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

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Richland, Washington  99352

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[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] Because of their potential it is important to understand the demand-response (DR) performance and characteristics of HPWHs. 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, the DR characteristics of HPWHs researched and how these characteristics will impact DR programs and overall grid stability now and in the future must be considered.

This project evaluates and documents the DR performance of two Sanden $CO_2$ HPWHs for two primary types of DR events: oversupply mitigation 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 water heaters: 1) a Baseline test, 2) an Oversupply test, and 3) a Balancing INC test (balancing reserves). The purpose of the Baseline test was to understand the normal operation of each unit before DR testing began and quantify the energy use of each of the water heaters. The Oversupply test was conducted to identify how much energy could be stored during a period of excess generation. In order to create storage capacity, the water heater was turned off for a period of time before the oversupply event. The Balancing INC test was conducted to show the response of sub-hourly changes in demand. 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. Balancing INC is used when generation and load are mismatched because the load is higher than the generated power.

The water heaters in the PNNL Lab Homes were operated under near-identical simulated occupancy conditions with a 130 gallons/day draw profile for all the tests. Testing was conducted 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/

To create storage capacity, the Oversupply schedules for the testing began with the water heaters powered-down at 6:00 PM through midnight, and then, for the next 7 days, the power down 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 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.

Table S.1 details the peak demand shift ("Dispatchable Power") and the resulting recovery Energy Shift 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. More details about these DR events and their effect on delivered water temperature can be found in Sections 3.5 and 3.6.

**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 |
| Energy Shift (kWh)[a] | 2.65 | 2.95 |
| Oversupply Duration (hours)[d] | 6 | 6 |
| Maximum Off Period while Delivered Temperature Met (hours) | 6 | 12 |
| *Balancing INC Experiment* | | |
| Dispatchable Power (kW)[b] | 1.7 | 1.6 |
| Energy Shift (kWh)[c] | 1.7 | 1.6 |
| Balancing INC Duration (hours) | 1 | 1 |

[a] The Oversupply Energy Shift is the water heater energy use, as measured during 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.

[d] The water heater was allowed to run for up to 6 hours during the hypothetical oversupply event but completed its full tank recovery in far less time (typically 1.75 hours for the unitary and 2 hours for the split system.

The experimental procedures showed that both Sanden HPWHs are capable of implementing the DR Balancing INC and Oversupply Mitigation protocols. Both systems could provide Balancing INC services with no interruption in hot water delivery. When creating storage for Oversupply Mitigation services, the Unitary System was able to stay off for 6 hours and the Split System for 12 hours, impacting the amount of energy that could be absorbed during an Oversupply Mitigation event.

# 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 |
| DEC | an event where generated power is higher than load |
| 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 |
| Oversupply Mitigation | Providing load in times when the utility system has excess generation capacity that cannot necessarily be turned off such as wind energy |
| 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 significantly efficient option for the 41% of houses across the country and 55% of houses across the PNW with electrically heated water heaters (Baylon 2012).[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. Demand Response Performance of GE Hybrid Heat Pump Water Heater, Widder, et al. PNNL, 2013.

## 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

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[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).

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.

## 1.2 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 a 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 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. In preparation for storage, the water heater being used must be turned off to create future capacity for storing energy as hot water.
- *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 to 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. 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 water heaters in DR programs and overall grid stability now and in the future. Several studies have begun to answer these questions for integrated HPWHs with traditional refrigerants (Widder 2013, Broad 2014). This study advances the state of the knowledge for integrated- and split-system $CO_2$ HPWHs.

# 2.0 Water Heater Experimental Plan

Given the need to understand the DR characteristics and capabilities of the 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, 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 water 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. Water heater operation data including heat pump power and all water temperatures were taken in 1-minute 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 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<br>• power profiles<br>• time-series energy use<br>• 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 |
| Mixed Water Temperature | Insertion thermocouple | Temperature, °F | Monitor mixed water temperature post mixing valve |
| Flow Rate Measurements | | | |
| Outlet Water Flow Rate | Impeller 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), the hot water issued from the tank and the mixed water temperature delivered to the fixture. All temperature measurements were taken with T-type thermocouples at1-minute intervals by the 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 tank hot-water outlet. A thermostatic mixing valve is installed after the tank outlet but before the final delivery point to regulate the temperature to a nominal 120°F. Ecotope and NEEA, 2015, *Heat Pump Water Heater Model Validation Study*, March 2, 2015. An additional thermocouple measures the tempered water outlet temperature.

Water flow rates were measured using low-flow, impeller-type flow meters installed on the hot water outlet of the tank prior to the mixing valve. The same water draw schedule was implemented in each home,

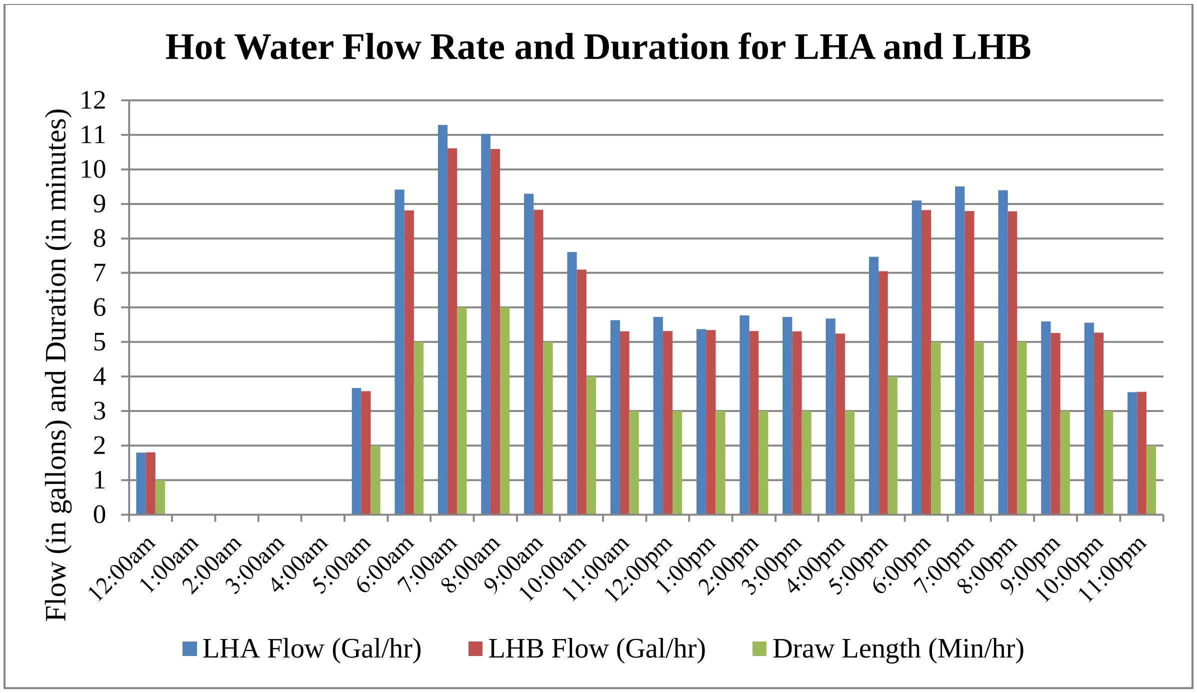

**Figure 2.1**. PNNL Lab Homes Water Draw Profile for the Sanden HPWH Experiment

### 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. This type of control was used with the unitary system in France with no adverse impact on the inverter drive equipment.

