Shift (kWh)[a]	2.65	2.95
Oversupply Duration (hours)[b]	6	6
Maximum Off Period while Delivered Temperature Met (hours)	6	12

[a] The Oversupply Recovery Energy Shift is the water heater energy use at the conclusion of the Oversupply period.
[b] The Oversupply Duration of the Split-System presented was for the 6-hour interval and provided for comparison to the Unitary System.

3.6 Balancing INC DR Protocol

The Balancing INC schedules presented in Section 3.2 were implemented across the two water heater types. The testing was completed in November 2014. Notable for the Balancing INC testing were the unseasonably cold outdoor air temperatures during the week of testing; temperatures below 20°F were recorded at night, and the water supply temperature averaged 57.9°F. These colder temperatures affect the HPWH performance as noted in the increased demand (larger wattage draws compared to other experimental periods) to accommodate these lower source air temperatures (see Table 3.4).

3.6.1 Sanden Unitary HPWH Balancing INC Results

The protocol for the Sanden Unitary HPWH Balancing INC testing included two separate tests; the schedules were presented in Table 3.2. The first protocol implemented was an off period of 1 hour starting at 2:00 PM. The second protocol expanded the off periods to three 1-hour periods, powering down the HPWH at 2:00 AM, 8:00 AM, and 8:00 PM. Figure 3.15 and Figure 3.16 present the demand profiles of the single-hour and then the three, single-hour protocols, respectively. The accompanying delivered water temperature profiles were not included because they did not result in an appreciable drop in delivered water temperature.

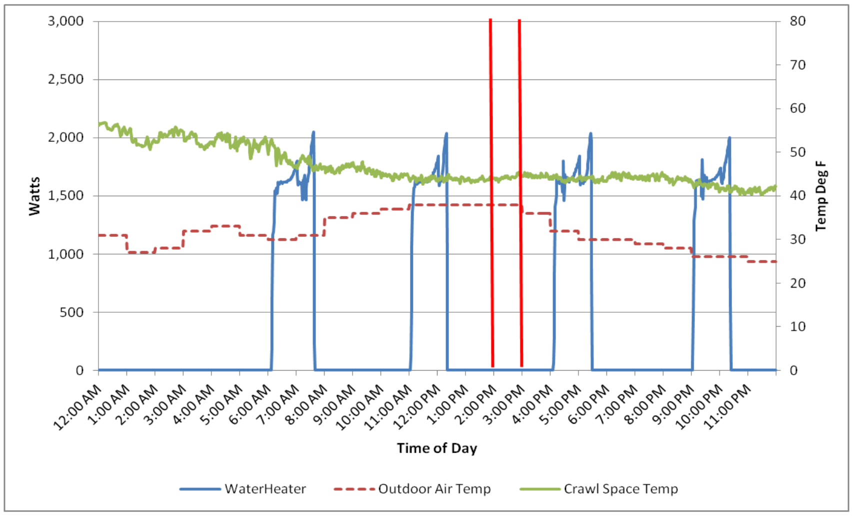

Figure 3.15. Sanden Unitary Balancing INC Power Profile: 2:00 PM (1 hour powered-down protocol), November 11, 2014

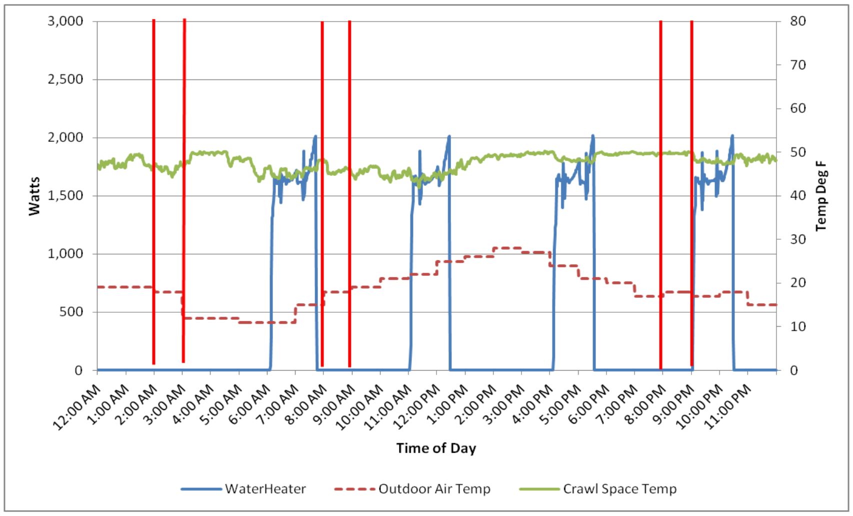

Figure 3.16. Sanden Unitary Balancing INC Power Profile: 2:00 AM, 8:00 AM, and 8:00 PM (1 hour powered-down protocol), November 16, 2014

In comparison with the Sanden Unitary HPWH baseline, the Balancing INC DR power profile highlights a wattage demand shift potential of about 1.7 kW. This is approximately a 0.4 kW increase over previous Unitary HPWH demand shifts because of decreased source air and supply water temperatures and the resulting increased HPWH energy use. Refer to Table 3.4 for the changes in source air and supply water changes over the experimental periods.

For this experiment, the only actual demand shift was noted during the 8:00 PM DR event, with the demand (~1.7 kW) being shifted to when the water heater was allowed to cycle back on at 9:00 PM.

