PNNL-23527

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Evaluation of the Demand Response Performance of Large Capacity Electric Water Heaters

March 2015

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

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under Contract DE-AC05-76RL01830

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Richland, Washington 99352

Summary

The electric power grid is being modernized to accommodate large-scale integration of clean energy resources, such as wind and solar. However, increased penetration of these intermittent resources will require additional stabilizing resources to balance generation and demand. Using traditional generation resources such as coal or natural gas plants to balance intermittent renewable sources and provide grid stability services is fraught with cost issues and undesirable environmental impacts that offset the potential benefits of renewable generation. Controlling loads rather than supply, which is referred to as demand-side management or demand response (DR) (DOE 2006), is expected to play a key role in ensuring grid stability, reliability, and efficient power grid operations in a more convenient and cost-effective way. Existing DR programs most commonly offer peak load management services, requiring long duration responses, up to several hours, from loads. Future DR programs are expected to provide short-term (i.e., ramping) and very short-term (i.e., regulation, spinning reserves) responses to enable large-scale renewable integration.

In a residential environment, thermal storage 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, large-tank residential electric resistance water heaters (ERWHs) have been identified as ideal candidates for DR because they contain significant thermal storage, they contribute a significant amount of the residential load, they have relatively high power consumption and a large installed base, and 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, thus the efficiency of the ERWH is not affected by frequent switching and it does not require reactive power support to operate (Diao et al. 2012).

New models of electric water heaters that rely on a heat pump to heat water, rather than or in addition to electric resistance elements, are available and have the potential to save to 63% per water heater[1] and up to 11% of residential energy use (EIA 2009). These heat pump water heaters (HPWHs) will inherently reduce peak load, due to the reduced energy use associated with water heating. However, the ability of heat pump water heaters to provide flexible and dynamic DR has not been demonstrated. Utilities have raised concerns that HPWHs and ERWHs with a storage capacity of less than 55 gallons do not have the same load-balancing capability as large-tank ERWHs. However, it is not clear that the same utility load balancing DR services provided by large-tank ERWHs cannot be met with the more efficient HPWHs without loss of efficiency or capability to provide acceptable quality of service to utilities and homeowners.

The purpose of this project is to verify or refute many of the concerns raised by utilities regarding the ability of large tank HPWHs to perform DR by measuring the performance of HPWHs compared to ERWHs in providing DR services. This project was divided into three phases. Phase 1 consisted of week-long laboratory experiments designed to demonstrate technical feasibility of individual large-tank HPWHs in providing DR services compared to large-tank ERWHs. In Phase 2, the individual behaviors of the water heaters were then extrapolated to a population by first calibrating readily available water

[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 = 2.33)

heater models developed in GridLAB-D[1] simulation software to experimental results obtained in Phase 1. These models were used to simulate a population of water heaters and generate annual load profiles to assess the impacts on system-level power and residential load curves. Such population modeling allows for the inherent and permanent load reduction accomplished by the more efficient HPWHs to be considered, in addition to the temporal DR services the water heater can provide by switching ON or OFF as needed by utilities. The economic and emissions impacts of using large-tank water heaters in DR programs are then analyzed from the utility and consumer perspective, based on National Impacts Analysis in Phase 3. Phase 1 is discussed in this report. Details on Phases 2 and 3 can be found in the companion report (Cooke et al. 2014).

The goal of the experiments in Phase 1 was to demonstrate technical feasibility of large-tank HPWHs compared to ERWHs in delivering services for existing (i.e., peak load reduction) and future (i.e., short-term and very short-term) DR programs compared to an 80-gallon class ERWH. In particular, the availability and impacts on customer service, energy consumption, and equipment life cycles were assessed. Each experiment included side-by-side testing of an 80-gallon class ERWH and HPWH, with the same scheduled draw pattern and water temperature set point, over a 7-day period. The scheduled draw pattern was varied daily to represent and capture the impacts of draw pattern on water heater performance.

Through experimental testing, it was demonstrated that large-tank HPWHs are technically capable of performing DR services in both existing DR programs (e.g., peak load reduction) and future programs that require frequent short-term responses (i.e., ramping), without adversely impacting efficiency, consumer delivery temperatures, or equipment life. Even though ERWHs have 4 times the power demand than HPWHs, the HPWH showed to be ~10% and 5% more available to provide peak load reduction and short-term response services, respectively.

Experimental results indicate that future programs requiring frequent and very short-term responses (i.e., frequency regulation) could significantly impact efficiency or consumer delivery temperatures depending on the mode of operation, as well as considerably increase compressor cycling. In particular, if the HPWH is operated in efficiency mode, the water heater would not deliver water at acceptable temperatures or would sacrifice efficiency to deliver hot water at adequate temperatures if operating in hybrid mode. In addition, cycling increased five times compared to the baseline scenario. On the other hand, the HPWH was at least 10% more available than the ERWH in the very short-term response scenario, similar to the peak load reduction and short-term response scenarios.

It is worth noting that the negative impacts on efficiency and acceptable water temperature delivery are dependent on the device level controls in place for responding to DR signals, as well as the strategies for coordinating the collective response to meet DR program objectives. Therefore, more intelligent designs of population coordination strategies and device level controls may aid in mitigating impacts observed while still meeting overall objectives. Further investigation via population modeling and analysis is needed to determine if mitigation is possible.

[1] GridLAB-D is an open-source, DOE-funded time series simulation tool that facilitates the study of many operating aspects of a smart grid from the substation level down to loads in unprecedented detail. In this work, GridLAB-D was used to model the population behavior of demand responsive water heaters.

Acknowledgments

The experimental team is grateful to John Cymbalsky and Ashley Armstrong, the Program Managers for the DOE Appliance and Commercial Equipment Standards Program, as well as Joe Hagerman and George Hernandez who also provided guidance on project scope and direction.

The team also wishes to acknowledge Dennis Stiles and Rob Pratt for their management support; Jason Fuller, Andrew Fisher, Laurentiu Marinovici for their technical assistance running GridLAB-D simulations; Dave Winiarski for his technical insights and guidance; and Marye Hefty who assisted in the project planning and analysis of industry comments.

Acronyms and Abbreviations

ACE	area control error
BPA	Bonneville Power Administration
CSA	Canadian Standards Association
CT	current transformer
DAS	data acquisition systems
DOE	U.S. Department of Energy
DR	demand response
ERWH	electric resistance water heater
ETS	electric thermal storage
gpm	gallons per minute
HPWH	heat pump water heater
LBNL	Lawrence Berkley National Laboratory
NOPR	Notice of Proposed Rulemaking
RFI	Request for Information

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1.0 Introduction

The electric power grid is now being modernized to accommodate large-scale integration of renewable energy resources, such as wind and solar. However, increased penetration of these intermittent resources will require additional stabilizing resources to balance generation and demand. Using traditional generation resources such as coal or natural gas plants to balance intermittent renewable sources and provide grid stability services is fraught with cost issues and undesirable environmental impacts that offset the potential benefits of renewable generation. Controlling loads rather than supply, which is referred to as demand-side management or demand response (DR) (DOE 2006), is expected to play a key role in ensuring grid stability, reliability, and efficient power system operations in a more convenient and cost-effective way. Several types of grid services can be provided using DR on different timescales:

- Peak curtailment, or peak load reduction, which drops noncritical loads for a period of 4–6 hours during the time when power use is highest and the strain on the grid is greatest. This can decrease use of inefficient, fossil fuel-fired "peaking plants" that exist solely to generate electricity during the peak 4–6 hour period and are otherwise turned down or off.

- Balancing reserves, or load following, responds to hourly or sub-hourly changes in generation capacity either due to inherent variability in the generation resource or large disturbances in the grid (e.g., transmission fault) (Diao et al. 2012). As increasing amounts of wind and solar are introduced on the grid, the need for balancing to respond to fluctuations in wind speed or insolation will be needed (Konodoh et al. 2011). Using DR for balancing reserves can also increase overall grid efficiency and decrease stress on mechanical generators from frequent ramping (Konodoh et al. 2011).

- Ancillary services, or regulation support, which consists of adapting to sub-minute fluctuations in voltage or frequency to maintain consistent electricity service and distribution. Previous studies have also demonstrated a strong link between increased renewable penetration and ancillary service requirements (Ela et al. 2011; Makarov et al. 2009; Loutan 2009).

In a residential environment, thermal storage 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 electric resistance water heaters (ERWHs) have been identified as ideal candidates for DR because they contain significant thermal storage, they contribute a significant amount of the residential load, they have relatively high power consumption and a large installed base, and 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 have previously evaluated the potential of ERWHs to provide peak curtailment, load following, and ancillary services and found significant potential and benefit for ERWHs 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). Many utilities are employing large tank ERWHs to reduce power consumption at times of peak power demand (typically in the afternoon) by heating water off-peak and turning off water heaters for up to 6 hours during the day, when power demand is highest. These programs are typically referred to as electric thermal storage (ETS) programs, since they store thermal energy in the form of hot water, generated at times of low energy demand for use during times of high energy demand. Utilities typically use water heaters with large storage volumes, such as 80–90 gallon tanks, to ensure that participating customers have sufficient hot water during the peak period when electricity is not provided to the ERWH and no water heating can occur.

New electric water heating technology that employs a heat pump to heat water, instead of an electric resistance element, is available and becoming more widespread. Heat pump water heaters (HPWHs) are up to 63% more efficient than traditional ERWHs and, if deployed at a large scale, have the potential to decrease residential energy use up to 11% (EIA 2009). However, use of more efficient heat pump technology may impact the potential of water heaters to perform grid services. While utilities and efficiency advocates have significant interest in encouraging the adoption of HPWHs, no modeling or field studies were identified that have evaluated the DR potential of a population of large tank HPWHs in comparison to that provided by ERWHs. Previous work in the PNNL Lab Homes[1] has demonstrated the DR potential of 50 gallon HPWHs compared to 50 gallon ERWHs and shown HPWHs capable of providing reasonable DR services without sacrificing HPWH efficiency, although the ability of a single HPWH was reduced compared to the ERWH (Widder et al. 2013). The study did not evaluate the inherent peak load reduction due to the increased efficiency of the HPWH or the ability of a population of HPWHs to provide equivalent DR services, as it was focused purely on a comparison of the equipment-level operation of the units. If ERWHs are to be replaced with HPWHs at a large scale to improve residential energy efficiency, it is important to understand how such a change will impact DR programs and overall grid stability now and in the future.

The U.S. Department of Energy (DOE) recently amended its energy conservation standards for residential water heaters, including standards for water heaters with storage capacity larger than 55 gallons (large-tank water heaters) (75 FR 20112; April 16, 2010). Compliance with these amended standards is required for water heater products manufactured or imported into the United States on or after April 16, 2015. The amended standards established for large-tank water heaters currently can only be met by HPWHs, not conventional ERWHs. Utilities, particularly in the Midwest, are now concerned that the large-tank ERWHs they typically use in their ETS programs will not be available in the future and HPWHs may not be able to provide the same services. The following concerns were listed throughout 389 letters responding to the DOE issued Request for Information (RFI), regarding the impact of the amended standard on ETS programs that use large-tank ERWHs (77 FR 35299; June 13, 2012):

Technical Concerns[2]

1. HPWHs have longer recovery times, which may require even larger tank sizes to obtain the same effective capacity as ERWHs or to ensure hot water delivery with DR programs.

2. Demand response may cause increased compressor cycling, which would negatively impact the product's service life.

[1] See http://labhomes.pnnl.gov/ for more information.
[2] The specific concerns in response to DOE's RFI are located at www.regulations.gov in docket number EERE-2012-BT-STD-0022.

3. With HPWHs, DR programs will lose ability to store low-carbon, renewable energy (wind and solar).

4. The HPWH storage temperature is limited to 130 degrees Fahrenheit, which may limit the types of DR services a HPWH can provide.

Economic Concerns

5. HPWHs are more expensive to purchase than ERWHs.

6. Without the discounted energy rate from ERWH DR programs, other fuels gain a competitive advantage.

Installation and Comfort-related Concerns

7. Banning ERWHs greater than 55 gallons "poses a severe hardship on larger families, the elderly and disabled."

8. HPWHs require more space to operate effectively.

9. HPWHs vent cold air into conditioned space (a problem for colder climates).

10. Miscellaneous issues (not mentioned repeatedly) include the noise of HPWHs

To immediately address these concerns, DOE issued a Notice of Proposed Rulemaking (NOPR) that proposes a waiver process allowing any electric utility company to request a 1-year, renewable waiver granting exemption from the energy conservation standards established in the April 16, 2010 final rule (75 FR 20112) for certain electric water heaters with rated storage volumes greater than 55 gallons manufactured exclusively for the purpose of installation in residences enrolled in a specific utility company ETS program (78 FR 12969; Feb. 26, 2013).