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. More detailed information on the electrical loads used to simulate occupancy and the relevant schedules is provided by Widder et al. (2013).

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[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.

## 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 installation 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. 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 attempt 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.

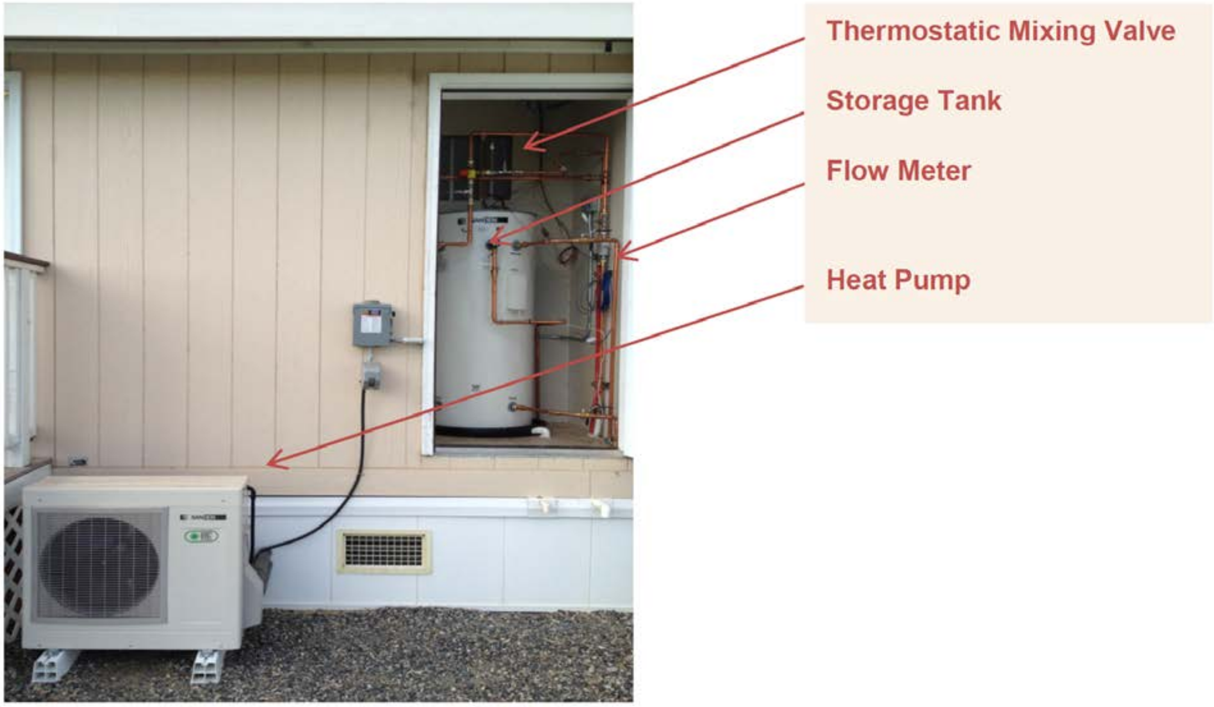

**Figure 2.2**. Sanden Split-System Heat Pump Water Heater as Installed in PNNL Lab Home B

### 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. No backup resistance heating elements are employed. Both the supply air inlet and exhaust outlet of the water heater are ducted. Supply air was drawn from beneath the home (the home has a roughly 3-foot crawlspace) by a variable speed centrifugal fan through an 8-inch ducted intake. This air passes over a coil where the heat exchange from the supply air to colder $CO_2$ refrigerant occurs. After heat exchange, the cooled air is discharged through the outlet duct to the exterior. 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 2.3The top section contains the compressor and heat exchanger and the bottom section is the tank assembly.

As with the Split System, hot water was produced 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.

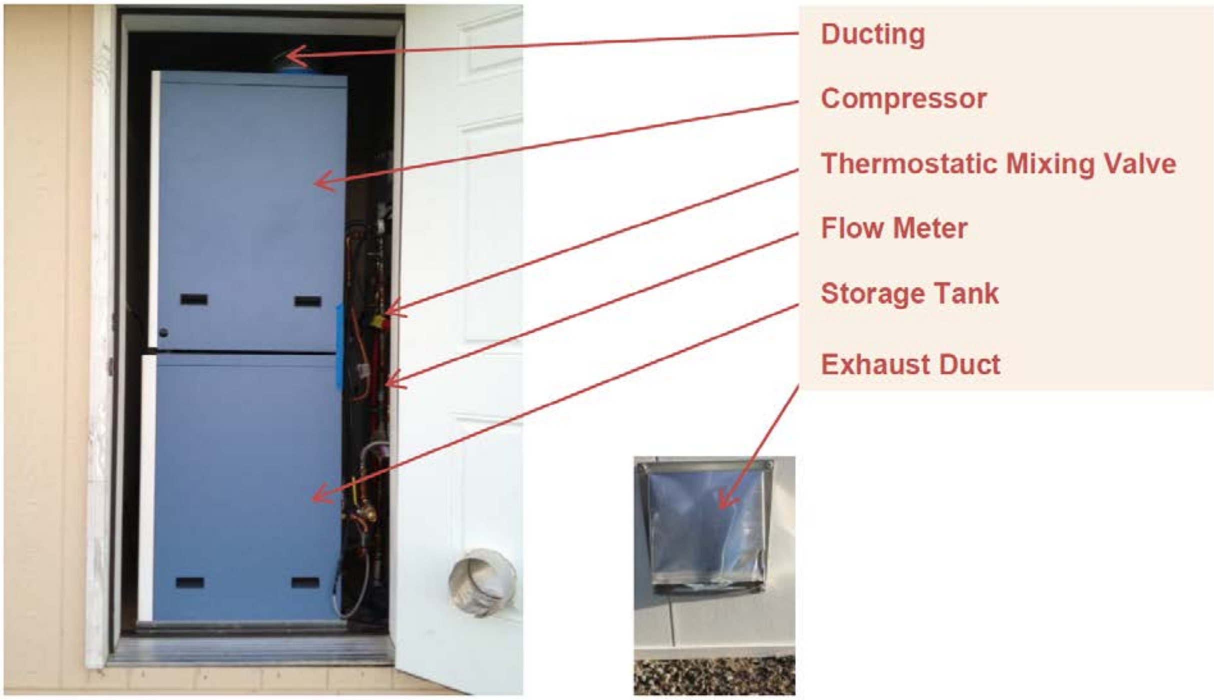

**Figure 2.3**. Sanden Unitary Heat Pump Water Heater as Installed in PNNL Lab Home A

# 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 load shifting capacity with each experiment. The schedule for the Sanden HPWHs was implemented over 7 days and consisted of increasing the time that the unit is off, beginning at 6 hours, to a total of 12 hours by the seventh day. The whole purpose of this off period is to create storage space within the water heater. The longer the water heater is off before the nighttime oversupply event, the more energy it can soak up. At the same time, leaving the water heater off runs the risk of not having enough hot water in the tank to meet the user demand. The day-by-day hourly increase in off time 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 test schedules are shown in Table 3.1 for the Sanden HPWHs.

**Table 3.1**. Sanden HPWHs Oversupply DR Test Schedule

| Day | Start Time | End Time | Pre-Event Power Down 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. Balancing INC calls can come at various times during a day depending on grid resources and utility operating characteristics. The Balancing INC events were spread over the day with relatively short 1-hour duration. The Balancing INC protocol was applied to both homes at identical times.