3.6.2 Sanden Split-System HPWH Balancing INC Results

As with the Unitary Balancing INC testing, the Split-System testing included two separate tests. The schedules were presented in Table 3.2. The first protocol implemented was a 1-hour off period starting at 2:00 PM. The second protocol expanded the off periods to three 1-hour periods, powering down the HPWH at 2:00 AM, 8:00 AM, and 8:00 PM. Figure 3.17 and Figure 3.18 present the demand profiles of the single-hour and then the three, 1-hour periods, respectively. The accompanying delivered water temperature profiles were not included in these figures because they did not result in an appreciable drop in delivered water temperature.

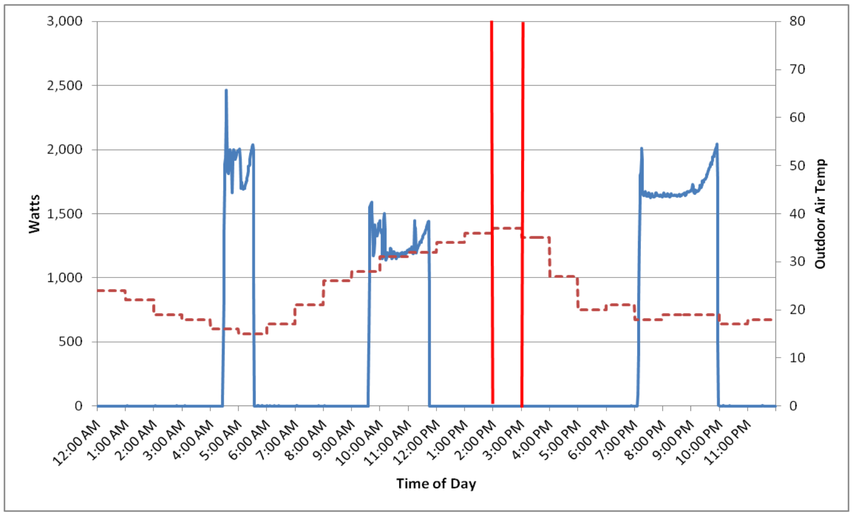

Figure 3.17. Sanden Split-System Balancing INC Power Profile: 2:00 PM (1 hour powered-down-protocol), November 12, 2014

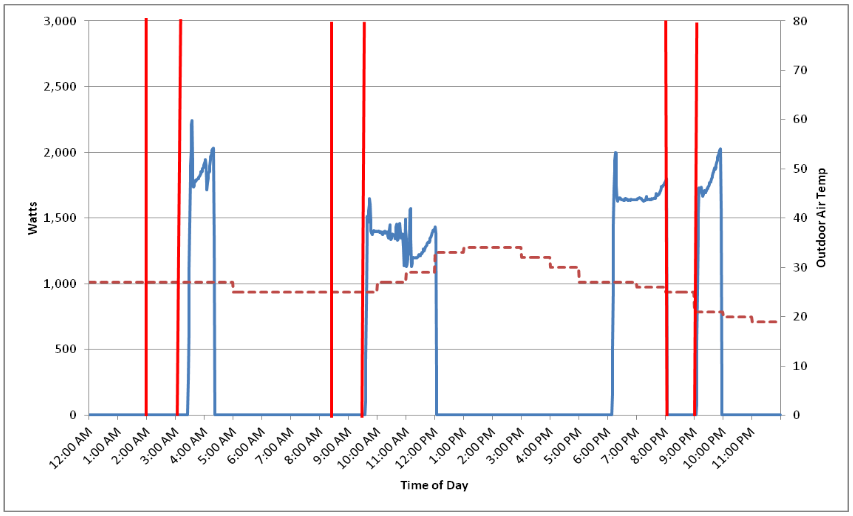

Figure 3.18. Sanden Split-System Balancing INC Power Profile: 2:00 AM, 8:00 AM, and 8:00 PM (1 hour powered-down protocol), November 14, 2014

Based on the DR event (6-hour oversupply), the ambient conditions present, and the assumed draw pattern, this protocol yields a demand reduction of roughly 1.3 kW and a storage capacity of 2.35 kWh. This event was shown to have minimal impact on the residential water heating end-use and likely could be enacted without affecting the end-users.

In comparison with the Sanden Split-System HPWH baseline, the Balancing INC DR power profile highlights a wattage demand shift potential of ~1.6 kW. This is approximately a 0.6 kW increase over previous Unitary HPWH demand shifts because of the decreased source air and supply water temperatures and the resulting increased HPWH energy use. Refer to Table 3.4 for the changes in source air and supply water changes over the experimental periods.

For this experiment, a very visible demand shift was noted during the 8:00 PM DR event when the event curtailed a water heater activation period. This curtailment and resulted in a demand shift of ~1.6 kW to after at 9:00 PM when the water heater was allowed to cycle back on.

Table 3.6 presents the DR summary finding for the Balancing INC protocols that were implemented. The Dispatchable Power related to the peak watts available to be shifted through Balancing INC implementation. For the HPWHs, these values are greater than for the oversupply period because the outdoor air and source water temperatures were lower. The Recovery Energy Shift is the value of energy (kWh) shifted to the post-Balancing INC period. These values assume that there is complete alignment between the Balancing INC protocol and the water heater power profile. As such, the values listed in the table are considered the maximum Recovery Energy Shift. The Balancing INC duration indicates the number of hours the protocol was enacted while still affording appropriate water heater delivery temperatures.