1.1 Project Scope

In this work, focus was placed on responding to technical and economic concerns regarding the ability of HPWHs to operate as effectively as large-tank ERWHs in DR programs. Many of the installation and comfort-related concerns have already been addressed in the literature and other related research projects. Specifically, previous work in the PNNL Lab Homes has evaluated the space conditioning and comfort-related impacts of HPWHs venting cold air into conditioned space (Widder et al. 2014). With regard to comfort concerns, the Lab Home research found no significant temperature impacts in adjacent conditioned spaces and, thus, did not anticipate a comfort concern in a majority of installations. The study also evaluated the impact of HPWHs with no ducting, with exhaust only ducting, and with supply and exhaust ducting on space conditioning and whole house energy use. The data indicate a much smaller space conditioning penalty than has previously been assumed in models exploring this issue (Larson et al, 2011; Wilson and Christensen 2012) and found HPWHs to save energy in all cases in the Richland, WA, climate (Widder et al. 2014). Regarding the noise of HPWHs, HPWHs typically produce mechanical noise associated with the operation of the compressor and fan on the order of 45–60 decibels, which is commensurate with the noise made by a residential refrigerator.

To respond to the technical concerns utilities raised in response to the RFI, PNNL conducted research measuring the performance of a HPWH compared to an ERWH under normal and high hot water usage scenarios, as well as several types of DR services. Individual and population performance of water heaters were studied to evaluate technical feasibility and assess national economic and emissions-related impacts of utilizing HPWHs compared to ERWHs. To do this, the project was divided into three phases:

1. Laboratory evaluation—experimental testing of individual 80-gallon ERWHs and HPWHs used to demonstrate technical feasibility of large-tank HPWHs compared to ERWHs in delivering both existing (i.e., peak load reduction) and future (i.e., short-term and very short-term) DR services in terms of:
    - Impacts on equipment life, consumer service, efficiency, and energy consumption
    - Availability (percentage of time a water heater is able to respond during a DR event)
2. Population modeling—extrapolates individual ERWH and HPWH behavior to a diverse population of water heaters
3. National Impacts Analysis modeling—estimates financial value, to both the consumer and the power grid, of using HPWHs compared to ERWHs in existing DR programs, including the value of avoided emissions associated with any reduction in energy use observed from the HPWHs.

The first two phases help with evaluating technical feasibility and addressing some of the concerns from utilities, which is the focus of this report. The third phase helps to understand the impacts of using HPWHs in DR programs on emissions and economics. A description of phase 3 can be found in the companion report (Cooke et al. 2014).

2.0 Laboratory Evaluation

Providing peak load reduction DR service is most commonly practiced today in existing DR programs. Future DR programs are expected to provide short-term (i.e., ramping) and very short-term (i.e., regulation, spinning reserves) responses to enable large-scale renewable integration. The goal of the experiments is to evaluate how well an 80-gallon class[1] HPWH can perform the services for existing and future DR programs compared to an 80-gallon class ERWH. In particular, the availability and impacts on customer service, energy consumption, and equipment life cycles were assessed.

Each experiment included side-by-side testing of an 80-gallon class ERWH and HPWH, with the same scheduled draw pattern and water temperature set point, over a 7-day period. The scheduled draw pattern was varied daily to represent and capture the impacts of draw pattern on water heater performance. The experimental phase explored four DR scenarios:

1. Baseline: representing normal behavior of water heaters without any scheduled DR events.
2. Type 1 DR: Peak load reduction—representing existing DR program practices where 6-hour load reduction events are scheduled at 1:00 pm on each day of the 7-day experiment.
3. Type 2 DR: Short-term DR—demonstrates performance of water heaters participating in future DR programs requiring responses on an hourly timeframe. The 1-hour recurring load reduction events were scheduled every 5 hours over the course of the week-long test.
4. Type 3 DR: Very-short term DR—demonstrates performance of water heaters participating in future DR programs requiring responses for periods of seconds to minutes. In this scenario load increase and decrease events were scheduled based on typical area control error (ACE) regulation signal.

Section 2.1 explains the experimental approach in terms of selection of the equipment, installation, selection of experimental parameters (e.g., hot water draw profiles, set points, flow rates, etc.), protocols to implement DR scenarios considered, the monitoring approach and control approach. Section 2.2 highlights key performance results from the experiments.

2.1 Experimental Approach

The two large-tank water heaters selected were installed in a high-bay laboratory space as shown in Figure 2.1. The monitoring and control equipment was rack-mounted surrounding the two water heaters. Although the water heaters were installed in a conditioned laboratory space, all experiments were conducted with uncontrolled ambient temperature, relative humidity, and incoming water temperature. Ambient conditions have been observed to be relatively constant in high-bay laboratories such as that being used for this experiment. It should be mentioned that these variables were monitored and were found to be identical for the HPWH and ERWH cases that were being compared.

[1] The rated storage tank capacity of the ERWH was chosen to be within a 5-gallon tolerance of the HPWH so that the performance of the water heaters selected for the experiments are comparable.

Figure 2.1. Two Water Heaters Installed in PNNL Test Facility Shown with Monitoring and Control Equipment.

Subsequent subsections describe the experimental approach in further details. Section 2.1.1 discusses the selection and installation of specific water heaters used for experiments. Sections 2.1.2–2.1.3 explain how important experimental parameters were chosen, such as water heater setpoints, water flow rates, and water draw profiles. More detail on the specific protocols and implementation for each of the experimental scenario is given in Section 2.1.4. The monitoring approach and control approach used during testing of water heaters are explained in Sections 2.1.5 and 2.1.6.

2.1.1 Equipment Selection and Installation

The HPWH selected for the test was the 80-gallon A.O. Smith Voltex® Hybrid Electric HPWH, model# PHPT-80, illustrated in Figure 2.2. This is the most common large-tank (>55 gallon) HPWH available for residential applications. The ERWH water chosen for comparison is the 85-gallon Rheem Marathon ERWH, model# MR85245, illustrated in Figure 2.3. This water heater is the most commonly referenced in the comments submitted by utilities describing their current programs in response to the RFI and NOPR for large-tank residential electric storage water heaters (Docket No. EERE-2012-BT-STD-0022) and is in the 80-gallon class of water heaters. Therefore, it was determined that the 85-gallon Marathon would provide the most suitable "baseline" against which the HPWH performance could be compared, as this is the unit that is typically being installed by utilities today for ETS programs.

The equipment performance characteristics for each water heater are summarized in Table 2.1 according to manufacturer specifications.

Figure 2.2. Heat Pump Water Heater

Figure 2.3. Electric Resistance Water Heater

Table 2.1. Equipment Performance Characteristics

	Units	ERWH	HPWH
Make		Rheem Marathon	A.O Smith Voltex
Model		MR85245 B	PHPT-80 102
Serial #		0413 W 40607	1334J006704
Tank Volume	gal	85	80
Energy Factor	EF	0.92	2.33
First Hour Rating	gal	91	84
Upper Element Rating	kW	4.5	4.5
Lower Element Rating	kW	4.5	2.0
Compressor Rating	kW	N/A	0.7

The installation of the water heaters and primary sensors were plumbed in accordance with ASHRAE Standard 118.2 -2006, "Method of Testing for Rating Residential Water Heaters" (ASHRAE 2006). The test lab was provided with a single potable-water supply line (cold water). A tee connection was installed to split the water line to provide parallel make-up water lines to the HPWH and ERWH. Figure 2.4 illustrates the basic plumbing installation for the ERWH, with cold-water make-up and hot-water discharge connections on the top of the storage tank. Figure 2.5 illustrates the basic plumbing installation for the HPWH with the cold-water make-up connection on the side, near the bottom of the tank and the hot-water discharge connection located on the side near the top of the storage tank. The hot-water discharge lines were routed to a nearby open drain line.

As part of the equipment installation and set-up, balancing valves were installed on the hot water discharge lines as flow regulators, illustrated in Figure 2.4 and Figure 2.5. With both water heaters in continuous flow, the balancing valves were manually set so that the flow rate through each water heater was as close to being equal as possible. One of the data acquisition systems (discussed in more detail in Section 2.1.6.1) was set up to act as a master controller for the hot water draw profiles. When the schedule called for simulated hot water demand, a single relay activated both motorized control valves installed on the hot water discharge lines. Thus, both water heaters operated simultaneously on the same hot water draw schedules throughout the week-long experiments.

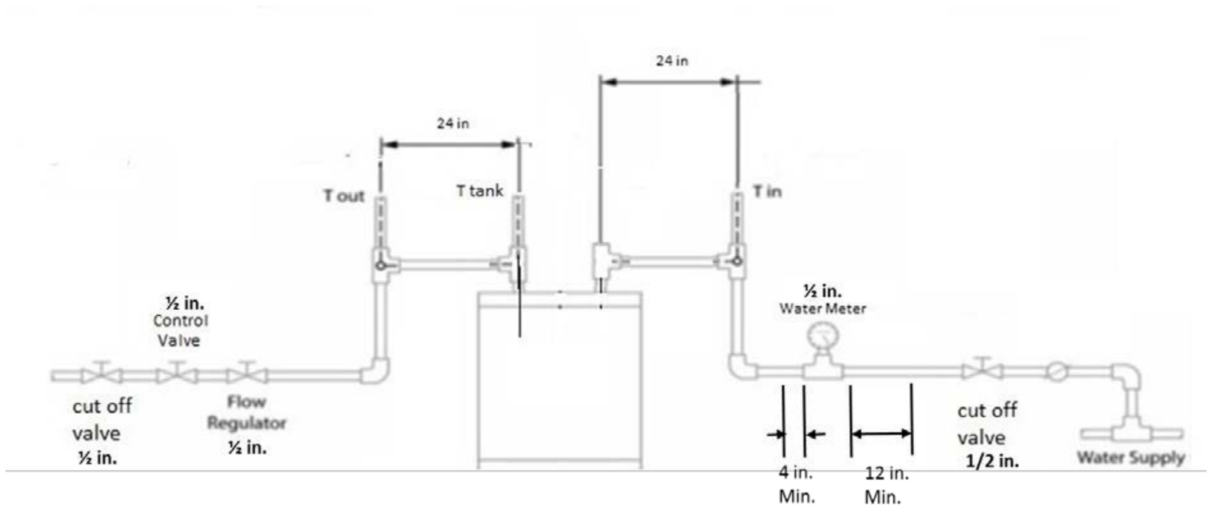


Figure 2.4. Plumbing Schematic for the ERWH

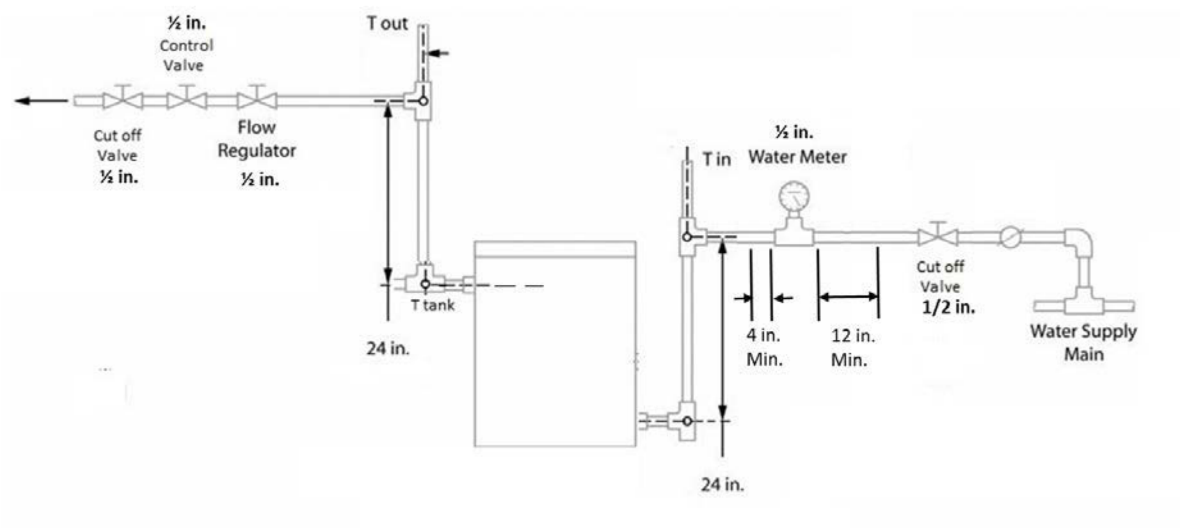


Figure 2.5. Plumbing Schematic for the HPWH

2.1.1.1 Power Supply

The laboratory facility was equipped with three-phase, four-wire, 120/208-volt power. Because the water heaters are designed to be operated with split-phase 120/240-volt power, Square D model 750SV46F (0.75-kVA) boost transformers were installed on each of the two circuits used to power the water heaters. Each water heater was fed from a separate two-phase 30-amp breaker located inside a 225-amp electrical panel. A local fused cut-off switch was provided to allow the system to be safely isolated. The boost transformer was installed to raise the delivered voltage differential across the two lines to a nominal 240-volt.