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[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<br>2:00 PM<br>8:00 PM | 9:00 AM<br>3:00 PM<br>9:00 PM | 1 hour<br>1 hour<br>1 hour |
| 5 | 8:00 AM<br>2:00 PM<br>8:00 PM | 9:00 AM<br>3:00 PM<br>9:00 PM | 1 hour<br>1 hour<br>1 hour |
| 6 | 8:00 AM<br>2:00 PM<br>8:00 PM | 9:00 AM<br>3:00 PM<br>9:00 PM | 1 hour<br>1 hour<br>1 hour |

## 3.3 Experiments and Schedules

The two styles of water heaters studied (HPWH Unitary and HPWH Split-System) were operated over three different experimental periods as shown in Table 3.3

**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 |

Seasonal temperature variations occurred over the experimental schedule that were not part of the original experimental design. Operational issues encountered with the unitary HPWH 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. Consequently, there were significant seasonal changes in the environmental conditions (outdoor air and cold water supply temperature) between the different experiments.

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, with no power interruptions (DR events), were conducted to benchmark standard operation. These baseline tests were completed in August 2014. In each case, a standard series of water draws was 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 tempered water temperature as measured after the mixing valve.

### 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 draws air from beneath the home, the effect of outdoor air temperature on system energy use is significantly dampened by the crawlspace temperatures. This effect is more noticeable as the temperature drops. 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.

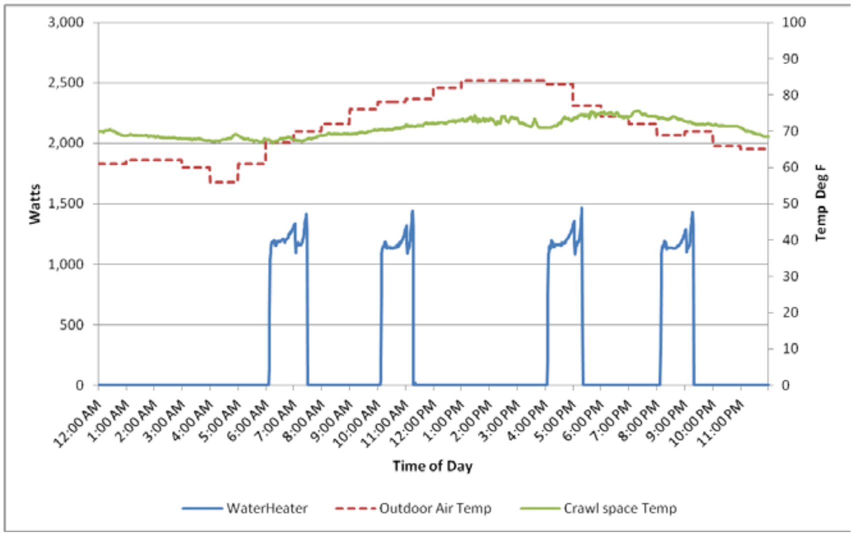


**Figure 3.1**. Sanden Unitary HPWH Baseline Power Profile, August 22, 2014

Figure 3.2 presents the resulting temperature profile of delivered water measured after the thermostatic mixing valve.

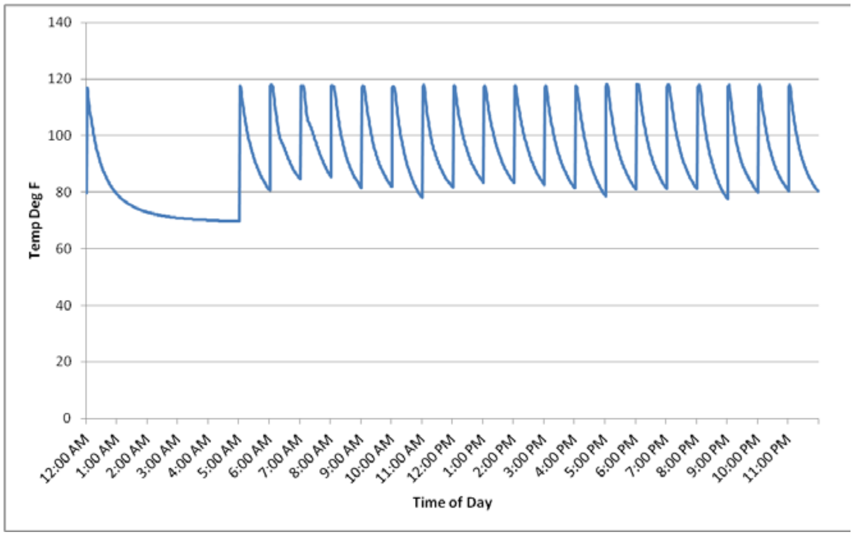


**Figure 3.2**. Sanden Unitary HPWH-Delivered Water Temperature Profile, August 22, 2014

The sawtooth pattern shown in Figure 3.2 is a result of plotting all the temperature data. The measurements are only useable as a hot water temeprature when the water is flowing (i.e. the spikes on the graph). As water is drawn, the temperature jumps 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 occured at which time the cycle begins again. 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.

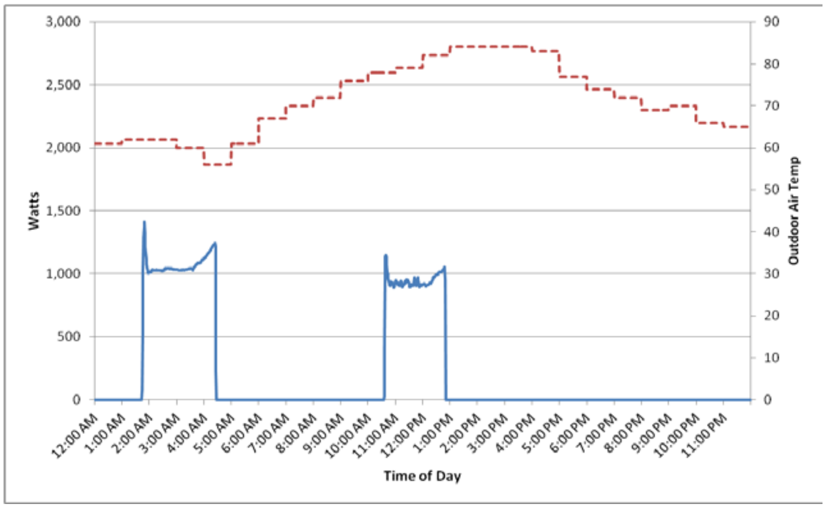


**Figure 3.3**. Sanden Split-System HPWH Baseline Power Profile, August 22, 2014

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 draws. 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.

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.