Table 3.6. Balancing INC DR Protocol Summary Findings

Experiment Metric	Unitary System HPWH	Split System HPWH
Dispatchable Power (kW)[a]	1.7	1.6
Recovery Energy Shift (kWh)[b]	1.7	1.6
Balancing INC Duration (hours)	1	1

[a] The increase in HPWH Dispatchable Power for the Balancing INC experiments results from the cooler source air and supply water during this period.
[b] The Balancing INC Recovery Energy Shift is reported assuming the protocol period aligns with a water heater activation event. Assuming alignment and the 1-hour event, the values listed are the maximum energy shifts.

4.0 Energy Analysis

The water heaters were exercised throughout the testing from the 130 gal/day draw used from Baseline through the DR tests. This research question focused on the impact of the DR tests on system efficiency. The answer is complicated by the fact that, because of equipment issues, substantial time elapsed between the Baseline and the DR tests. This time differential resulted in the systems experiencing very different supply water and outside air temperatures during the three tests as shown in Table 4.1.

Table 4.1. Testing Parameters

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

[a] Air is taken from the crawlspace beneath Lab Home A and exhausted outside through a vent in the water heater closet door.
[b] Air is sourced at the Split-System evaporator adjacent to Lab Home B (i.e., outdoor air).

Table 4.2 shows the normalized relative energy used during the three tests. The decreased outside air temperature during both tests was low enough to influence the energy use. This is particularly true in the Balancing INC tests for the Split System.

Table 4.2. Energy Usage 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

The Oversupply test results confirm the expected similarity in normalized energy use, with the Split System showing a slightly higher energy use. The Balancing INC tests reveal a significant difference in normalized energy use. This difference is driven by the large difference in average source air temperature for which the Unitary System average supply air temperature (sourced from under the home) was 46.8°F while the Split System (sourced outside air) was 23.7°F.

5.0 Conclusions

The experimental procedures showed that both Sanden HPWHs are capable of implementing the DR experiments. The magnitude of the peak demand shift of the Sanden units remained similar within each experiment. In comparison between experiments, differing variables such as supply water and outdoor air temperature affected the other efficiency of the water heaters and subsequently the total Dispatchable Power seen in the experimental period. In its most general form, the Unitary System provides a more predictable event (cycling on) profile and a larger Dispatchable Power (kW) draw compared to the Split System. As shown, this is a function of both storage tank capacity and operational set point. The thermal capacity and size of the Split System's water tank played a large role in the Oversupply experiment. As can be seen in Table 5.1, the Split-System was able to maintain the delivered water temperature to the home for a total of 12 hours compared to the 6 hours of the Unitary System. This can be important when developing DR impacts, particularly when compared to a system that experiences less frequent and/or less predictable power draw events. Table 5.1 summarizes the findings of these experiments.

Table 5.1. Details the Specific Findings of the Sanden HPWH Experiment

Experiment Metric	Unitary System HPWH	Split-System HPWH
Oversupply Experiment		
Dispatchable Power (kW)	1.3	1.2
Recovery Energy Shift (kWh)[a]	2.65	2.95
Oversupply Duration (hours)	6	6
Maximum Off Period while Delivered Temperature Met (hours)	6	12
Balancing INC Experiment		
Dispatchable Power (kW)[b]	1.7	1.6
Recovery Energy Shift (kWh)[c]	1.7	1.6
Balancing INC Duration (hours)	1	1

[a] The Oversupply Recovery Energy Shift is the water heater energy use at the conclusion of the Oversupply period.
[b] The increase in HPWH Dispatchable Power for the Balancing INC experiments results from the cooler source air and supply water during this period.
[c] The Balancing INC Recovery Energy Shift is reported assuming the protocol period aligns with a water heater activation event. Assuming alignment and the 1-hour event, the values listed are the maximum possible energy shifts.

Regardless of outdoor air temperature and supply water temperature, the energy consumption per gallon of water was comparable between the two Sanden water heaters. This can be seen in Table 5.2.

Table 5.2. Energy Use Normalized by Water Usage for Each DR Event

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

This has been verified in the laboratory setting (Larson 2013; Larson and Logsdon 2013) where testing of each Sanden water heater was completed under different ambient temperature set points and a 64 gallon draw profile. The inherent efficiency of the HPWH was relatively consistent across the DR experiments and for similar environmental conditions.

From this DR perspective, and in addressing the research questions of this experiment, the CO_2 HPWH offers advantage in dispatchability, energy-storage capacity versus loading and DR protocols, and DR potential impact of HPWH efficiency. These advantages are discussed below.

5.1 Dispatchability

Originally the experimental control called for grid-based services to provide for dispatchability; however, this protocol was not available. The Sanden water heaters tested did not have the necessary software or hardware to receive and implement a utility-generated DR signal. Sanden originally intended to have an integrated system controlled by CEA-2045, but the protocol was not developed sufficiently to be available at the time the research was conducted.