2.1.2 Selection of Water Heater Set points and Flow Rates

A set point of 125 °F was selected because it is a typical set point for water heaters based on a meta-analysis Lawrence Berkley National Laboratory (LBNL) recently performed of field hot water use data in residential homes (Lutz et al. 2012). The report concluded that, based on the available field data, 122.7 °F was the average tank temperature and the majority of draws were between approximately 1 and 1.5 gallons per minute (gpm) and between 1 and 4 minutes in length (Lutz et al. 2012). Therefore, all flows for this experiment are simulated using an average 1.66–1.67 gpm flow rate. As part of the equipment installation and set-up, the balancing valves were manually set so that the flow rate through each water heater was as close to being equal as possible.

2.1.3 Hot Water Draw Profiles

The LBNL report (Lutz et al. 2012) also defined high, medium, and low daily water volumes of 44.22, 66.48, and 86.37 gal/day, respectively. The maximum flow rate reported in the LBNL meta-analysis was 163.8 gal/day. The seven experimental draw profiles were selected to represent medium to high usage, as efficiency is dependent on draw volume, as well as the rate or frequency of draws.

To select a hot water draw profile for experiments, PNNL researched other draw profiles implemented by previous research, available standards, and data on typical field usage. Seven draw profiles were selected based on the Building America House Simulation Protocols (med, high, and extreme draw volumes), previous Bonneville Power Administration (BPA) funded research (alternative draw profiles), and Canadian Standards Association (CSA) standard profiles (medium and high draw volumes. A comparison of all hourly draw volumes is shown in Figure 2.6. The individual 24-hour draw profiles selected were each used for one day of the week. Table 2.2 lists the total hot water use per draw profile.

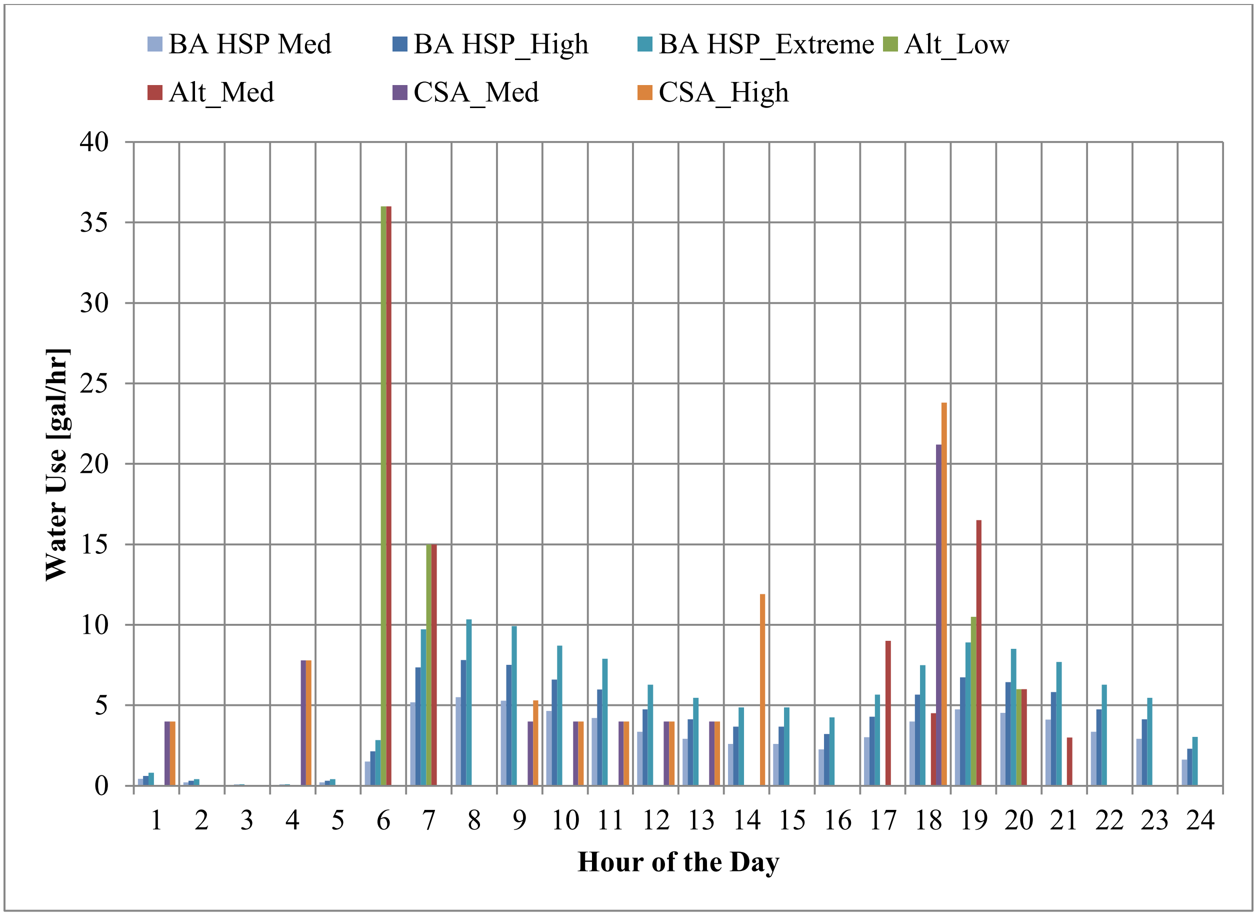


Figure 2.6. Comparison of the Seven Hot Water Draw Profiles

Table 2.2. Total Hot Water Use per Draw Profile

Profile	Daily Hot Water Use *[gal/day]*
BA HSP Med	69
BA HSP High	98
BA HSP Extreme	130
Alt Low	68
Alt Medium	81
CSA Med	53
CSA High	69

2.1.3.1 Building America (BA) House Simulation Protocol (HSP) Profiles

PNNL selected three of the draw profiles based on the 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 fraction of total daily load), as shown in Table 2.3, below (Hendron and Engebrecht, 2010).

Table 2.3. Domestic Hot Water Heater Daily Use

End Use	End-Use Water Temperature	Water Usage
Clothes washer	Water heater set point	Calculated using MEF* in Table 36
Common laundry	Water heater set point	Calculated using MEF in Table 36
Dishwasher	Water heater set point	Calculated using EF in Table 35
Shower	110°F	$14.0 + 4.67 \times N_{br}$ gal/day
Bath	110°F	$3.5 + 1.17 \times N_{br}$ gal/day
Sinks	110°F	$12.5 + 4.16 \times N_{br}$ gal/day
Office/public sink	110°F	$0.028 \times N_{units}$ gal/day

PNNL determined the hot only portion of the 110 °F water draws based on an energy balance, to define to daily flow volume of hot water only.

The Building America House Simulation Protocol profile is an "aggregated population" average in that it has rounded usage typical of a population of homes, with draws occurring every hour for a specific duration. The three draw profiles selected have the same shape, but vary based on the daily draw volume from medium (representative of a 2-bedroom, 1-bathroom home) to extreme (representative of a home with 8 occupants). These align with the “medium,” “high,” and near-maximum use cases identified in a recent meta-analysis of available field data, performed by LBNL (Lutz et al. 2012).

2.1.3.2 Alternative Profiles

PNNL also employed a hot water draw profile, which was implemented in BPA’s evaluation of HPWHs (Larson et al. 2011). The BPA evaluation exercised two draw profiles, one that was similar to the Building America House Simulation Protocol, as discussed in Section 2.1.3.1 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 targets 90 gal/day for four persons while the second profile targets 80 gal/day. Both profiles are similar, exhibiting increased water use in the morning and evening, but the “representative” profile contains more variations, with dramatic increases and decreases in water throughout the day. The 80 gal/day profile may be more representative of a single home or occupant, but is not necessarily better for understanding a “typical” home from a utility perspective.

For this experiment, PNNL chose to simulate the 80 gal/day representative profile for the medium daily water volume case, and scaled to a lower total daily gallon draw of 67.5 gal to be representative of a “low”case.

The flow rates and duration of draws required to simulate such a variable profile are quite large, from 0.5 to 3 gpm and 1 to 9 minutes. This is extremely difficult to simulate reliably and, as such, where flow rates are in excess of the selected 1.67 gpm they have been adjusted by approximating the volume with a longer draw.

2.1.3.3 Canadian Standard Association (CSA) Profiles

The draft CSA Standard C191[1] for domestic hot water heaters, “Performance of electric storage tank water heaters for domestic hot water service” (draft CSA Standard C191), which was recently revised to be more representative of typical use cases, recommends a draw profile for the “medium usage” case resulting in 67.2 gal/day. The draft CSA Standard C191 profile is similar to the DOE Energy Factor test procedure in that it requires a 77 °F temperature differential between inlet and outlet water and a 135 °F tank temperature. However, the draft CSA Standard C191 profile involves more variable draw volumes and flow rates, so 20 unique water draw events are specified throughout the 24-hour period. Similar to the BPA profile discussed in Section 2.1.3.2, the CSA profile also exhibits increased water use in the morning and evenings and a similar total volume, but larger evening draws than the other profiles. A list of the draft CSA Standard C191 draws is given in Table 2.4.

[1] Note, a final amended CSA Standard for domestic water heaters was published in March 2013 and includes a slightly different draw profile than that referenced here.

Table 2.4. Draft CSA Standard C191 Hot Water Draw Profile

		WATER HEATER CLASSIFICATION					
		LOW USAGE		MEDIUM USAGE		HIGH USAGE	
Draw No.	TIME OF DAY (HH:MM:SS)	VOLUME DRAWN (gal)	FLOWRATE (gal / Min)	VOLUME DRAWN (gal)	FLOWRATE (gal / Min)	VOLUME DRAWN (gal)	FLOWRATE (gal / Min)
1	00:00:00	2.6	1.0	4	1.0	4.0	1.0
2	3:00:00	2.6	1.0	2.6	1.0	2.6	1.0
3	3:07:38	2.6	1.0	2.6	1.0	2.6	1.0
4	3:13:17	2.6	1.0	2.6	1.0	2.6	1.0
5	8:00:00	--	--	4	1.0	5.3	1.0
6	9:00:00	1.3	1.0	4	1.0	4.0	1.0
7	10:00:00	1.3	1.0	2.6	1.0	4.0	1.0
8	11:00:00	1.3	1.0	2.6	1.0	4.0	1.0
9	12:00:00	--	--	2.6	1.0	4.0	1.0
10	13:00:00	--	--	--	--	11.9	3.0
11	17:00:00	4.0	3.0	9.2	3	9.2	1.0
12	17:06:19		1.0	--	--	--	--
13	17:08:05	--	--	4.0	1.0	--	--
14	17:13:16	4.0	1.0	--	--	--	--
15	17:14:14	--	--	--	--	5.3	1.0
16	17:15:02	--	--	4.0	1.0	--	--
17	17:21:13	4.0	1.0	--	--	--	--
18	17:21:59	--	--	4.0	1.0	--	--
19	17:22:41	--	--	--	--	5.3	1.0
20	17:30:58	--	--	--	--	4.0	1.0
*	18:15:00	End Test					

2.1.4 Demand Response Scenarios

The DR scenarios are described in the subsequent sections. Each scenario uses the same water draw schedule; however, the DR event schedule varies depending on the type of service and the time scale of response expected by the existing (e.g., peak load reduction) and future (e.g., short-term and very short-term) DR programs assumed. For these experiments, the HPWH is operated in efficiency mode.

2.1.4.1 Baseline

Prior to implementing any FR control, the performance of the HPWH and ERWH is characterized as a baseline for comparison to the performance of each water heater under the various DR modes. Therefore, no DR events were scheduled for the baseline, and the water heaters were examined under normal water usage patterns according to water draw schedules selected. In addition, the data collected were helpful in determining heat loss of the tank (UA) and other performance parameters necessary for calibrating ERWH and HPWH models, which will be used in population studies.

2.1.4.2 Type 1 DR: Peak Load Reduction

In the peak load reduction scenario (also referred to as Type 1 DR in this document), the HPWH and ERWH are sent conserve signals to “coast” for a period of 6 hours, from 1–7 pm in the afternoon each day of the 7-day test period. This DR scenario enables evaluation of the ability of each water heater to provide peak load reductions. The time period for the peak load reduction event was selected to be representative of those currently implemented in existing ETS program. The time period for the peak load reduction event was selected based on comments submitted by utilities to the large-tank residential electric water heater RFI and NOPR (Docket No. EERE-2012-BT-STD-0022), describing the characteristics of their existing programs.

2.1.4.3 Type 2 DR: Short-term Response

Future DR programs are expected to provide short-term response (e.g., ramping and spinning reserves), which is useful for large-scale integration of renewable energy resources and for maintaining generation/load balance due to contingencies in the power grid. This type of demand response is not typically implemented by utility programs at a large scale. The short-term response (also referred to as Type 2 DR in this document) scenario was designed for evaluation of the load reduction performance of HPWHs compared to ERWHs with sub-hourly to hourly decreases in generation capacity, given the normal water usage patterns. This type of demand response is not typically implemented by utility programs at a large scale. However, the scenario was simulated in the experiments by establishing a schedule of a 1-hour DR event followed by 4 hours of normal operation to cycle over the week-long testing period. This causes the DR event to occur at least once at each hour of the day and in a variety of draw conditions throughout the 7-day experimental period.