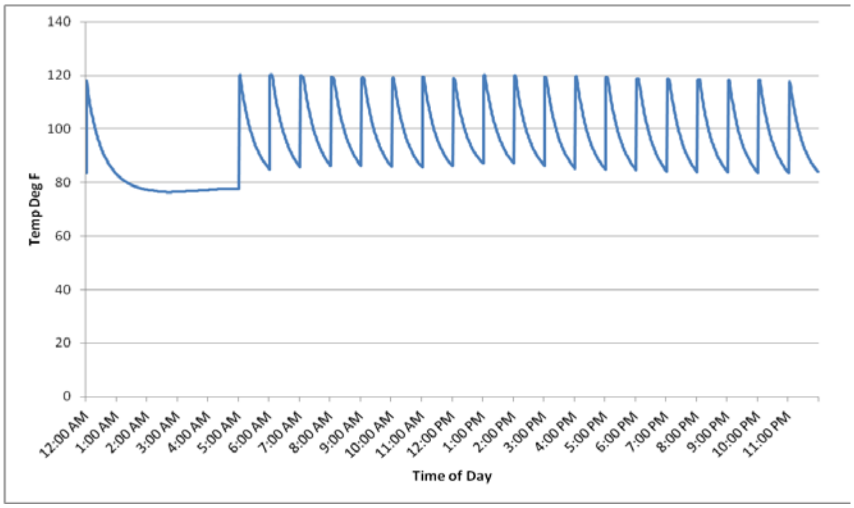


**Figure 3.4**. Sanden Split-System HPWH-Delivered Water Temperature Profile, August 22, 2014

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 affects the total number of recovery cycles that can be seen throughout the experimental period. Given an identical water draw pattern, the Unitary System, with its smaller tank, necessarily has a higher frequency of the recovery cycles than 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

As shown previously in Table 3.1, the DR schedule for the Sanden Unitary HPWH Oversupply testing began with the water heater powered-down at 6:00 PM through midnight. Then, for the next 7 days, this period was increased toward noon 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. Figure 3.5 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 energy shift by eliminating one of the four activation events noted in the Sanden Unitary baseline graph (Figure 3.1). Because this schedule 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. Instead, the water heater remained colder creating storage space to be later used during the oversupply period. The demand was shifted, in this case, to when the water heater was allowed to cycle back on at 12:00 AM (not shown on the graph). The recovery energy shifted out of the 6-hour off period and in to the next day was 2.35 kWh. The recovery energy shift is the amount of electrical energy, created using this DR protocol, which the water heater can store during the nighttime oversupply period.

Based on the length of power-down, the ambient conditions present, and the assumed draw pattern, this protocol yields a storage capacity of 2.35 kWh, which would equate to a load increase of 1.3 kW over 1.8 hours starting at midnight when the heater is allowed to operate again. Figure 3.6 shows that, during the power down period, hot water availability remained plentiful with supplied temperatures reaching 120°F. Consequently, this event could likely 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

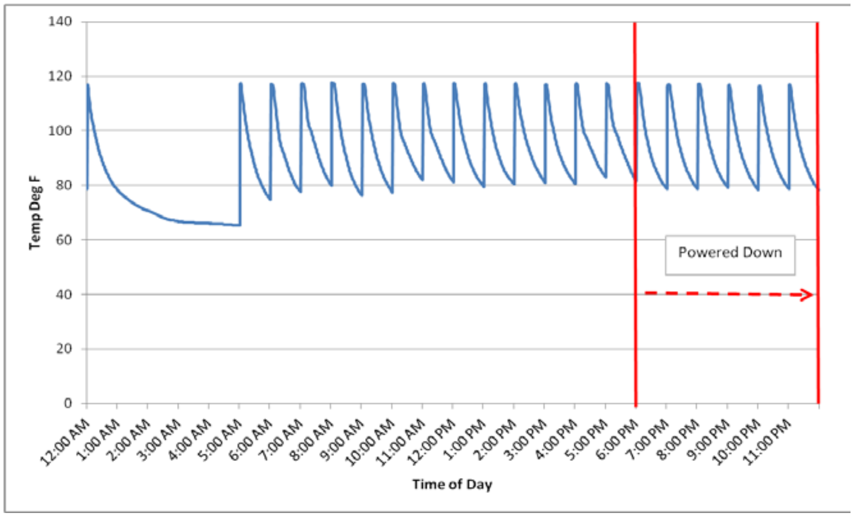


**Figure 3.6**. Sanden Unitary HPWH Oversupply Delivered Water Temperature Profile: First DR Event (6 hours powered-down), October 21, 2014

Figure 3.7 and Figure 3.8 present the next step in the scheduled series—the powered-down period extended to 5:00 PM. As shown, the same energy shifting occurs; however, the water temperature begins to drop below the set point to about 115°F after 6 hours. This drop to 115°F is still useable hot water but the 7 hour off period begins to show the limits of the hot water storage with this tank under this draw pattern.

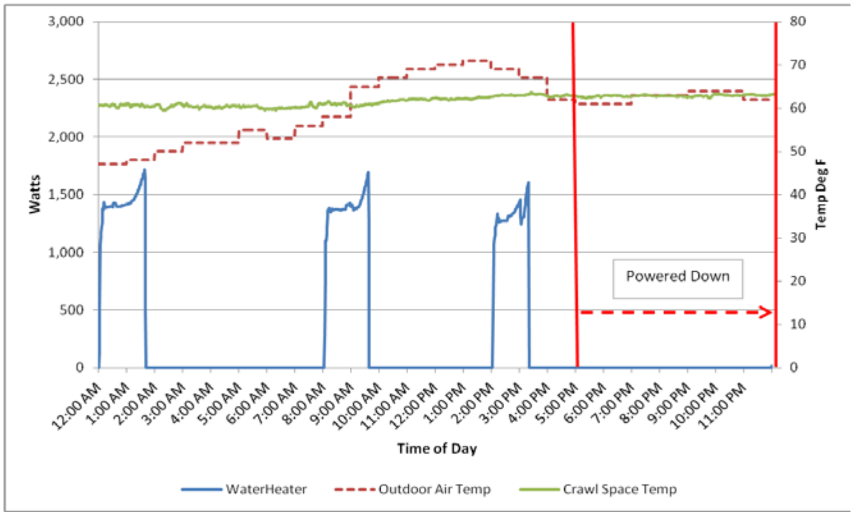


**Figure 3.7**. Sanden Unitary Oversupply Power Profile: Second DR event (7 hours powered-down), October 22, 2014

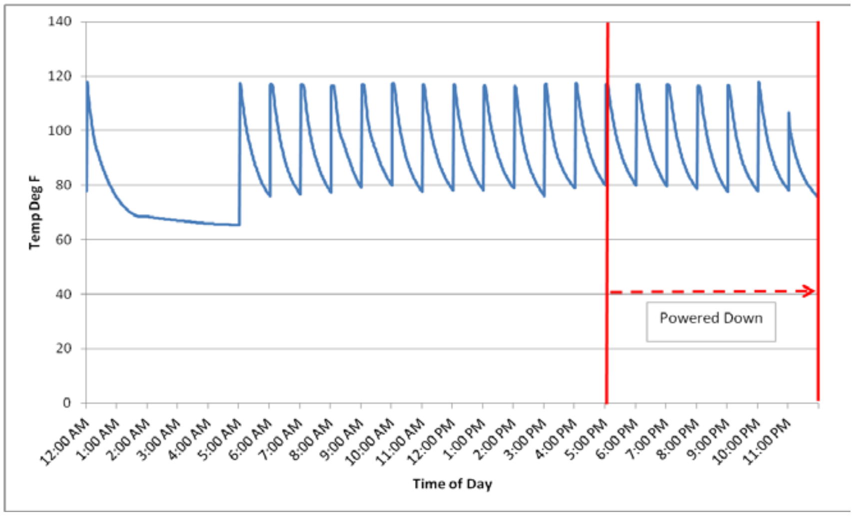


**Figure 3.8**. Sanden Unitary HPWH Oversupply Delivered Water Temperature Profile: Second DR Event (7 hours powered-down), October 22, 2014

The final series of Sanden Unitary HPWH Oversupply graphs are presented in Figure 3.9 and Figure 3.10, which highlight the longest power-down time at 12 hours and the resulting heat pump operation. 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 and continues to fall, with each subsequent draw, until the tank has run out of hot water.