Fortunately, the PNNL Lab Homes were able to affect dispatchability using a unique controllable (i.e., programmable) electrical panel. While this controllability is specific to the Lab Homes, it provides validation and proof-of-concept of the ability to have a functional control and response system operating via utility-generated signals with these water heaters. The manufacturer is committed to developing a state-of-the-art integrated DR control strategy in the second generation of its U.S. product line. This technology will benefit from the research done in this project allowing optimization of the DR performance of these systems.

5.2 Energy-Storage Capacity versus Loading and DR Protocols

The storage capacity of the two HPWHs examined varied by a factor of two; the Unitary System has a 40-gallon capacity and the Split System has an 83-gallon capacity. In relation to the DR protocols (Oversupply and Balancing INC), this difference was most notable when the Oversupply DR protocol was implemented.

With the Oversupply protocol implemented, the Unitary-System HPWH was able to maintain function and requisite delivery temperature for the first Oversupply event (6-hour event), but could not maintain delivery temperature (>120°F) when the event incremented to the 7-hour (or greater) oversupply event. It is acknowledged that the draw pattern used in this experiment is greater than the average residential draw pattern. The Split-System HPWH was able to maintain requisite delivery temperatures for the entire Oversupply protocol, including the last event during which the unit was powered-down for a full 12 hours. This capability is attributed to both the higher hot water temperature and large storage capacity.

When the Balancing INC protocols were implemented (1-hour duration), but HPWH were able to function within the protocols implemented and provide the requisite water delivery temperatures.

5.3 DR Protocol Impact of HPWH Operation

Given early challenges with the Unitary System operation, a protracted experimental schedule, and significant seasonal changes in HPWH source air and water temperatures, detailed calculations of system efficiency, seen in Table 5.1 and Table S.1, should be viewed in the context of each experimental period for each technology.

There was an interesting relationship noted (see Table 3.4, Table 3.5, and Table 3.6) between the Split-System HPWH demand and outdoor air temperatures. Additional experiments would provide insight into the following areas:

- Potential for improved/decremented performance of the HPWH based on temperatures of source air (i.e., seasonal variability of outdoor air temperatures and water supply temperature). The Unitary HPWH saw a 0.4-kW increase and the Split System a 0.7-kW increase in demand over the study period, attributed to changes in ambient conditions.
- Implications of demand variability based on load shifting to later, possibly cooler, nighttime periods with lower air temperatures.
- Developing DR schedules to take advantage of diurnal temperature variation for both improved water heater efficiency and Oversupply/Balancing reserve optimization.
- Impacts on system efficiency from source air temperature variations between the crawlspace temperature and the outside air. Areas for additional research include:
  - The relationship (efficiency curve development) for air source temperature variability
  - The seasonal limit on under-home supply air on annual efficiency impact.

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Appendix A

Occupancy Simulation: Electrical Loads

Appendix A

Occupancy Simulation: Electrical Loads

Controllable breakers were programmed to activate connected loads on schedules to simulate human occupancy. The bases for occupancy simulation were data and analysis developed in previous residential simulation activities (Hendron and Engebrecht 2010; Christian et al. 2010). The occupancy simulations and schedules developed here were based specifically on the home style, square footage, and an assumed occupancy of three adults. The per-person sensible heat generation and occupancy profiles were mapped from previous studies to be applicable to this demonstration.

Occupancy and connected-lighting heat generation were simulated by activating portable and fixed lighting fixtures throughout the home. Each bedroom was equipped with a table lamp to simulate human occupancy; occupancy and lighting loads in other areas of the home were simulated via fixed lighting. In both cases (portable and fixed lighting), schedules were programmed into the electrical panel for run times commensurate with identified use profiles. The enabled profiles sought to match daily total occupancy characteristics with less emphasis on defined hourly simulation. Equipment loads were simulated identically in both homes using electric resistance wall heaters in the living/dining room: one 500 W and one 1500 W heater run simultaneously for a set number of minutes each hour. This set of experiments focused on sensible loads only; latent loads were not simulated and were not anticipated to significantly impact the performance of the HPWH. Table A.1, Table A.2, and Table A.3 present the load simulation and occupancy schedules for the Lab Homes HPWH experiments.

The occupancy simulation protocol was robustly commissioned and verified daily throughout the baseline development and data collection periods. Following each table, an example of occupancy schedule agreement is depicted from real data collected during the baseline period (Figure A.1, Figure A.2, and Figure A.3). The loads agree between homes and across days within ~1%.

Throughout the experiment, the heating, ventilating, and air conditioning systems were operated identically in the two homes. The 2.5-ton, SEER[1]-13 heat pumps maintained an interior set point of 76°F with no setback, as per Building America House Simulation Protocols (Hendron and Engebrecht 2010).

Table A.1. Daily Occupancy Schedules and Simulated Load

Time of Day	Simulation Strategy	Simulated Watts	Load Locations
1:00 AM–700 AM	Three 60-W table lamps	180	Lamps in master and each bedroom
7:00 AM–8:00 AM	Three 60-W table lamps	180	Lamps in master and each bedroom
8:00 AM–9:00 AM	One 60-W table lamp	60	Lamp in master bedroom
9:00 AM–4:00 PM	One 60-W table lamp	60	Lamp in master bedroom
4:00 PM–5:00 PM	One 60-W table lamp	60	Lamp in master bedroom
5:00 PM–6:00 PM	Two 60-W table lamps	120	Lamps in master and East bedroom
6:00 PM–9:00 PM	Three 60-W table lamps	180	Lamps in master and each bedroom
9:00 PM–12:00 AM	Three 60-W table lamps	180	Lamps in master and each bedroom
Wattage Total		3,180	

[1] Seasonal Energy Efficiency Ratio.