2.1.4.4 Type 3 DR: Very Short-term Response

In addition to being able to provide short-term response, future DR programs are also expected to deliver services, such as frequency and voltage regulation, on a very short-term timescale. The Type 3 DR, very short-term response scenario, was intended to evaluate the ability of the HPWH and ERWH to provide load increases and reductions for DR programs providing ancillary services in a 4-second to 1–2 minute timeframe. To demonstrate Type 3 DR performance, a 24-hour schedule was generated, based on a “typical” ACE signal normally used for frequency regulation. ACE thresholds were chosen to signal times and durations of desired load increase and reduction events. This typical or representative ACE schedule was repeated daily for this very short-term DR scenario. ACE signals are typically sent on a 2- to 4-second basis, so a 4-second signal was used in this scenario.

The “typical” ACE signal was constructed using historic regulation data from PJM. In particular, the regulation signal sent to the MidAtlantic Control Zone for 84 days of 2009 (first week of each month of the year) (PJM 2013). The PJM data consisted of 2-second samples of the normalized ACE based on a traditional regulation signal which is composed of both frequency bias and interchange bias. The data were first gathered and converted into one continuous 4-second signal, and generic characteristics regarding the nature of the ACE signal were discerned. A histogram of the signal amplitude (Figure 2.7), normalized by the total number of observation points, was then used to determine the distribution of amplitudes.

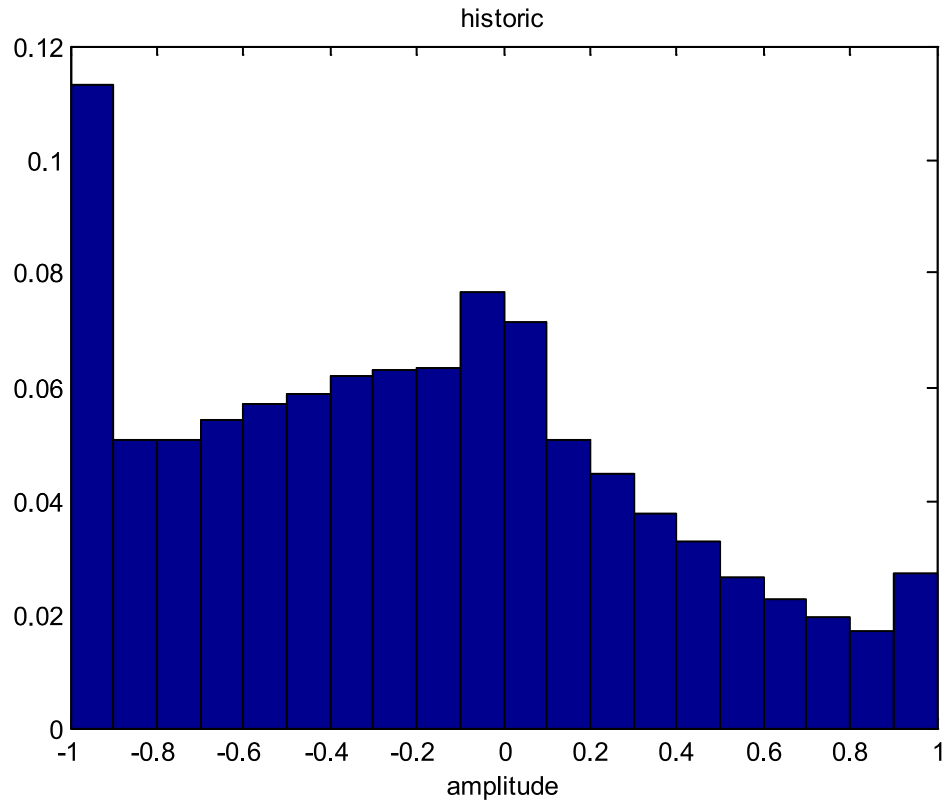


Figure 2.7. Histogram of Amplitude of PJM Regulation Signal Sent to the MidAtlantic Control Zone in 2009 (84 days)

Next, a day with a similar looking distribution of amplitudes was selected from the 84-day ACE signal, which is shown in Figure 2.8. To classify the 24-hour ACE signal as a representative signal, the 24-hour signal should exhibit a similar distribution of amplitudes as the 84-day signal. By comparing Figure 2.9, showing the histogram for amplitudes for the 24-hour ACE signal, to Figure 2.7, it was decided that the ACE signal for the similar looking day selected should be modified to better match the 84-day signal.

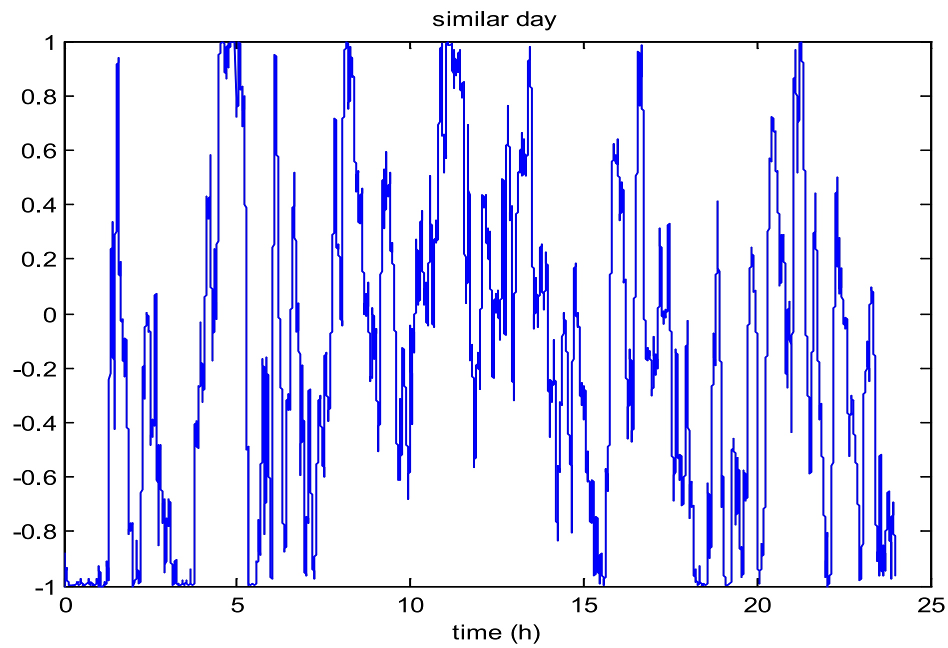


Figure 2.8. Regulation Signal for Similar Day Chosen from the 84-Day PJM Regulation Signal sent to the MidAtlantic Control Zone in 2009

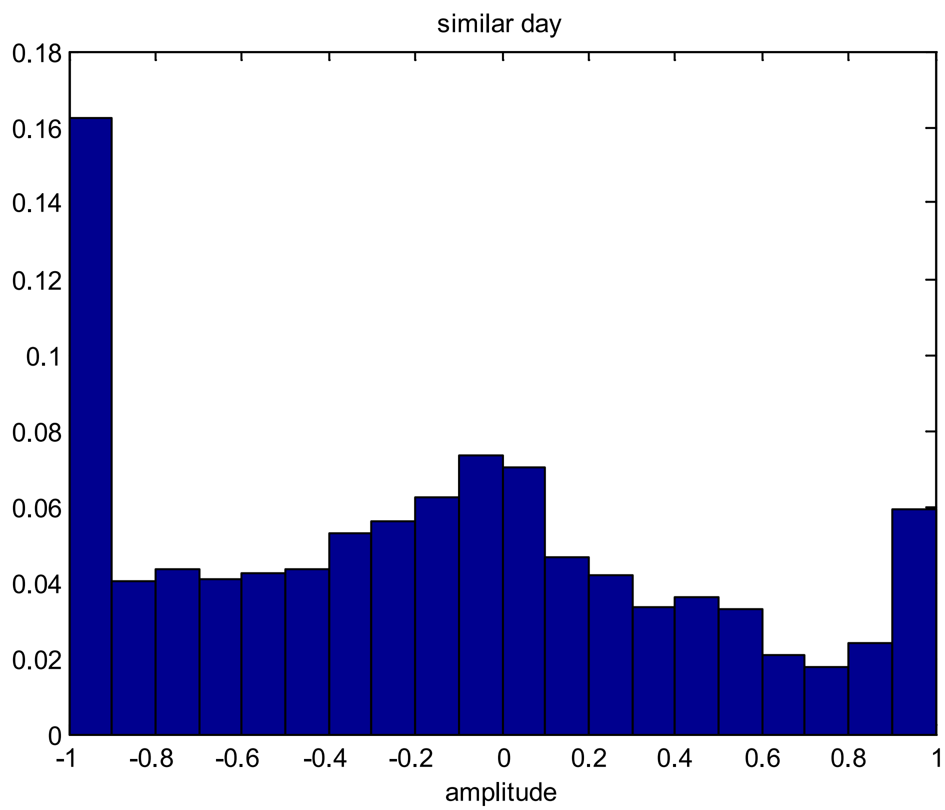


Figure 2.9. Histogram of Regulation Signal Amplitudes for the Similar Day Chosen

Therefore, data for the similar day selected were modified by hand to match the distribution of amplitudes for the 84-day PJM regulation signal considered shown in Figure 2.7. This was done by finding how many data points needed to be in each bin to match the distribution of the 84-day signal. Points were then added or removed to match the distributions. A new histogram of the 24-hour ACE signal amplitudes after modifications is shown in Figure 2.10.

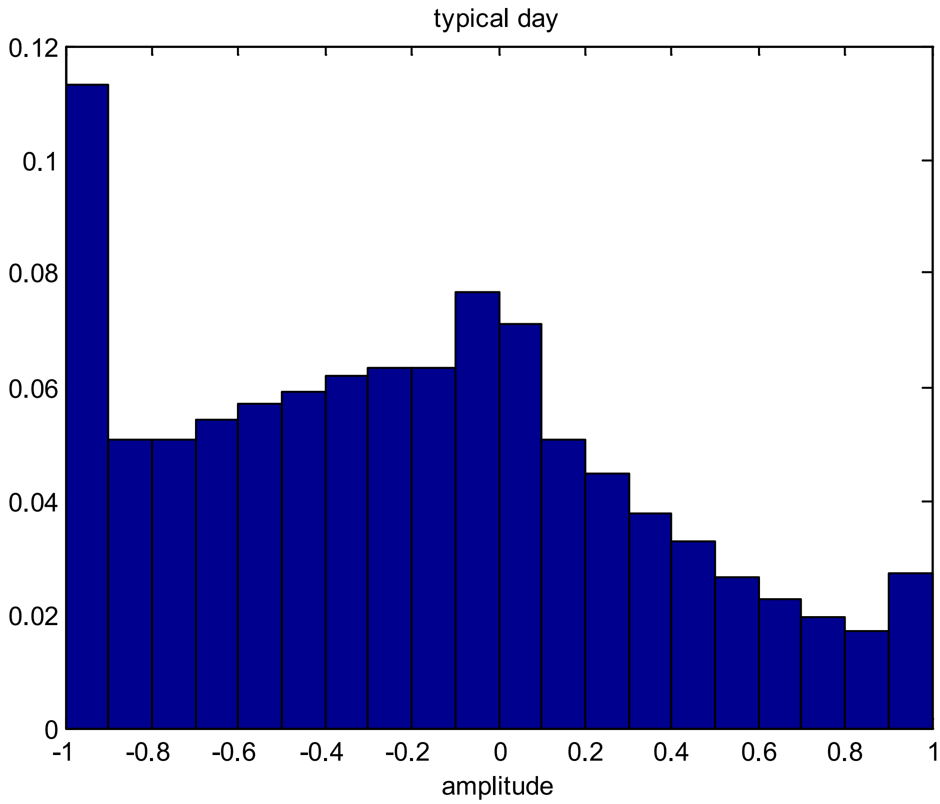


Figure 2.10. Histogram of Regulation Signal Amplitudes Representative of a "Typical" Day

A plot of the "typical" regulation signal is shown in Figure 2.11. This representative signal allows for scheduling a wide-range of very short-term continuous DR events that are somewhat comprehensive and realistic. The values are normalized between -1 and 1. Positive values correspond to over-generation, which means that load should be increased to balance generation and load. Negatives values correspond to under-generation, so load should be decreased to balance generation and load. Since Type 3 DR is not typically implemented in existing ETS programs, upper/lower ACE thresholds of 0.2/–0.15 were arbitrarily selected to signal load increase and reduction DR events, respectively. This means that if the normalized regulation signal is above 0.2, an increase in load is called for. If the regulation signal is below -0.15, a load reduction event is scheduled. Different thresholds will impact the sensitivity of the water heaters to respond. Higher positive and negative thresholds will lead to the water heaters being less responsive. Lower thresholds will cause more frequent cycling of the water heaters. The approach used to control the water heaters according to the DR event schedules is discussed in the Section 2.1.5.