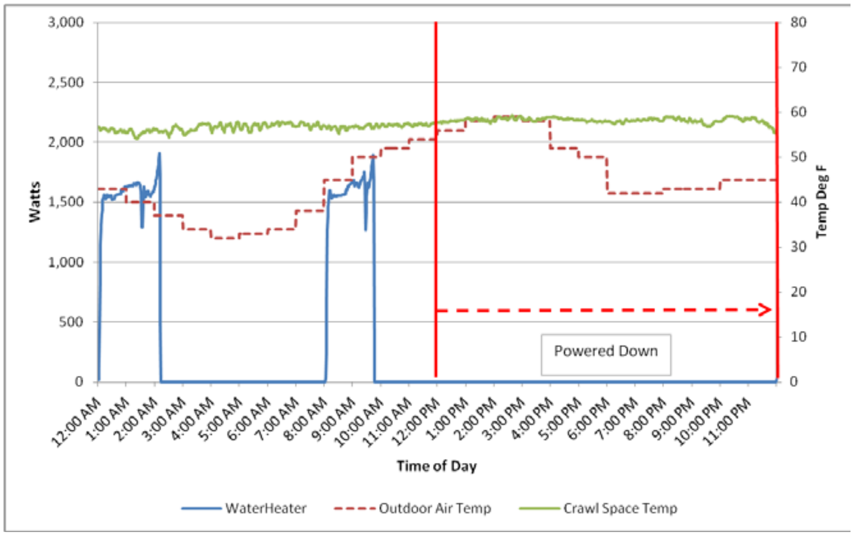


**Figure 3.9**. Sanden Unitary Oversupply Power Profile: Seventh DR Event (12 hours powered-down), October 27, 2014

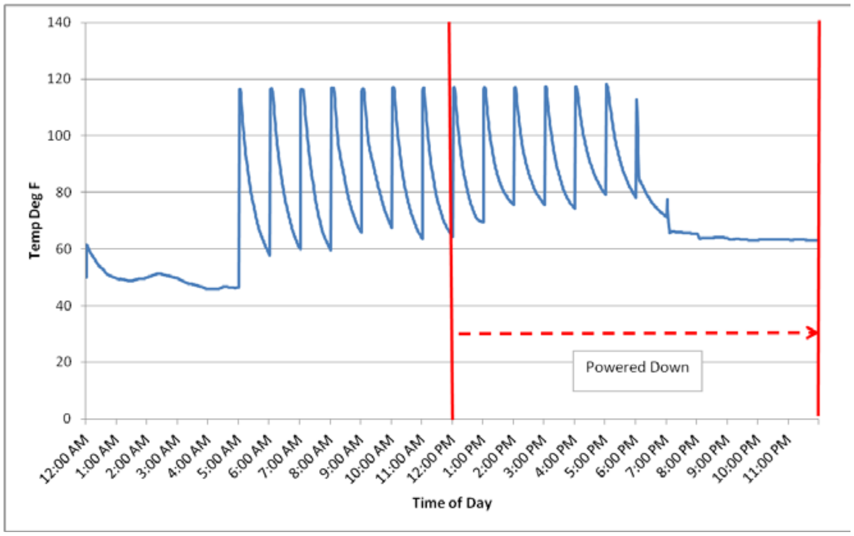


**Figure 3.10**. Sanden Unitary HPWH Oversupply Delivered Water Temperature Profile: Seventh DR Event (12 hours powered-down), October 27, 2014

For the conditions examined, the Sanden Unitary HPWH, created an electric energy storage opportunity of 2.35 kWh and concomitant demand shift of 1.3 kW. Because the Sanden units are HPWHs, the wattage of the shifted demand and energy, are a function of the HPWH source temperatures. When the source air temperature or supply water temperature is colder, the values are larger. Regardless of draw pattern or duration of the off period, this protocol will always tend to shift the load to the period after the power-down 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 a power-down period of up to 6 hours in duration, creating a storage capacity of 2.35 kWh during this period. However, as is expected with the given draw pattern and a 39.7 gallon tank capacity, after 6 hours of being powered off, 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.

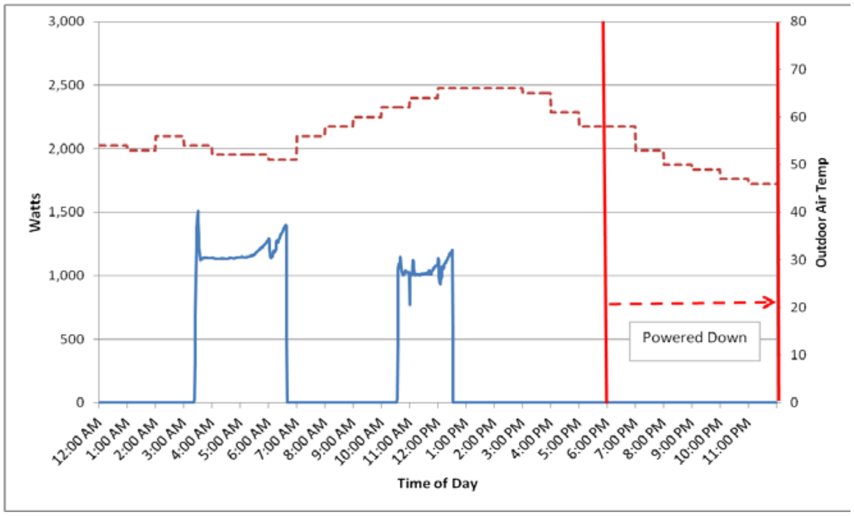


**Figure 3.11**. Sanden Split-System Oversupply Power Profile: First DR Event (6 hours powered-down), October 21, 2014

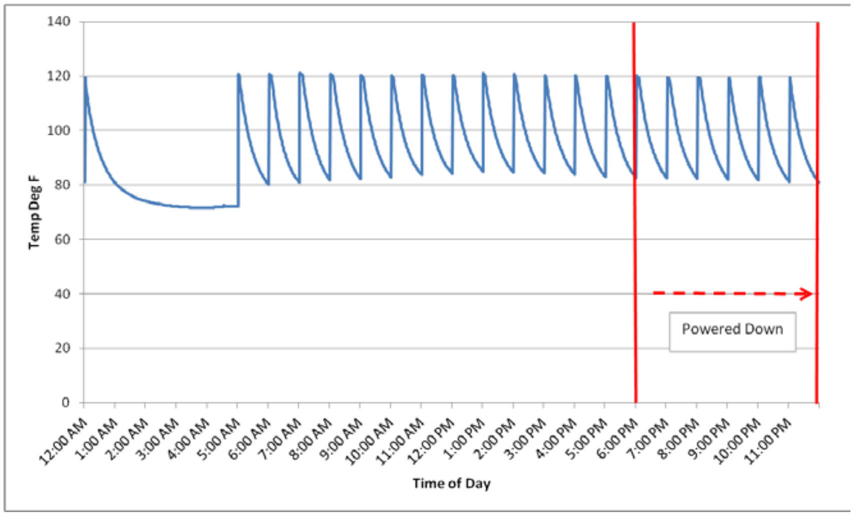


**Figure 3.12**. Sanden Split-System HPWH Oversupply Delivered Water Temperature Profile: First DR Event (6 hours powered-down), October 21, 2014

This test did not result in creating any new electric storage capacity because the water heater would normally not have 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. The calculation is the number of gallons of water provided during the shut off period plus the water added to temper the water multiplied by the difference between the delivered and supply water temperature.