Table A.2. Daily Lighting Schedules and Simulated Load

Time of Day	Simulation Strategy	Simulated Watts	Load Locations
1:00 AM–4:00 AM	Ceiling fixture, 1 60-W lamp	60	Hall fixture
4:00 AM –5:00 AM	Ceiling fixture, 2 60-W lamps	120	Entry and living room fixtures
5:00 AM–6:00 AM	Two ceiling fixtures, two 60-W lamps each	240	Kitchen fixtures
6:00 AM–7:00 AM	Two ceiling fixtures, two 60-W lamps each	240	Kitchen fixtures
7:00 AM–8:00 AM	Two ceiling fixtures, two 60-W lamps each	240	Kitchen fixtures
8:00 AM–9:00 AM	Ceiling fixture, two 60-W lamps	120	Kitchen fixtures
9:00 AM–3:00 PM	Ceiling fixture, one 60-W lamp	60	Hall fixture
3:00 PM–4:00 PM	Ceiling fixture, two 60-W lamps	120	Entry and living room fixtures
4:00 PM–5:00 PM	Two ceiling fixtures, two 60-W lamps each	240	Kitchen fixtures
5:00 PM–6:00 PM	Three ceiling fixtures, two 60-W lamps each	360	Kitchen and entry fixtures
6:00 PM–7:00 PM	Five ceiling fixtures, two 60-W lamps each	600	Master, kitchen, and two bedroom fixtures
7:00 PM–8:00 PM	Five ceiling fixtures, two 60-Watt lamps each	600	Master, kitchen, and two bedroom fixtures
8:00 PM–9:00 PM	Five ceiling fixtures, two 60-W lamps each	600	Master, kitchen, and two bedroom fixtures
9:00 PM–10:00 PM	Four ceiling fixtures, three 60-W lamps each	420	Master, kitchen, and hall fixtures
10:00 PM–11:00 PM	Two ceiling fixtures, two 60-W lamps each	240	Kitchen fixtures
11:00 PM–12:00 AM	Ceiling fixture, one 60-W lamp	60	Hall fixture
Wattage Total		4,800	

Table A.3. Daily Equipment Schedules and Simulated Load

Time of Day	Simulation Strategy	Duration of Load (Minutes)	Simulated Watts	Load Locations
1:00 AM–2:00 AM	One 500 W & one 1,500 W wall heater	5	170	Living/dining room
2:00 AM–3:00 AM	One 500 W & one 1,500 W wall heater	5	157	Living/dining room
3:00 AM–4:00 AM	One 500 W & one 1,500 W wall heater	4	149	Living/dining room
4:00 AM–5:00 AM	One 500 W & one 1,500 W wall heater	4	148	Living/dining room
5:00 AM–6:00 AM	One 500 W & one 1,500 W wall heater	4	147	Living/dining room
6:00 AM–7:00 AM	One 500 W & one 1,500 W wall heater	5	181	Living/dining room
7:00 AM–8:00 AM	One 500 W & one 1,500 W wall heater	8	258	Living/dining room
8:00 AM–9:00 AM	One 500 W & one 1,500 W wall heater	9	284	Living/dining room
9:00 AM–3:00 PM	One 500 W & one 1,500 W wall heater	8	268	Living/dining room
3:00 PM–4:00 PM	One 500 W & one 1,500 W wall heater	8	250	Living/dining room
4:00 PM–5:00 PM	One 500 W & one 1,500 W wall heater	7	243	Living/dining room
5:00 PM–6:00 PM	One 500 W & one 1,500 W wall heater	7	236	Living/dining room
6:00 PM–7:00 PM	One 500 W & one 1,500 W wall heater	7	229	Living/dining room
7:00 PM–8:00 PM	One 500 W & one 1,500 W wall heater	7	222	Living/dining room
8:00 PM–9:00 PM	One 500 W & one 1,500 W wall heater	7	235	Living/dining room
9:00 PM–10:00 PM	One 500 W & one 1,500 W wall heater	7	220	Living/dining room
10:00 PM–11:00 PM	One 500 W & one 1,500 W wall heater	8	282	Living/dining room
11:00 PM–12:00 AM	One 500 W & one 1,500 W wall heater	11	356	Living/dining room
Wattage Total			5,875	