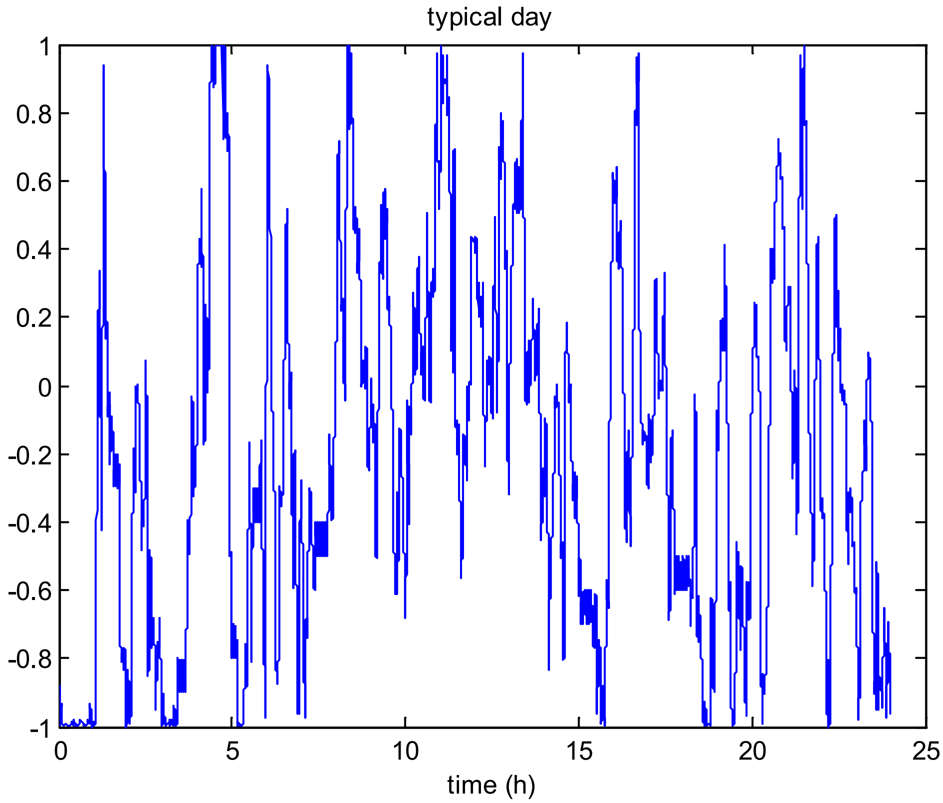


Figure 2.11. Regulation Signal for "Typical" Day Based on 84-day PJM Regulation Signal Sent to the MidAtlantic Control Zone in 2009

2.1.5 Control Approach for Water Heater Demand Response

Since the Type 1 and 2 DR only consider load reduction events, the same control approach was used for both scenarios to enable DR events/control during the testing period according to the established schedule.[1] The control strategy for peak load reduction and short-term demand response includes the following logic:

- Open relay switch to TURN OFF WH at initial time of event.
- Close relay switch to allow power to WH at the end of event. Note that the control strategy implemented does not force water heaters ON or elevate water temperatures beyond the desired set point. It simply allows power to be supplied to the water heaters so that they can operate normally.

Type 3 DR involves both load increase and decrease event schedules, or 0.2/–0.15, therefore, a slightly different control strategy was used for the threshold-based control for very short-term demand

[1] It is well known that water heaters can be forced ON to elevate tank temperatures to avoid unacceptably low water delivery temperatures (Widder et al. 2013). However, elevated temperatures can be unsafe for consumers, so are not considered in this work.

response. As stated previously, the upper and lower ACE thresholds are used to indicate when load increase and reduction events are called for, respectively. The WH will operate normally unless the ACE signal at a given time is less or greater than the specified lower or upper threshold, respectively. If the ACE signal, at a particular time, is lower than the specified lower threshold, the relay switch is opened to TURN OFF WH. If the ACE signal is greater than the specified upper threshold, the relay switch is closed to allow power to WH. Note that the control strategies implemented do not force water heaters ON and enable elevated water temperatures beyond the desired set point. The strategies simply allow power to be supplied to the water heaters so that they can operate normally. The following subsections explain normal operation of the selected ERWH and HPWH.

2.1.5.1 Normal Operation of ERWH

In an ERWH, hot water is typically drawn from the top of the tank to service the home's water loads, with cold make-up water injected near the bottom of the tank. Water is typically heated by one of two elements in an ERWH, one located near the bottom of the tank and one located higher in the tank, usually halfway to two-thirds of the way to the top as shown in Figure 2.12. The lower element provides most of the heating load, with the upper element engaging only when the cold water layer has moved up the tank near or above the upper electric resistance element. The two elements are controlled by independent thermostats located near each element. However, only one element is permitted to be ON at a time, with the upper element having priority. The design is intended to allow rapid (re)heating of the smaller volume of water above the top element so that water at the desired temperature is available as soon as possible after depletion of the stored hot water in the tank.

In addition, thermostatic controls have a "dead band" associated with the setpoint, which prevents rapid cycling of power to the elements which would occur if the turn ON temperature equaled the turn OFF temperature. The dead band is typically a few degrees Fahrenheit above and below the nominal setpoint. If the water heater is ON and the temperature increases to the upper threshold of the dead band, the water heater turns off. The temperature then begins to drop due to standby losses. Once the lower threshold of the dead band is reached, the water heater will turn ON.

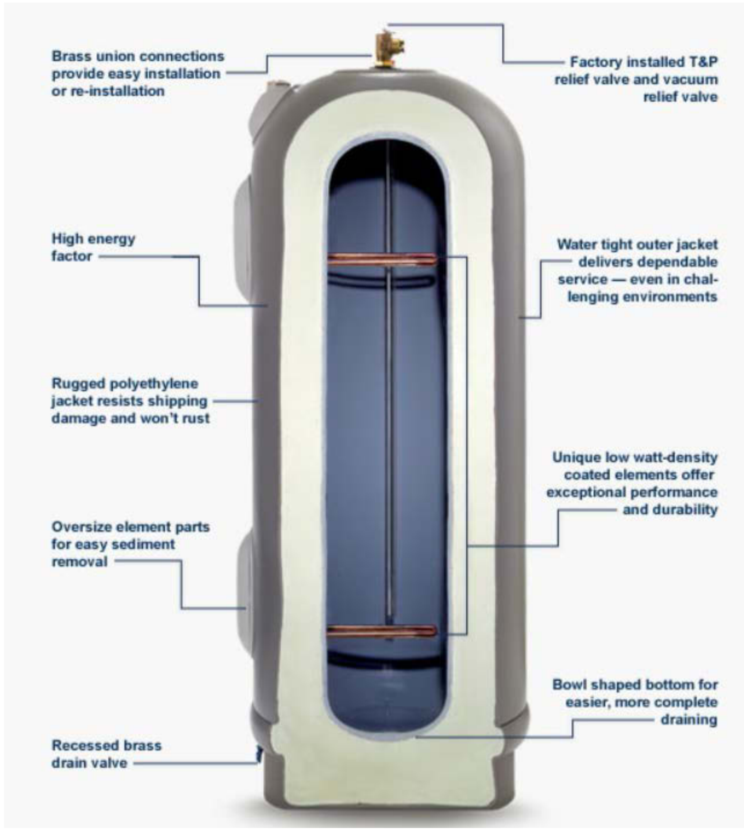


Figure 2.12. Cut-away Illustration of the 85-gallon Rheem Marathon ERWH

2.1.5.2 Normal Operation of HPWH

HPWHs typically have two heating mechanisms, a resistance element and a heat pump. The HPWH evaluated in these experiments has three modes of operation: efficiency, hybrid, and electric resistance mode. Such an operating scheme is typical of other commercially available HPWHs (Larson et al. 2011). Only efficiency and hybrid mode will be discussed here, since electric mode operation was not used during experiments or for analysis purposes. By using only the heat pump to heat the water, efficiency mode provides the highest level of efficiency and the lowest cost of operation. The recovery time and efficiency vary as a function of ambient temperature and relative humidity. In contrast to the ERWH, the HPWH uses a digital thermostat to control the tank temperature. In efficiency mode, the pump will be activated whenever T_{tank}, the weighted average of the upper and lower temperature sensor readings located near the upper and lower elements (see Figure 2.13), falls 9 °F below the temperature setpoint (Larson et al. 2011).

$$T_{tank} = (3 \cdot T_{upper} + T_{lower})/4$$

The operation of the heat pump is not allowed if the tank water temperature drops below 59 °F or if ambient temperature is less than 45 °F or greater than 109 °F. The unit would operate in electric resistance mode until the ambient and water temperatures return to a safe operating range for the heat pump.

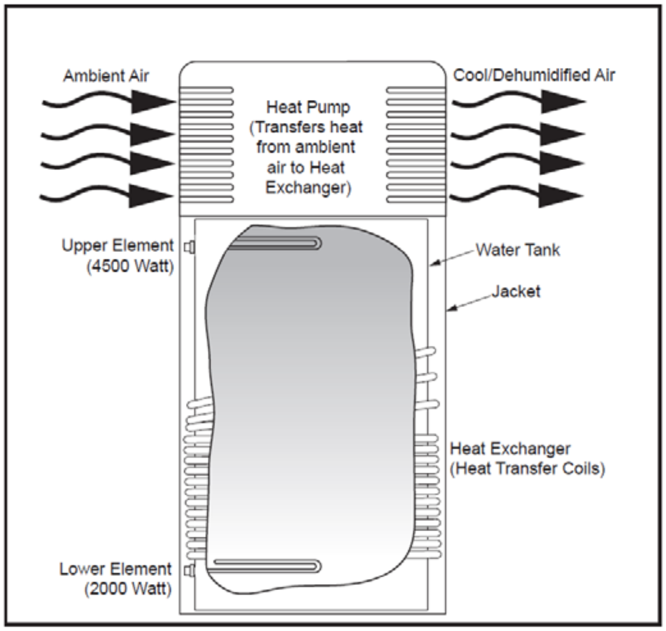


Figure 2.13. Schematic of 80-gallon A.O. Smith Voltex® Hybrid Electric HPWH

2.1.6 Monitoring Approach

Table 2.5 shows the data and recording frequency employed during each experiment scenario. All temperature data were collected in °C and later converted to °F for analysis. As noted earlier, the experiment assessed four operating scenarios. "All scenarios" refer to the baseline, peak-load reduction, short-term DR, and very-short term DR scenarios described in Section 2.1.4, respectively.

Table 2.5. Monitored Parameters and Data Recording Frequency

Monitored Parameter	ERWH	HPWH	Units	All Scenarios	Type 4 DR Scenario only	Table Data Recorded
- Sub-parameter				**1-min interval**	**4-sec interval**	
Water flow rate	X	X	gpm	X		Average
Power total	X	X	Watts	X	X	Average
Power resistance element 1	X	X	Watts	X	X	Average
Power resistance element 2	X	X	Watts	X	X	Average
Power compressor HPWH		X	Watts	X	X	Average
Power fan HPWH		X	Watts	X	X	Average
Water heater total system						
- Real power	X	X	Watts	X	X	Average
- Frequency	X	X	Hz	X	X	Average
- Voltage	X	X	volts	X	X	Average
- Current	X	X	amps	X	X	Average
- Phase angle	X	X	radians	X	X	Average
Heat pump water heater compressor						
- Real power		X	Watts	X	X	Average

Monitored Parameter	ERWH	HPWH	Units	All Scenarios	Type 4 DR Scenario only	Table Data Recorded
- Sub-parameter				1-min interval	4-sec interval	
- Current		X	amps	X	X	Average
- Phase angle		X	radians	X	X	Average
Water heater resistance element 1						
- Real power	X	X	Watts	X	X	Average
- Current	X	X	amps	X	X	Average
- Phase angle	X	X	radians	X	X	Average
Water heater resistance element 2						
- Real power	X	X	Watts	X	X	Average
- Current	X	X	amps	X	X	Average
- Phase angle	X	X	radians	X	X	Average
Temperatures (average over interval)						
- Inlet water	X	X	°C	X		Average
- Outlet water	X	X	°C	X		Average
- Ambient air	X	X	°C	X	X	Average
- Inlet air temperature (HPWH)		X	°C	X	X	Average
Temperatures (sample at end of interval)						
- Tank stratification level 1	X	X	°C	X	X	Sample
- Tank stratification level 2	X	X	°C	X	X	Sample
- Tank stratification level 3	X	X	°C	X	X	Sample
- Tank stratification level 4	X	X	°C	X	X	Sample
- Tank stratification level 5	X	X	°C	X	X	Sample
- Tank stratification level 6	X	X	°C	X	X	Sample
- Ambient air	X	X	°C	X	X	Sample
- Relative Humidity	X	X	%	X	X	Sample

2.1.6.1 Data Acquisition System

The monitoring system included three Campbell Scientific, model CR1000, data acquisition systems (DASs). Each water heater was monitored by its own DAS. In addition, a third DAS was used to control the hot water demand profiles, as well as record the ambient air temperature and relative humidity in the laboratory. The DASs serving the water heaters were each equipped with Campbell Scientific, model AM25T, 25-channel solid-state multiplexers for recording the thermocouple temperature sensors.