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.

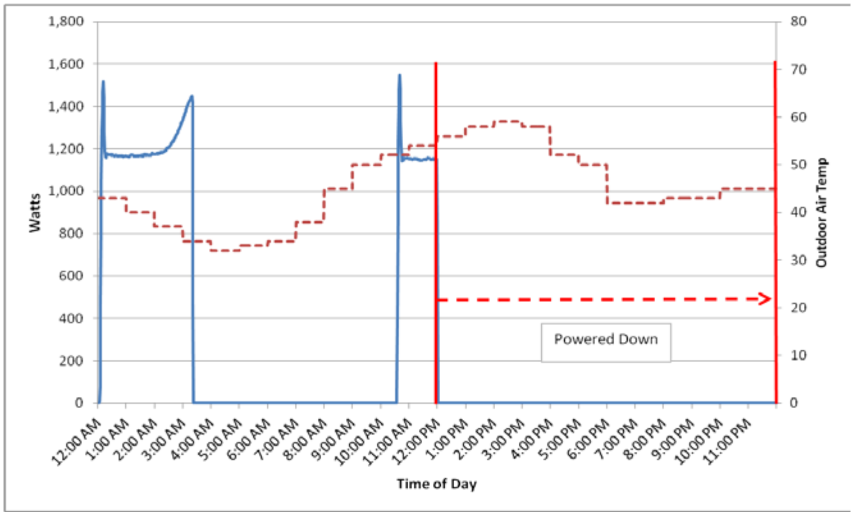


**Figure 3.13**. Sanden Split-System Oversupply Power Profile: Last DR Event (12 hours powered-down), October 27, 2014

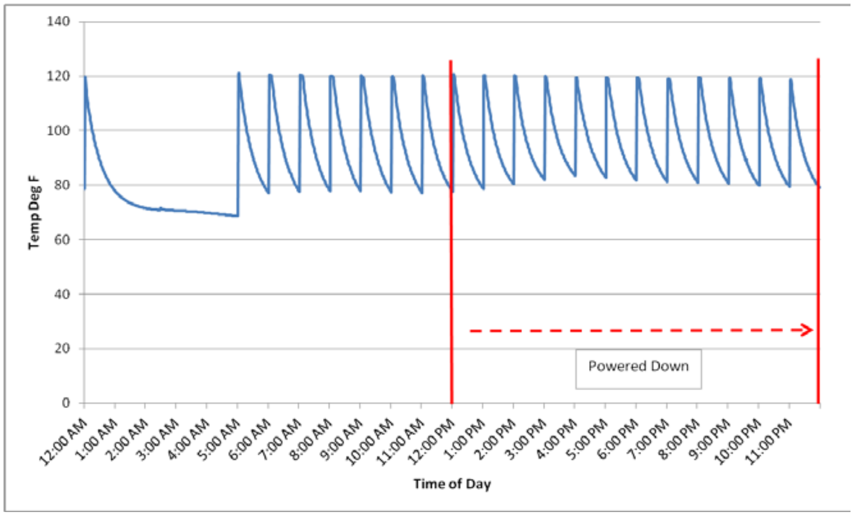


**Figure 3.14**. Sanden Split-System HPWH Oversupply Delivered Water Temperature Profile: Last DR Event (12 hours powered-down), October 27, 2014

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 shows a wattage reduction of about 1.3 kW. Assuming there is alignment between the oversupply event and the call for power use, the Sanden Unitary HPWH results in a demand shift of about 1.3 kW.

The Sanden Split-System HPWH temperature profiles show that, for the experimental water draw profile, this water heater can accommodate a powered down period of 12 hours 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 is the peak watts available to be shifted through Oversupply implementation. The Recovery Energy Shift is the amount of energy demand (kWh) that is stored for the post-power-down period. The Oversupply Preparation 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 Preparation 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.

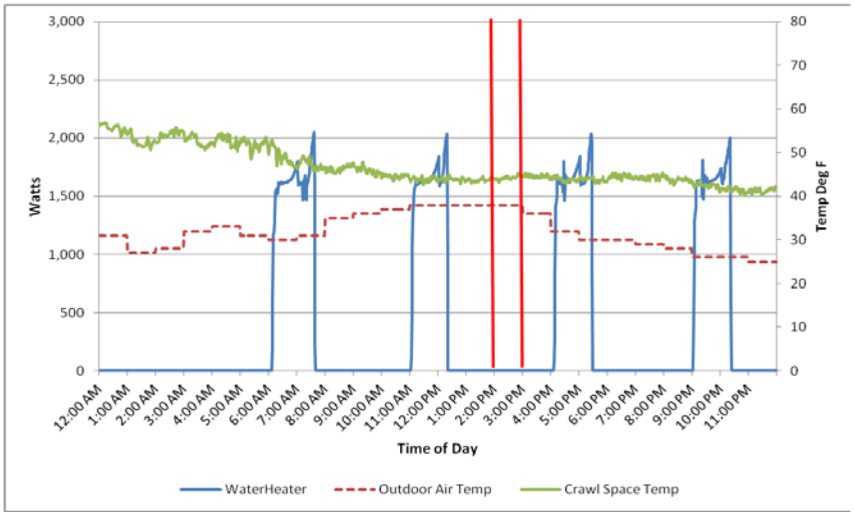


**Figure 3.15**. Sanden Unitary Balancing INC Power Profile: 2:00 PM (1 hour powered-down protocol), November 11, 2014

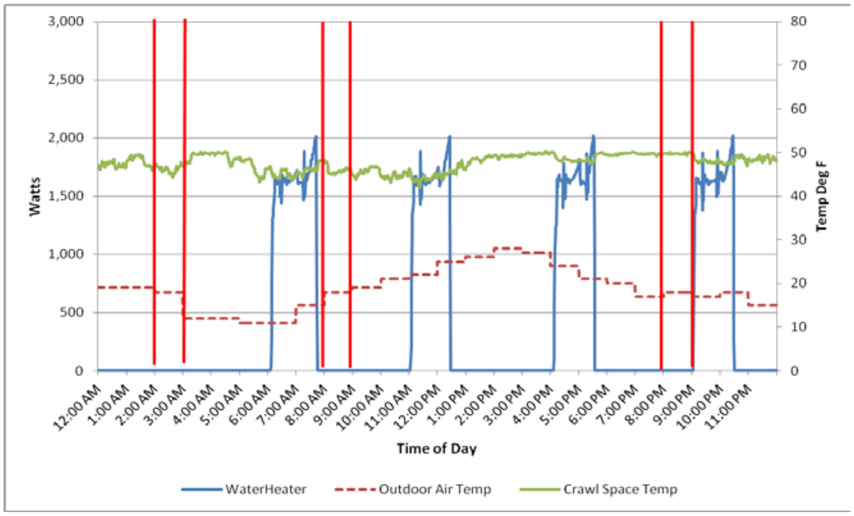


**Figure 3.16**. Sanden Unitary Balancing INC Power Profile: 2:00 AM, 8:00 AM, and 8:00 PM (1 hour powered-down protocol), November 16, 2014

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.