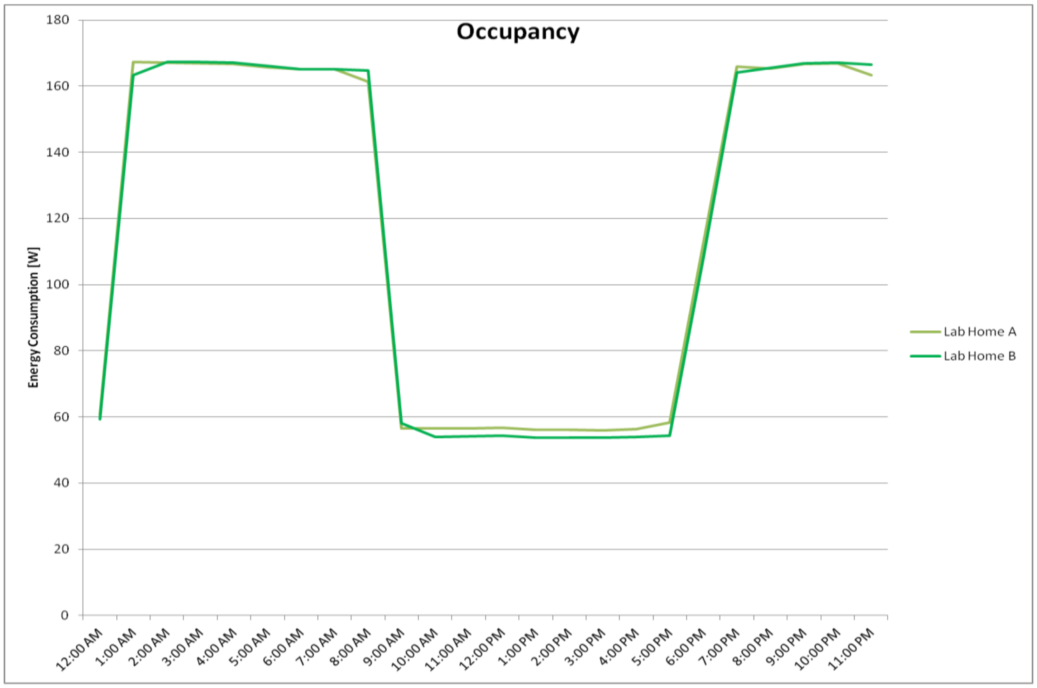


Figure A.1. Hourly Average Energy Consumption (W) Associated with Human Occupancy for an Example Day during the Baseline Period

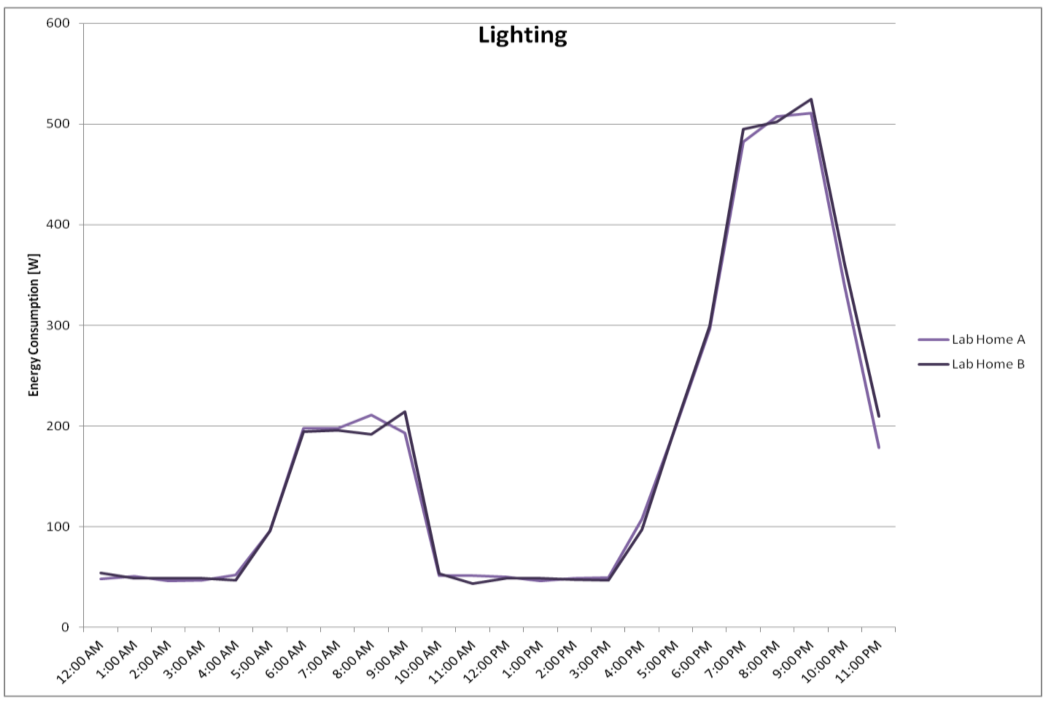


Figure A.2. Hourly Average Energy Consumption (W) Associated with Lighting for an Example Day during the Baseline Period