The three DASs were synchronized to a personal computer acting as the central data-polling computer. Each DAS was equipped with a Campbell Scientific, model NL-201, network link interface. A common network hub linked all three DASs to a single Cisco 802.11-n network router, which allowed the three DASs to communicate through the internal PNNL equipment network. The central polling computer equipped with Campbell Scientific LoggerNet™ version 4.2 software automatically communicated over the PNNL internal network twice per day to download data from the three DASs.

Each DAS was programmed to scan each connected sensor once per second. Data storage tables were set up to record data according to the parameters identified in Table 2.5. For the 1-minute data tables, the average recorded values are the average of the 60 (1-second) scanned values read during the previous minute. The sample values are the measurements associated with the last (1-second) scanned value taken during the 1-minute interval. For the 4-second tables, associated with scenario 4, the average recorded values are the average of the 4 scanned values during the 4-second interval. The sample values are the measurements associated with the last (1-second) scanned value during the 4-second interval.

2.1.6.2 Electrical Measurements

Two types of power measurement devices were used for monitoring the electrical parameters identified in Table 2.5. Basic electric energy measurements were measured by pulse-type watt-hour transducers from Continental Control Systems model WNB-3D-240-P WattNode™ Pulse, Option 200-Hz. Each WattNode™ was equipped with revenue-grade current transformers (CTs) model Accu-CT™, ACT-075-xxx Option C0.6. With option C0.6, the Accu-CT™ is calibrated and verified to meet IEEE/ANSI C57.13-2008 class 0.6 accuracy and IEC 60044-1 class 0.5 S accuracy, and each CT is shipped with a certificate of calibration. The LoggerNet™ software was programmed to read the WattNode™ pulse frequency and calculate the average power (watts) resulting from the 1-second scan.

Additional electrical measurements were taken using the Campbell Scientific CR1000, with the LoggerNet™ ACPower() command, including real power (Watts), line frequency (Hz), current (amperes), voltage (volts), and phase angle—used to determine power factor. Supporting the ACPower() command, Accu-CTs were used to measure current, and voltage measurements were made using a Magnelab model SPT-0375-300 potential transformer.

2.1.6.3 Temperature and Environmental Sensors

Ambient air temperature and relative humidity for the laboratory space were measured using the Rotronic HygroClip2™ temperature and relative humidity probe (Campbell Scientific model HC2S3) connected directly to the DAS used to control the hot water draw profile schedules. A second Rotronic HygroClip2™ probe was used to measure the inlet air temperature to the HPWH evaporator coil, which was read and recorded by the DAS monitoring the HPWH.

Other temperature data were measured using Type T thermocouples connected to the Campbell Scientific AM25T multiplexers and recorded by the DAS for both the ERWH and HPWH. The configuration of thermocouples on the two water heaters was identical. Cold-water make-up and hot water discharge were measured using direct insertion thermocouples, as illustrated in Figure 2.4 for the ERWH and Figure 2.5 for the HPWH. As a backup measurement, surface mounted thermocouples were also installed on the cold-water make-up and hot water discharge lines. Insulation was added to the hot water discharge lines starting from the water heater and running to just past the location of the insertion and surface-mounted thermocouples. Insulation was also added to the make-up water pipe line in the area around the surface-mounted thermocouples. The insulation was added to reduce any potential impact on the insertion and surface-mounted temperature sensors from the cold air discharging from the HPWH evaporator fan or the ambient air conditions.

Storage tank interior temperature stratification was measured using custom-ordered temperature profile probes from Omega Engineering designed with six separate Type T temperature sensors. For the HPWH, a 6-foot probe was built with the first temperature sensor located on the tip and the remaining five temperature sensors installed every 11 inches along the probe. The profile probe was installed through a pipe tee connector installed on the top of the storage tank where the corrosion protection anode is installed. For the ERWH, a 6-foot 6-inch probe was built with the first temperature sensor located on the tip and the remaining five temperature sensors installed every 12 inches along the probe. The profile probe was installed through a pipe tee connector installed on the top of the storage tank where the hot water discharge connection is located. Each profile probe was installed such that the first thermocouple was located approximately 1-inch above the bottom of the storage tank. The equal spacing was specified such that the top temperature sensor would have been located just a few inches below the top of the storage tank.

2.2 Experimental Results

In the four sets of experiments run, the baseline scenario was used to understand normal behavioral characteristics of both water heater types in terms of ability to maintain outlet water temperature around set points, energy consumption, and cycling. The DR scenarios were compared to the baseline performance to understand how these normal behavioral characteristics are impacted by the DR events and to assess the availability of each water heater to provide the particular DR services.

2.2.1 Baseline

Figure 2.14 illustrates differences in normal behavior between the selected 85-gallon ERWH (top) and the 80-gallon HPWH (bottom). The blue and green lines represent the power consumption and water draw, respectively. The ERWH energy use is relatively more intermittent and consumes four times more power than the HPWH when ON. This is because a resistance element switches ON/OFF based on the temperature reading at the sensor located nearest to the element, but the compressor switches based on a weighted average of the upper and lower sensor readings located near the each of the resistance elements. In addition, heat input is distributed to the water by the compressor differently than the resistance elements. This can be shown in Figure 2.13, where the heat transfer coils of the compressor are in contact with the bottom half of the tank. The resistance elements in both water heaters, shown in Figure 2.12 and Figure 2.13, are similar. These elements are in contact with a very small portion of the water in the tank, so the heat input to the water by the resistance element is more concentrated near the temperature sensor, which contributes to the ERWH cycling more frequently than the HPWH.

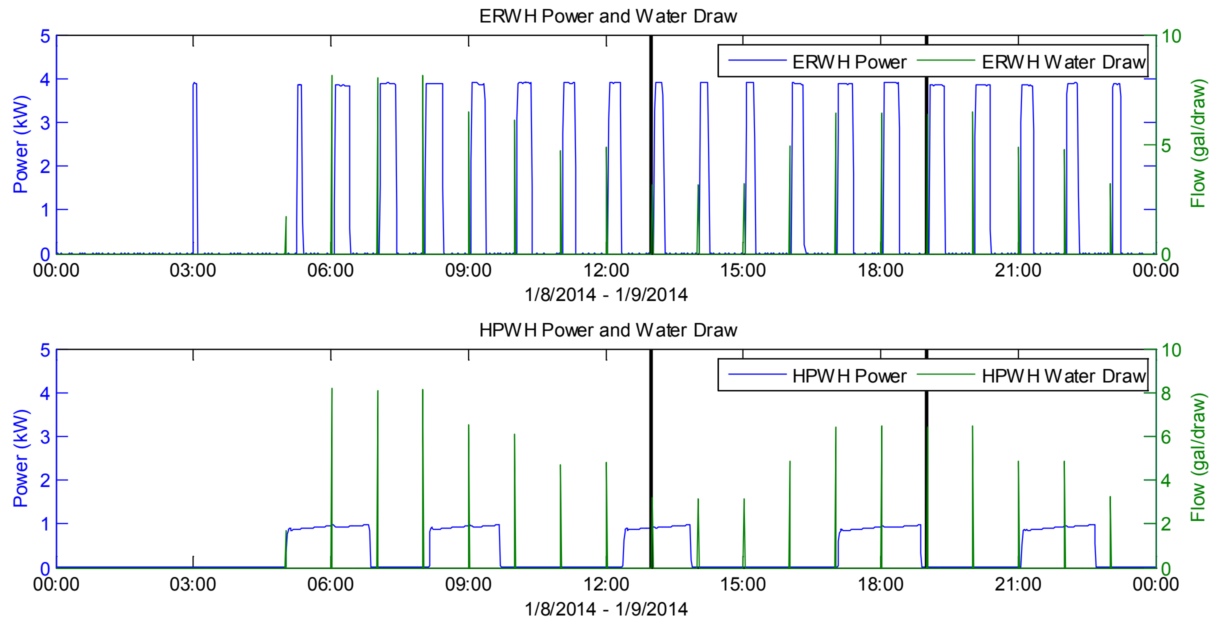


Figure 2.14. Power Consumption and Water Draw for Day 2 of Baseline - ERWH (top), HPWH (bottom)

2.2.2 Impact on Efficiency

HPWH use 60% less energy in all cases, regardless of the type of DR service being provided, as shown in Figure 2.15. This is due to the HPWH being more efficient than the ERWH, operating at an energy factor (EF) of ~2.33 compared to the ERWH, which has an EF of ~0.92.

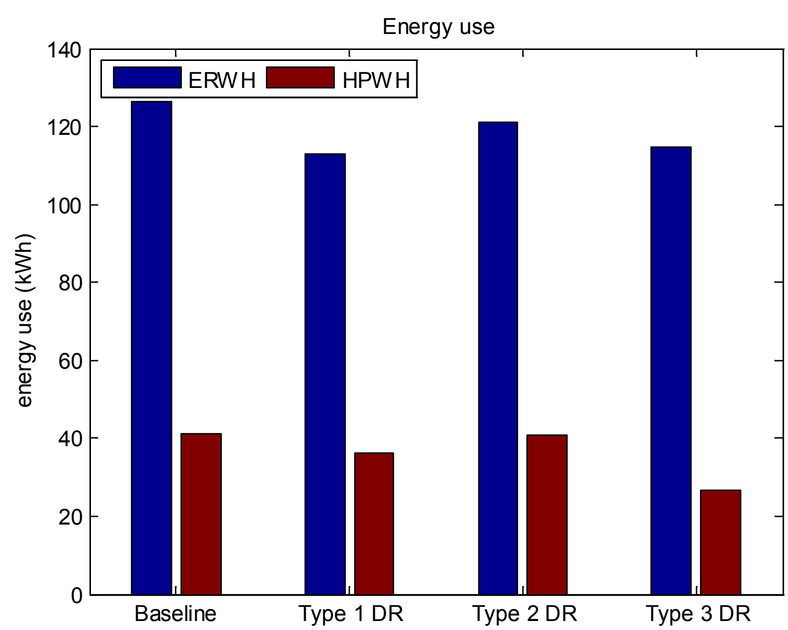


Figure 2.15. Total Energy Use of the ERWH and HPWH During Each Scenario Run

These energy savings are representative of savings from the HPWH, since the HPWH was operated in efficiency mode where only the more efficient heat pump is used to heat water. If the HPWH were to be operated in hybrid mode, either the heat pump or the upper electric resistance element can heat the water, depending on the water demand and tank temperature, which can affect the overall efficiency of the unit. The upper electric resistance element would only be triggered if the temperature at the upper sensor were to drop 18 °F below the temperature set point. Because activating the resistance element is undesirable since it is less efficient than the compressor element, the minimum temperature threshold can be used to assess the ability of the HPWH to deliver acceptable temperatures to consumers in the most efficient way. In these experiments, since the temperature set point was chosen to be 125 °F, thus the minimum acceptable outlet water temperature is 107 °F. This temperature limit was not violated by the ERWH during any of the testing scenarios.

Note that the minimum ERWH temperature measured during the 7-day experiments was higher in almost every case than the minimum temperature measured in the HPWH. This trend is observed due to the differing control strategies employed by the ERWH and HPWH, respectively. Because the ERWH has a two-sided dead band and the HPWH heater has a one-sided dead band, the allowed temperature range was different even though both water heaters had the same temperature setting. The theoretical temperature range was 121.5–129.5 °F and 116–125 °F for the ERWH and HPWH, respectively, based on a 125 °F temperature setting. However, the ERWH is controlled via a bimetallic thermostat, which has a relatively broad temperature control region at each electric resistance element. On the other hand, the HPWH is controlled via more accurate digital thermostats. Therefore, thermostat controls employed in the ERWH are much less accurate than the digital HPWH. In addition, the ERWH water heater, having separate thermostat set points at the upper and lower elements, initiates the lower element more aggressively than the HPWH, since the electric resistance element is energized to reheat water any time the lower thermostat observes temperatures below the ERWH temperature band. Based on the collected data, the thermostat in the ERWH in this experiment appeared to initiate at approximately 130 °F and turn OFF at 135 °F. Also, the ERWH will have much quicker recovery than the HPWH and, thus, the observed minimum delivered hot water temperature for the ERWH was higher than that observed for the HPWH. Finally, the ERWH primarily heats using the lower element, which heats water to the desired thermostat temperature but, due to stratification in the tank and the fact that both the upper and lower thermostat were set at the same temperature, appears to result in overheating the water such that average tank temperature is significantly above the desired 125 °F set point. This is most significantly observed on day 2 of the baseline and Type 2 DR experiments.