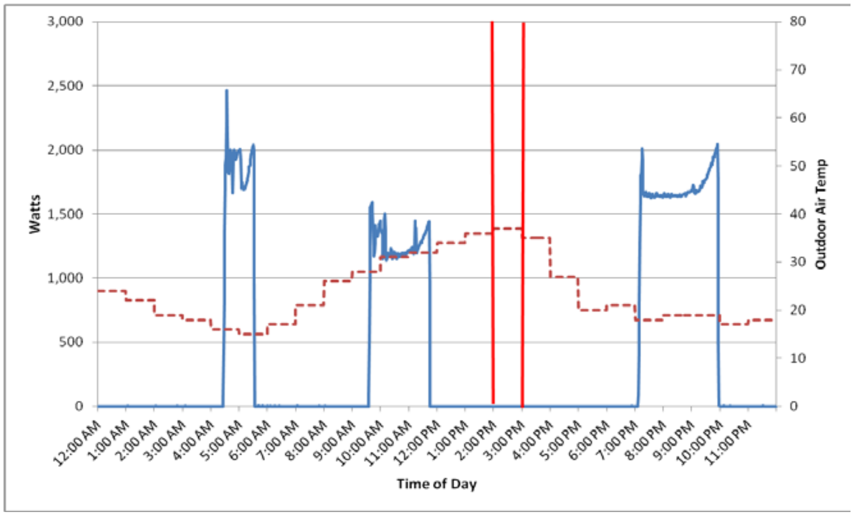


**Figure 3.17**. Sanden Split-System Balancing INC Power Profile: 2:00 PM (1 hour powered-down-protocol), November 12, 2014

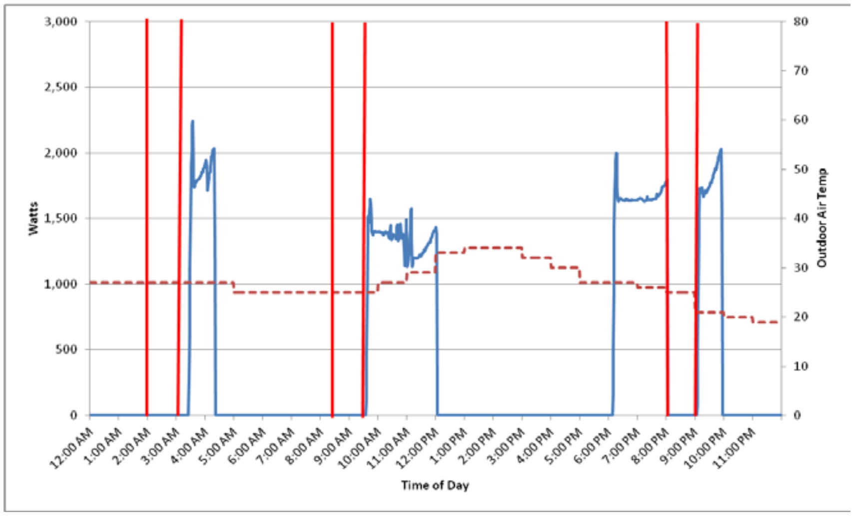


**Figure 3.18**. Sanden Split-System Balancing INC Power Profile: 2:00 AM, 8:00 AM, and 8:00 PM (1 hour powered-down protocol), November 14, 2014

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. If this test were run on the same day as the baseline, the “demand shift” would be equal to the power draw in the baseline.

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 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. 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

This section focuses 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 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 Balancing INC and Oversupply Mitigation protocols. 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 efficiency of the water heaters and subsequently the total Dispatchable Power seen in the experimental period. In general, the Unitary System provides a more frequent event (cycling on) profile and a larger Dispatchable Power (kW) draw compared to the Split System. As shown, this is a function of storage tank capacity. 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. These factors should be considered when developing DR programs and protocols. 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 Preparation 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.

Even though supply air temperature differed between the two water heaters, the energy consumption per gallon of water was fairly comparable—differing most where the temperature difference was greatest. 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 emulate dispatchability using a 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 coming generations of its U.S. product line.

## 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 the requisite delivery temperature in the power-down period leading up to the Oversupply event for the first scenario only (6-hour event), but could not maintain delivery temperature (120°F) when the power-down period incremented to the 7, or more, hours. It is acknowledged that the draw pattern used in this experiment is substantially 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 scenario during which the unit was powered-down for a full 12 hours. This capability is attributed to both the large storage capacity.

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. This is likely to require a DR protocol and equipment capability to assess the state of the water heater at the time of preparation for a likely DR event—particularly where that event is oversupply mitigation. A DR measure that requires a power draw may also specify that the HPWH be placed in operation mode at the appropriate time.

## 5.3 DR Protocol Impact of HPWH Operation

This was a major research question that could not be adequately addressed given early challenges with the Unitary System operation resulting in a protracted experimental schedule and significant seasonal changes in HPWH source air and water temperatures between the experiments.

## 5.4 DR Recommendations

Because the split system HPWH must obtain all its heat from outside air there is a direct relationship in energy use and supply air temperature (see Table 3.4, Table 3.5, and Table 3.6). 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.

# 6.0 References

Baylon, D., P. Storm, K. Geraghty, and B. Davis. 2012. *Residential Building Stock Assessment: Single-Family Home Characteristics and Energy Use*, Prepared for Northwest Energy Efficiency Alliance. Portland, OR. http://neea.org/docs/reports/residential-building-stock-assessment-single-family-characteristics-and-energy-use.pdf

BPA – Bonneville Power Administration. 2011. *Residential Heat Pump Water Heater Evaluation: Lab Testing & Energy Use Estimates.* Prepared by Ecotope, Inc., for the Bonneville Power Administration, Portland, Oregon. Accessed August 6, 2013, at http://www.bpa.gov/energy/n/emerging_technology/pdf/HPWH_Lab_Evaluation_Final_Report_20111109.pdf.

BPA – Bonneville Power Administration. 2010. *Residential Heat Pump Water Heater Evaluation Project Measurement & Verification Plan*. Prepared by Ecotope, Inc., for the Bonneville Power Administration, Portland, OR. Accessed August 6, 2013, at http://www.bpa.gov/energy/n/emerging_technology/pdf/HPWH_MV_Plan_Final_012610.pdf.

BPA – Bonneville Power Administration. 2011. *Residential Heat Pump Water Heater Evaluation: Lab Testing & Energy Use Estimates.* Prepared by Ecotope, Inc., for the Bonneville Power Administration, Portland, OR. Accessed August 6, 2013, at http://www.bpa.gov/energy/n/emerging_technology/pdf/HPWH_Lab_Evaluation_Final_Report_20111109.pdf.

Broad, D, K Spielman, and K Dragoon, ECOFYS 2014. *Heat Pump Water Heaters for Demand Response and Energy Storage.* Report #E14-296 prepared for the Northwest Energy Efficiency Alliance. Portland, Oregon. http://neea.org/docs/default-source/reports/final-hpwh-dr-report-and-summary.pdf.

CSA – Canadian Standards Association. 2012; DRAFT. *Testing Method for Measuring Energy Consumption and Determining Efficiencies of Gas-Fired and Fuel Oil-Fired Storage Water Heaters*. Canadian Standards Association, Ontario, Canada.

Christian J, T Gehl, P Bourdreaux, J New, and R Dockery. 2010. *Tennessee Valley Authority's Campbell Creek Energy Efficiency Homes Project: 2010 First Year Performance Report July 1, 2009 - August 31, 2010*. ORNL/TM-2010/206, Oak Ridge National Laboratory, Oak Ridge, Tennessee. Accessed August 6, 2013, at http://info.ornl.gov/sites/publications/files/pub26374.pdf

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=6345632EIA – U.S. Energy Information Administration. 2009. *Residential Energy Consumption Survey*. Accessed August 6, 2013, at http://www.eia.gov/consumption/residential/.