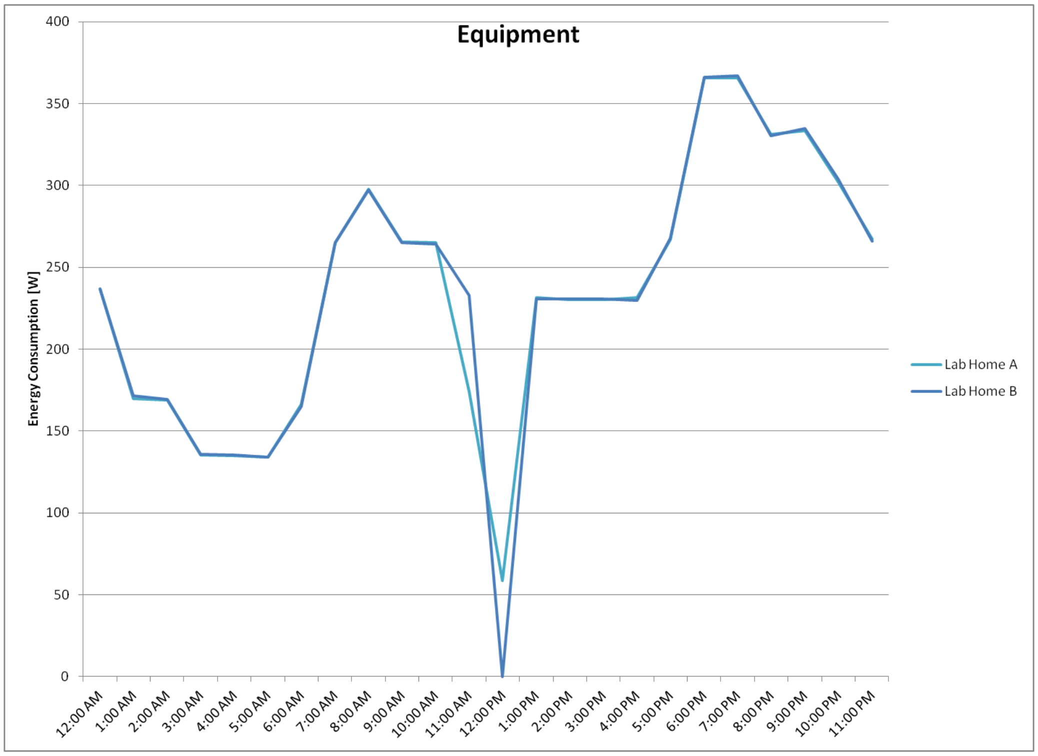


Figure A.3. Hourly Average Energy Consumption (W) Associated with Equipment Loads for an Example Day during the Baseline Period

Appendix B

Alternate Hot-Water Draw Profiles

Appendix B

Alternate Hot-Water Draw Profiles

In selecting a representative hot-water draw profile for the Lab Homes, Pacific Northwest National Laboratory (PNNL) also examined the hot-water draw profile implemented in Bonneville Power Administration's (BPA) evaluation of heat pump water heaters (BPA 2010). The BPA evaluation exercised two draw profiles, one similar to the U.S. Department of Energy (DOE) Building America Protocol, with moderate usage throughout the day, and one that was more representative of a typical household where the occupants are gone during the day. The first profile assumes 90 gal/day of hot-water use for four persons, while the second profile assumes hot-water use of 80 gal/day. Both profiles are similar, exhibiting increased water use in the morning and evening, but the "typical household" profile exhibits more spikes, with dramatic increases and decreases in water use throughout the day. This profile may be more representative of a single home or occupant, but is not necessarily better for understanding a "typical" home, or population of homes, from a utility perspective. In addition, with a tank water heater, efficiency depends more on total volume of draw than the variable rate or frequency of draws. Also, the flow rates and durations of draws needed to simulate such a variable profile are quite large, from 0.5 to 3 gallons per minute with durations of 1 to 9 minutes. While this may be representative of average usage in a home, it is difficult to simulate reliably in the PNNL Lab Homes.

The draft Canadian Standards Association (CSA) Standard testing method for domestic hot-water heaters, which was recently revised to be more representative of typical use cases, recommends a hot-water draw profile for the "high usage" case targeting 68.8 gal/day (CSA 2012). The CSA test is similar to the DOE Energy Factor (EF) Test (10 CFR 430.23(e)) profile in that it requires a 77°F temperature differential between inlet and outlet water and a 135°F tank temperature, but more "representative" draw volumes and flow rates throughout the 24-hour period, specified as 20 unique water draw events throughout a 24-hour period. The CSA profile also exhibits increased water use in the morning and evening and a similar total volume, but larger evening draws than the other profiles. A table of the CSA hot-water draws is given in Table B.1.