In the Type 1 DR scenario, the outlet temperature of the HPWH dropped below 107 °F once over the 7-day test during a water draw, as shown in Figure 2.16. However, the temperature only fell below this minimum threshold for less than 4-minutes (which is negligible) of a water draw event at the end of an extremely high water draw day. This means that if the 80-gallon HPWH heater is used to provide peak load reduction services, the water can be delivered to consumers within acceptable temperature limits, with only a negligible impact on efficiency if it were to be operated in hybrid mode. Also, from these data we can also conclude that when operated in efficiency mode, there would be negligible impact on the ability to deliver hot water within acceptable limits under Type 1 DR.

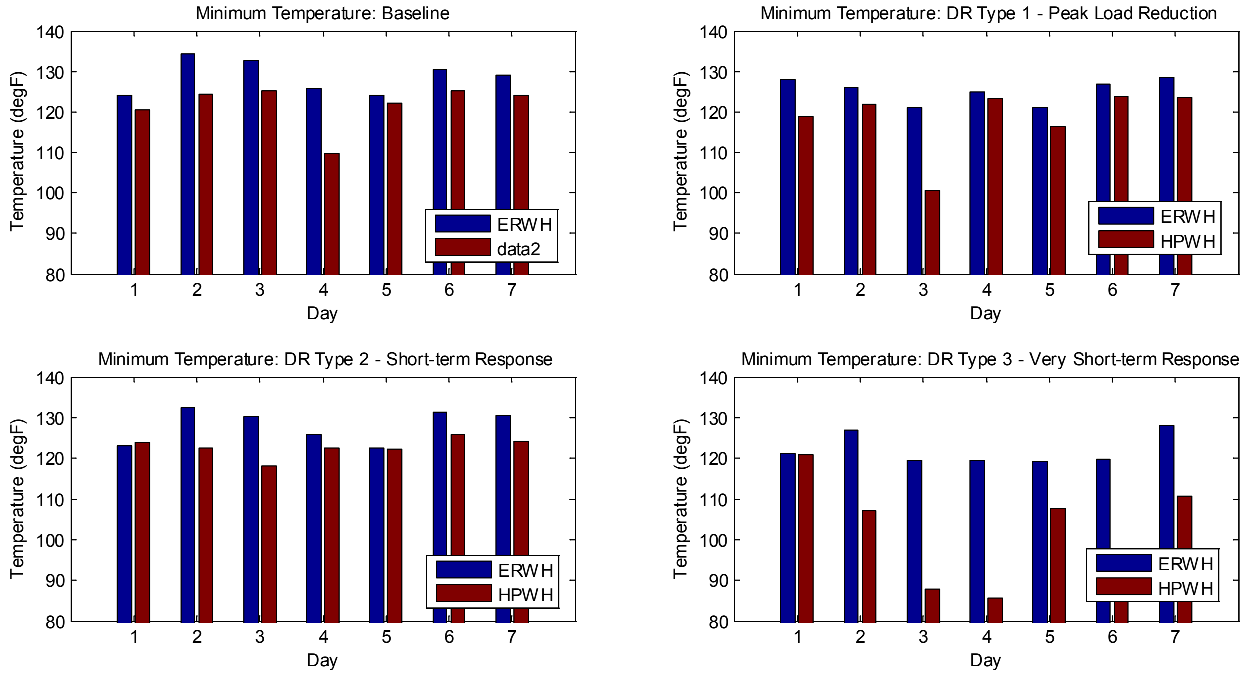


Figure 2.16. Minimum Outlet Temperatures Experienced per Day of Each Scenario Run

The minimum temperature threshold was not exceeded during the short-term response scenario. In this experiment, load reduction events lasted for only 1-hour and were called for 4 times throughout the day. Since the duration of the events were not long enough to affect the ability to maintain tank temperatures within acceptable limits, there would be no need for the electric resistance element to turn ON if operated in hybrid mode. This means efficiency of the HPWH would not be impacted if an 80-gallon HPWH is used for short-term DR services.

The very short-term response scenario did result in significant impacts on the ability of the HPWH to maintain tank temperatures within acceptable limits. Water outlet temperatures well below the minimum threshold were observed in 3 of the 7 days during the majority of the water draws. These more significant impacts are caused by the increased frequency and duration of DR events in this scenario, in addition to, the HPWH having a relatively slow temperature recovery time compared to the ERWH. In particular, a total of 31 load decrease and 26 load increase events were scheduled per day based on the "Typical Day" ACE signal and thresholds used in this experiment. Less than 5 load reduction events were called each day in the Type 1 and 2 DR experiments. Also, the load reduction events were on average longer in duration than the load increase events in the Type 3 DR scenario. Overall, the DR event schedule required the water heaters to be OFF more than 50% of the time each day. This is illustrated in Figure 2.17, where 1 and -1 indicate a load increase and decrease event, respectively, and 0 indicates that no event was called at that particular time of the day. Even though this case demonstrates significant impact on ability to deliver hot water on demand during this experiment, these impacts may be lessened through better water heater controls designed with logic to reject or override load reduction signals if water temperatures are expected to drop below acceptable limits. For example, more sophisticated controls could account for the measured tank temperature or the duration since the last DR event for each water heater when determining if a given water heater within a population is allowed to respond, so that the water heater is not required to respond to all DR calls. In addition, less aggressive ACE signal thresholds could also reduce the number of events and total duration of DR service requests, which may improve the ability of the HPWH to provide DR services without significant reductions in utility or increases in compressor cycling.

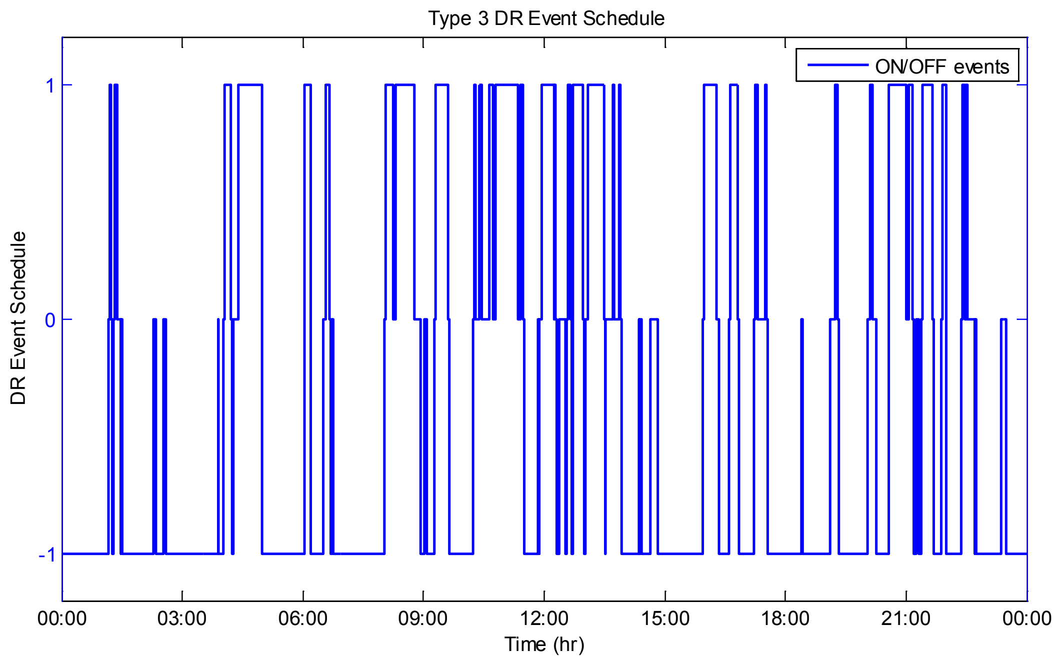


Figure 2.17. Daily DR Event Schedule for Type 1 DR Scenario

2.2.3 Availability to provide DR Services

Some DR programs may have specific objectives or minimum performance requirements that need to be met by the population of water heaters participating, which need to be projected onto individual water heaters. If water heaters are unavailable at times when DR is needed, they provide no benefit in terms of delivering the particular DR services. Therefore, there is a need to understand the likelihood that a water heater is in the opposite state when there is a call for a load reduction or load increase event to evaluate its ability to respond and provide DR services. In this work, availability is assessed by averaging the ratios of durations a WH is OFF/ON in baseline scenario during load increase/decrease events, respectively, and total durations of corresponding DR events. Figure 2.18 shows the availability of the ERWH compared to HPWH during each day and the average over the 7-day for each scenario considered. In the DR Type 1 scenario, the average availability over the 7-day period for the ERWH was ~22%. Since this type of DR with ERWH is currently practiced today and is considered acceptable, this value is used to determine whether the water heaters are adequately available to participate in the different types of DR programs. In all cases, the HPWH demonstrated acceptable levels of availability overall and was always more available than the ERWH.

It is worth noting that HPWH showed no availability in Day 4 of Type 1 and Day 1 of Type 2 DR. This is because the DR events scheduled coincided with periods when the HPWH is normally OFF according to the baseline. In Day 4 of each experiment, heavy water draw occurred during hours 6 and 7, as shown in Figure 2.6, which caused the HPWH to turn ON for several hours until ~2.5 hours before the 6-hour scheduled DR event in the Type 1 DR scenario. Another water draw did not occur until hour 19.

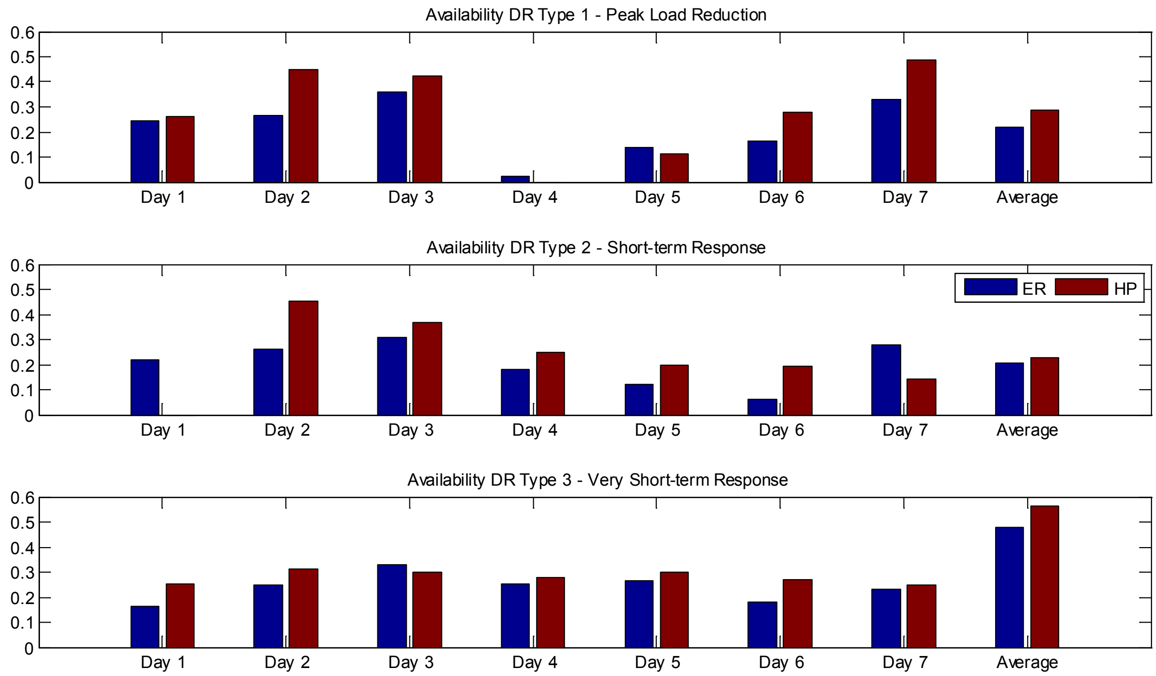


Figure 2.18. Availability of ERWH and HPWH During Each Demand Response Scenario

Between the two water draw periods on Day 4, the slow decreases in tank temperature were due to stand-by losses since there was no water draw. Therefore, the tank temperature did not drop low enough to trigger the water heater turn on during the scheduled DR event. In Day 1 of the Type 2 DR scenario, all DR events scheduled happen to correspond to normal OFF times of the water heater in the baseline, so the HPWH was unable to respond. Despite being coincidentally unavailable on a couple days, the HPWHs demonstrated to be 7%, 3%, and 8% more available than the ERWH in Type 1, 2, and 3 DR scenarios, respectively, over the week-long tests.

2.2.4 Impact on Cycling

Since cycling a compressor too often may significantly reduce the life of a HPWH, cycling impacts are assessed to determine technical feasibility of HPWHs participating in existing and future DR programs. The Figure 2.19 shows the total cycles of the HPWH experiences in all four scenarios considered for each day (top), as well as, each week (bottom).