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

Eklund, K and A Banks. 2014. *Advanced Heat Pump Water Heater Research First Midterm Field Study Report*. Washington State University Publication # WSUEEP15-005, WSU Energy Program for Bonneville Power Administration.

Hendron and Engebrecht. 2010. *Building America House Simulation Protocols.* TP-550-49426. National Renewable Energy Laboratory, Golden, CO. Accessed August 6, 2013, at http://www.nrel.gov/docs/fy11osti/49246.pdf.

Konodoh J, L Ning, and D Hammerstrom. 2010. *An Evaluation of the Water Heater Load Potential for Providing Regulation Service.* IEEE Transactions on Power Systems 26(3). Accessed August 6, 2013, at http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5668519&tag=1.

Kresta, D. 2012. *Heat Pump Water Heater Market Transformation Update*. Northwest Energy Efficiency Alliance. Portland, Oregon.

Larson, B. 2013. *Laboratory Assessment of Sanden GAU Heat Pump Water Heater.* Report # WSUEEP14-003, Ecotope, Inc, Portland, Oregon.

Larson, B and M Logsdon. 2013. NEEA Report: *Laboratory Assessment of Sanden GES-15QTA Heat Pump Water Heater*. REPORT #10172013, Ecotope Inc. for the Northwest Energy Efficiency Alliance, Portland, Oregon.

Lu S, N Samaan, R Diao, M Elizondo, C Jin, E Mayhorn, Y Zhang and H Kirkham. 2011. *Centralized and Decentralized Control for Demand Response.* Innovative Smart Grid Technologies (ISGT), 2011 IEEE PES, 17–19 Jan. 2011. DOI: 10.1109/ISGT.2011.5759191. Accessed August 6, 2013, at http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5759191.

Lutz J and M Melody. 2012. *Typical Hot Water Draw Patterns Based on Field Data*. Lawrence Berkeley National Laboratory, Berkeley, California.

Mathieu J, M Dyson, and D Callaway. 2012. *Using Residential Electric Loads for Fast Demand Response: The Potential Resource and Revenues, the Costs, and Policy Recommendations.* ACEEE Summer Study on Energy Efficiency in Buildings. Pacific Grove, California. Accessed August 6, 2013, at http://www.aceee.org/files/proceedings/2012/data/papers/0193-000009.pdf.

Saker N, M Petit, and J Coullon. 2011. *Demand Side Management of Electrical Water Heaters and Evaluation of the Cold Load Pick-Up Characteristics (CLPU).* 2011 IEEE Trondheim Power Tech, 19–23 June 2011. DOI: 10.1109/PTC.2011.6019312. Accessed August 6, 2013, at http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6019312.

Sepulveda, A, L Paull, W Morsi, H Li, C Diduch, and L Chang. 2010. *A Novel Demand Side Management Program using Water Heaters and Particle Swarm Optimization.* 2010 IEEE Electrical Power & Energy Conference (EPEC), August 25–27, 2010. DOI: 10.1109/EPEC.2010.5697187. Accessed August 6, 2013, at http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5697187.

Widder SH, JM Petersen, GB Parker, and MC Baechler. 2013. *Demand Response Performance of GE Hybrid Heat Pump Water Heater*. PNNL-22642, Pacific Northwest National Laboratory, Richland, Washington. Accessed March 2015 at http://labhomes.pnnl.gov/experiments/hpwh.stm

# Appendix A: 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 A.1.

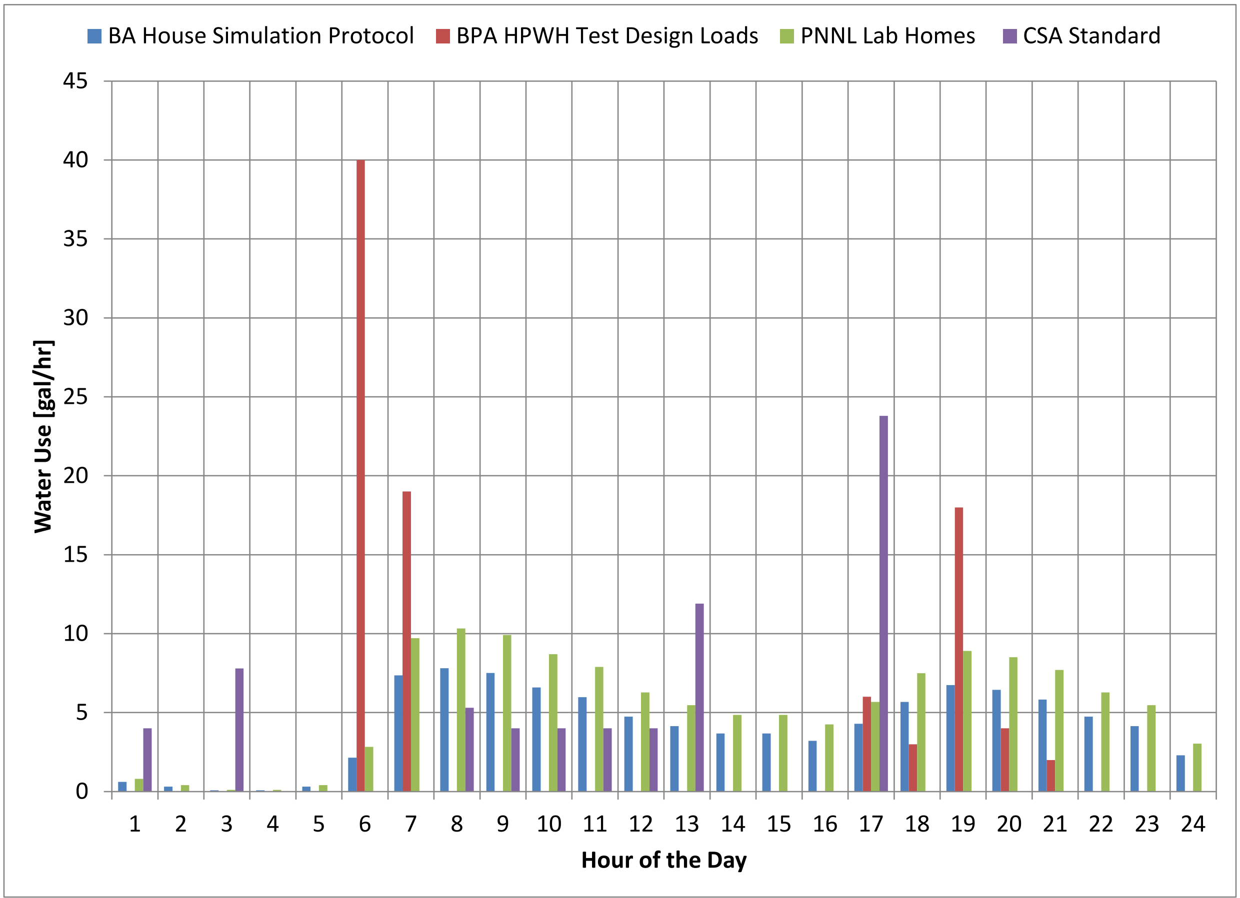
PNNL also explored using the "DHW Event Generator" (Hendron and Burch 2010), a spreadsheet tool developed by the National Renewable Energy Laboratory that produces an entire year of simulated draw profiles. However, the simulated draw pattern changes daily so it is extremely difficult to accomplish in 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 A.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 A.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 A.1**. Comparison of the Four Hot-Water Use Profiles

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