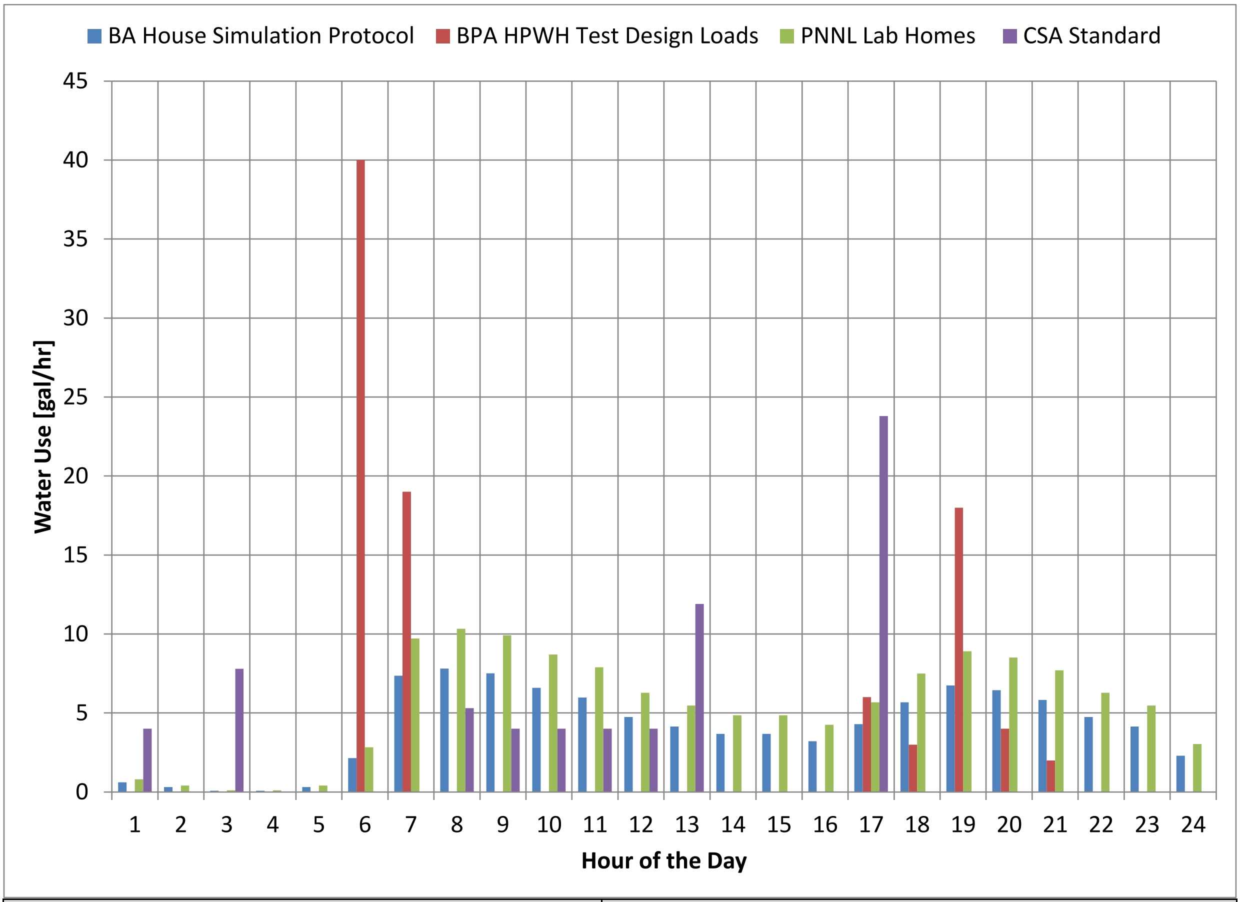
PNNL also explored using the "DHW Event Generator" (Hendron and Burch 2010), a spreadsheet tool developed by the National Renewable Energy Laboratory that produces an entire year of simulated draw profiles. However, the simulated draw pattern changes daily so it is extremely difficult to accomplish in physical testing, and some of the daily profiles did not appear to reasonably represent realistic daily draw patterns. Because the draw profile simulated in the PNNL Lab Homes needs to remain constant throughout the experiment to remove water draw profile as a variable from the comparison, choosing a draw pattern representative of aggregate average hot-water use, such as the Building America House Simulation Protocol, seemed most appropriate. Future work could explore the performance of heat pump water heaters as a function of variable draw patterns.

Table B.1. CSA Standard Hot-Water Draws (CSA 2012)

		Water Heater Classification					
Draw Number	Time of Day ((hh:mm:ss)	Vol. Drawn (gal)	Flowrate (gal/min)	Vol. Drawn (gal)	Flowrate (gal/min)	Vol. Drawn (gal)	Flowrate (gal/min)
1	12:00:00 AM	2.6	1.0	4.0	1.0	4.0	1.0
2	3:00:00 AM	2.6	1.0	2.6	1.0	2.6	1.0
3	3:07:38 AM	2.6	1.0	2.6	1.0	2.6	1.0
4	3:13:17 AM	2.6	1.0	2.6	1.0	2.6	1.0
5	8:00:00 AM	--	--	4.0	1.0	5.3	1.0
6	9:00:00 AM	1.3	1.0	4.0	1.0	4.0	1.0
7	10:00:00 AM	1.3	1.0	2.6	1.0	4.0	1.0
8	11:00:00 AM	1.3	1.0	2.6	1.0	4.0	1.0
9	12:00:00 PM	--	--	2.6	1.0	4.0	1.0
10	1:00:00 PM	--	--	--	--	11.9	3.0
11	5:00:00 PM	4.0	3.0	9.2	3.0	9.2	1.0
12	5:06:19 PM	--	1.0	--	--	--	--
13	5:08:05 PM	--	--	4.0	1.0	--	--
14	5:13:16 PM	4.0	1.0	--	--	--	--
15	5:14:14 PM	--	--	--	--	5.3	1.0
16	5:15:02 PM	--	--	4.0	1.0	--	--
17	5:21:13 PM	4.0	1.0	--	--	--	--
18	5:21:75 PM	--	--	4.0	1.0	--	--
19	5:22:41 PM	--	--	--	--	5.3	1.0
20	5:30:58 PM	--	--	--	--	4.0	1.0
	6:15:00 PM	End Test					

In addition, the DOE EF test procedure specifies the use of 64 gallons hot water for the purposes of evaluating the efficiency of residential water heaters (10 CFR 430.23(e)), although the draw profile is not representative of typical use.

Figure B.1 shows a comparison between the four hot-water use profiles.



Profile	Daily Hot-Water Use (gal/day)
Building America House Simulation Protocol	97 (6 people)
BPA HPWH Evaluation	90 (4 people)
Canadian Test Standard	68.8 (“high usage”)
PNNL Lab Homes	130

Figure B.1. Comparison of the Four Hot-Water Use Profiles

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