As a result of the HPWH being shut OFF for several hours at a time and the compressor having a relatively slow temperature recovery time, the peak load reduction scenario (Type 1 DR) actually shows a reduction in number of cycles. Comparing Day 2 of the baseline (see Figure 2.14) and the peak load reduction experiment (see Figure 2.20) emphasizes this point and demonstrates why cycling is reduced. Following a load reduction event, avoided energy usage during the event immediately commences being consumed. This causes the water heater to remain ON for a longer duration following the DR event without turning OFF until the tank temperature has reached the set point and resulted in a reduced number of cycles.

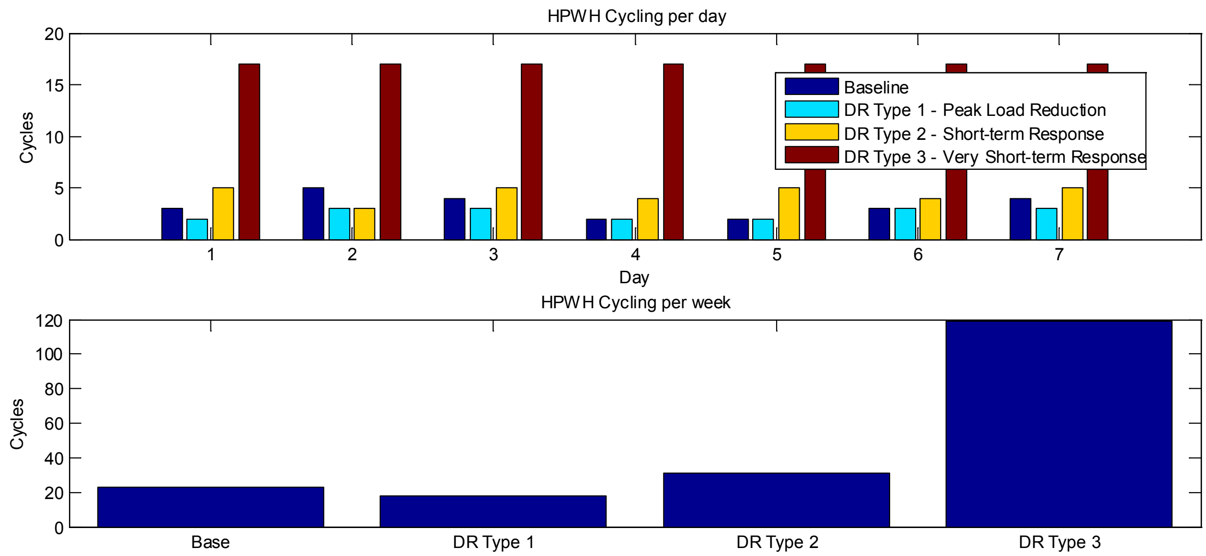
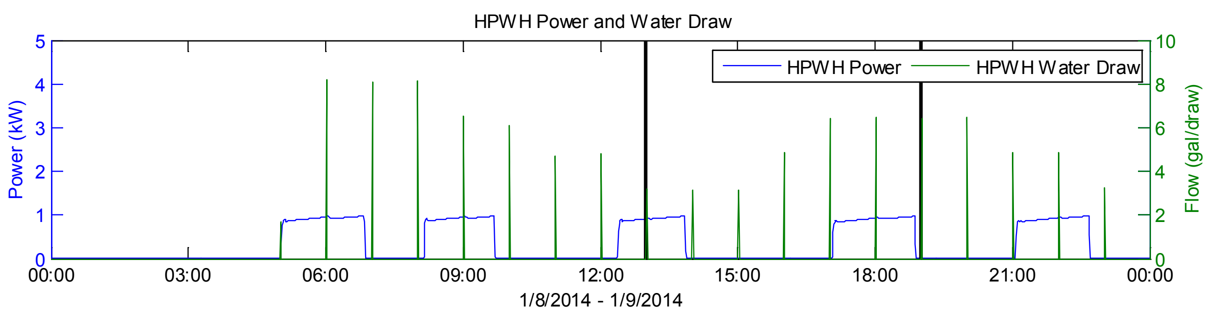
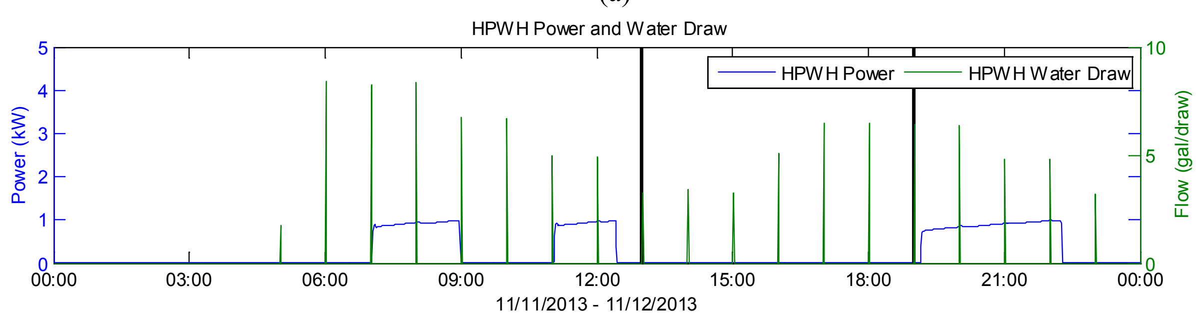


Figure 2.19. HPWH Cycling During each Scenario Run per Day (top) and per Week (bottom)



(a)



(b)

Figure 2.20. HPWH Power Consumption and Water Draw during Day 2 of (a) Baseline and (b) Peak Load Reduction Experiment

The short-term and very-short term scenarios both lead to increased cycling. The additional cycling that results depends on the number of DR events scheduled. In the short-term response scenario, four to five 1-hour load reduction events were scheduled each day. Therefore, roughly four to five cycles resulted each day, which average less than one more cycle per day compared to the baseline. This increase is not significant and indicates that five spinning reserve or load reduction events due to downward wind ramps can be scheduled daily without impacting technical feasibility of HPWHs participating in DR. On the other hand, load increase and reduction events were scheduled based on the chosen regulation signal depicted in Figure 2.11 in the very short-term response scenario. As mentioned before in Section 2.1.5, the two water heaters are not forced ON during DR increase events. Instead, the relay switch for each water heater is closed to allow normal operation. However, when the relay switch is open during a load reduction event, the water heaters are forced OFF. The DR event schedule derived from the regulation signal caused more than 5 times as many cycles (17 cycles/day) than the baseline. Mitigation of significant increases in compressor cycling may be accomplished through better population control strategies and water heater level controls designed with logic to reject override DR event signals if excess cycling is experienced. DR programs could be designed to randomize and send event signals less frequently to individual water heaters within a population such that the collective response enables minimum population performance requirements to be met without requiring the significant increase in cycling of individual water heaters. In addition, manufacturers could include new features in the compressor to protect the device from over-cycling to increase practicality of using it for providing frequency regulation. It should be noted that there is a trade-off between reduced cycling and availability during an event. The more DR signals are rejected to avoid increasing cycles, the less the HPWH will be available. Therefore, these trade-offs must be considered when designing these population and individual appliance level controls.

3.0 Conclusions

DR programs, when implemented at a large scale, have the potential to make the electric power grid of future more flexible and efficient in how power is created, distributed, and used. For example, DR can lead to cost effective and reliable integration of a significant proportion of renewable energy and increased reliability of grid services. Today, large tank ERWHs are used in peak load management programs that turn OFF the water heaters during the day with minimal impact on the consumers, due to the thermal energy stored in the water. In addition, ERWHs have relatively high power consumption, a large installed base, and follow a consistent load pattern that is often coincident with utility peak power periods, which makes ERWHs an ideal technology for a peak load management application. In the future, utilities may also explore DR programs that provide short-term (i.e., ramping) and very short-term (i.e., regulation, spinning reserves) responses to enable large scale renewable integration.

It is well known that new HPWH models are significantly more efficient than their ERWH counterparts, with the potential to save up to 63% per water heater. Due to the increased efficiency of these units, the peak power consumption is inherently and permanently reduced commensurate with the decreased energy consumption of these units, compared to ERWHs, at peak periods. However, the ability of large tank HPWHs to provide flexible and dynamic demand response in DR programs, similar to the services provided by the large tank ERWHs currently in use, had not been demonstrated and the impacts on efficiency of the HPWH or delivered water temperature had not been explored. This project measured the performance of HPWHs compared to ERWHs in providing DR services in the laboratory (Phase 1, discussed in this report) to demonstrate the technical feasibility of individual large-tank HPWHs in providing DR services compared to large-tank ERWHs. These data were used in subsequent analyses to evaluate the performance of a population of HPWHs, compared to a baseline population of ERWHs, on system-level power and residential load curves using a calibrated GridLAB-D model (Phase 2). These system-level impacts were then evaluated in terms of national economic and emission impacts based on National Impacts Analysis in Phase 3. Details on Phases 2 and 3 can be found in the companion report (reference companion report).

In particular, the availability, impacts on customer service, energy consumption, and equipment life cycles were assessed. Each experiment included side-by-side testing of an 80-gallon class ERWH and HPWH, with the same scheduled draw pattern and water temperature set point, over a 7-day period. The scheduled draw pattern was varied daily to represent and capture the impacts of draw pattern on water heater performance.

Through experimental testing of one large-tank ERWH and one large-tank HPWH under identical environmental conditions, hot water draw patterns, and DR scenarios, it was demonstrated that large-tank HPWHs are technically capable of performing DR services in both existing DR programs (e.g., peak load reduction) and future programs that require frequent short-term responses (i.e., ramping), without adversely impacting efficiency, consumer delivery temperatures, or equipment life. The experiments indicate that the HPWHs can effectively be utilized in DR programs, especially in existing peak load management programs, without sacrificing the efficiency of the HPWH. In addition, even though ERWHs have 4 times the power demand than HPWHs, the HPWH showed to be ~10% and 5% more available to provide peak load reduction and short-term response services, respectively. With the inherent peak load reduction resulting from increased efficiency of HPWHs and the increased availability of HPWHs to provide DR services, it appears that HPWHs can be effectively and efficiently used in DR programs to curtail peak power use and manage 1–2 hour ramping events (short-term).

In regard to specific concerns raised by utilities in response to DOE's recent RFI (77 FR 35299; June 13, 2012) investigating this topic, Table 3.1 outlines the primary concerns addressed by these experiments (Phase 1 of the project) and the related conclusions drawn from these experiments.

Table 3.1. Technical Concerns Regarding HPWHs Performing DR Raised by Utilities and Related Experimental Findings

Utility Concern	Experimental Findings
HPWHs have longer recovery times, which may require even larger tank sizes to obtain the same effective capacity as ERWHs or to ensure hot water delivery with DR programs.	**Minimal impact on delivered water temperature*** Very small impact on water delivery temperature (outlet temp dipped below 107 °F, the assumed acceptable threshold, for less than 4 minutes on an extremely high water draw day; otherwise never lower than 116 °F). No impact in short-term DR
Demand response may cause increased compressor cycling, which would negatively impact the product's service life.	**Minimal impact on compressor cycling*** Compressor cycling decreases slightly for peak load management (Type 1 DR). Small (<one cycle per day) increase in cycling for short-term DR (Type 1 DR).

* This result applies for all scenarios except for Type 3 DR where there are frequent and very short-term responses.

Experimental results indicate that future programs requiring frequent and very short-term responses (i.e., frequency regulation; DR 3) could significantly impact efficiency or consumer delivery temperatures depending on the mode of operation, as well as considerably increase compressor cycling. In particular, if the HPWH is operated in efficiency mode, the water heater would not deliver water at acceptable temperatures or would sacrifice efficiency to deliver hot water at adequate temperatures if operating in hybrid mode. In addition, cycling increased five times compared to the baseline scenario. However, these negative impacts on efficiency and acceptable water temperature delivery are dependent on the device level controls in place for responding to DR signals, as well as the strategies for coordinating the collective response to meet DR program objectives. Therefore, more intelligent designs of population coordination strategies and device level controls may aid in mitigating impacts observed while still meeting overall objectives. Further investigation via population modeling and analysis is needed to determine if mitigation is possible.

The experimental testing protocols used in this work are a prototype for how appliances can be characterized based on the types of services provided. The approach used can be adapted for other types of appliances to determine whether the appliance can appropriately provide DR services. Through more intelligent design of device- or population-level control strategies that consider important objectives (e.g., minimize impacts on cycling, consumer quality of service, availability and efficiency), some of the technical issues encountered may be mitigated. Testing protocols can also be adapted for population scenarios through population modeling of appliances to further assist in evaluating technical feasibility of a particular type of appliance providing a particular type of DR service according to newly developed control strategies.

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