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CO_2 Combination Space Conditioning and Water Heating Stress Tests in the PNNL Lab Homes

September 2017

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PACIFIC NORTHWEST NATIONAL LABORATORY
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BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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Prepared for
the City of Santa Clara
under Strategic Partnership Projects Agreement No. 68131

Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

If energy-saving heat pump water heaters (HPWHs) could be applied to space conditioning and water heating loads in a combined system in homes with electric water heating, the national energy savings potential would be large. To help determine the viability of such a system, Pacific Northwest National Laboratory and the Washington State University Energy Program conducted an experiment that evaluated a carbon dioxide split-system HPWH and the demand-response (DR) potential of the system using PNNL's side-by-side Lab Homes in Richland, Washington. The Lab Homes provide a platform for evaluating energy-saving and grid-responsive technologies in a controlled environment. The American Public Power Association through Silicon Valley Power, the Bonneville Power Administration, Ecotope, Inc., and Efficiency Solutions provided additional project support.

This experiment answered research questions related to the cold-weather performance of the combination (combi) system under typical and stressed loads. The DR capability of the system under typical and stressed loads was also tested. All of the research questions focused on whether or not the combi system can meet space conditioning and water heating loads under various simulated occupant conditions.

The combi system was found to:

- meet average space and water heating loads in the Lab Homes, as long as the outdoor temperature is above 40°F (conservatively),
- meet all space conditioning and water heater loads, even with high-use patterns, as long as the outdoor temperature was above 40°F,
- meet the space conditioning set point, and a domestic hot water outlet temperature of about 100°F, at typical occupancy loads with outdoor temperatures down to about 25°F,
- struggle to meet the space conditioning and DHW set points when there was low outdoor temperatures and a scheduled DR event where the power was cut off from the heat pump from 4-9 pm each day.

Acknowledgments

This project required a lot of collaboration from outside stakeholders and the authors greatly appreciate all of the people who helped to make this work possible. The authors acknowledge Mark Jerome of CLEAResult, and Greg Sullivan of Efficiency Solutions for their expertise in the installation and commissioning of the carbon dioxide combination systems. The efforts of Katie Cort of Pacific Northwest National Laboratory in deputy project management and the technical insights provided by Ben Larson of Ecotope were most helpful. The authors would like to extend extra appreciation for the dedication, leadership, and support of the Washington State University Principal Investigator, Ken Eklund. Finally, this work would not have been possible without the funding support provided by Silicon Valley Power, the American Public Power Association's Demonstration of Energy and Efficiency Developments (DEED) Program, and the Bonneville Power Administration.

Acronyms and Abbreviations

APPA	American Public Power Association
BPA	Bonneville Power Administration
CSA	Canadian Standards Association
DEED	Demonstration of Energy and Efficiency Developments
DOE	U.S. Department of Energy
DR	demand response
DHW	domestic hot water
EF	Energy Factor
ERWH	electric resistance water heater
GPD	gallons per day
HPWH	heat pump water heater
HSPF	heating seasonal performance factor
kW	kilowatt
NEEA	Northwest Energy Efficiency Alliance
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 and space conditioning represent ~50% of residential energy consumption, amounting to about 5 Quads[1] annually (EIA 2009). If one system could decrease energy use from both load types, significant energy savings could be achieved in the residential sector. If heat pump water heaters (HPWHs), which have a theoretical energy savings of up to 63%[2], could be applied to both space conditioning and water heating loads (a.k.a. combination systems) for homes with electric water heating, the national savings potential would be large.

However, significant barriers must be overcome before this technology will reach widespread adoption. One barrier is the lack of a proof of concept for a combination (combi) system that uses a water-to-air heat exchanger and a forced air furnace, such as the equipment in the Pacific Northwest National Laboratory (PNNL) Lab Homes. Another potential barrier is the impact of such a system on demand-response (DR) programs. Many utilities currently employ electric resistance water heaters (ERWHs) to reduce peak load by turning off the water heaters during times of peak demand or to store energy when there is an oversupply of generation. Some utilities are demonstrating the potential of using HPWHs in these scenarios and trying to understand the overall impact these systems might have on the grid. In this project, the combi system will be tested using a DR strategy where the water heater is turned off for 5 hours between 4pm and 9pm.

1.1 Project Scope

The project reported here was a collaborative effort between PNNL with support from the American Public Power Association (APPA) through Silicon Valley Power, and the Washington State University Energy Program (WSU) with support from the Bonneville Power Administration (BPA). WSU has subcontracted with Ecotope, Inc. for analytical support, and PNNL has contracted with Efficiency Solutions for technical support.

The project evaluated a CO_2 split-system HPWH developed by Sanden International, Inc. that was used as a combination space and water heating system. The project also evaluated the DR potential of this system.

The BPA portion of this project was part of a larger effort designated "Technology Innovation Project 338" or "TIP 338." TIP 338 includes an evaluation of this combi system in the PNNL Lab Homes, which represent typical existing homes in the Pacific Northwest, as well as the field testing of similar systems installed in 10 efficient, newly constructed homes. This report focuses on the experimental setup, plan, and results of the tests conducted in PNNL's Lab Homes, which are described in more detail in Section 2.1.

This project answered the following research questions:

1. During cold weather, does the system meet average space and water heating needs in the PNNL Lab Homes?
2. During cold weather, what is the impact on the system's ability to meet space and water heating needs when occupant-controlled variables such as thermostat settings, hot-water draws, and hot-water temperature settings are moved beyond average?

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[1] Approximately 1.5 billion MWh nationally

[2] Based on the U.S. Department of Energy test procedure (10 CFR 430.32(d)) and comparison of an electric resistance water heater (Energy Factor, EF = 0.90) versus a HPWH (EF = 2.4).

3. What is the DR capability of the system and the impact on its ability to meet average space and water heating needs in the PNNL Lab Homes during cold weather?
4. What is the DR capability and the impact on its ability to meet loads when occupant-controlled variables are moved beyond average?

2.0 Experimental Setup

The experiment conducted in PNNL's Lab Homes involved installation of a combination CO_2 heat pump water heater and space conditioning system.

2.1 PNNL Lab Homes

The experiments were conducted in PNNL's side-by-side Lab Homes, which provide a platform for evaluating energy-saving and grid-responsive technologies in a controlled environment. The PNNL Lab Homes are two factory-built homes installed on PNNL's campus in Richland, Washington. These 1500 ft^2 homes have three bedrooms, two bathrooms, and are equipped with a 7.7 HSPF (Heating Seasonal Performance Factor) heat pump and an electric forced air furnace. The insulation levels include R-22 floors, R-11 walls, and R-22 ceiling insulation (Figure 2.1).

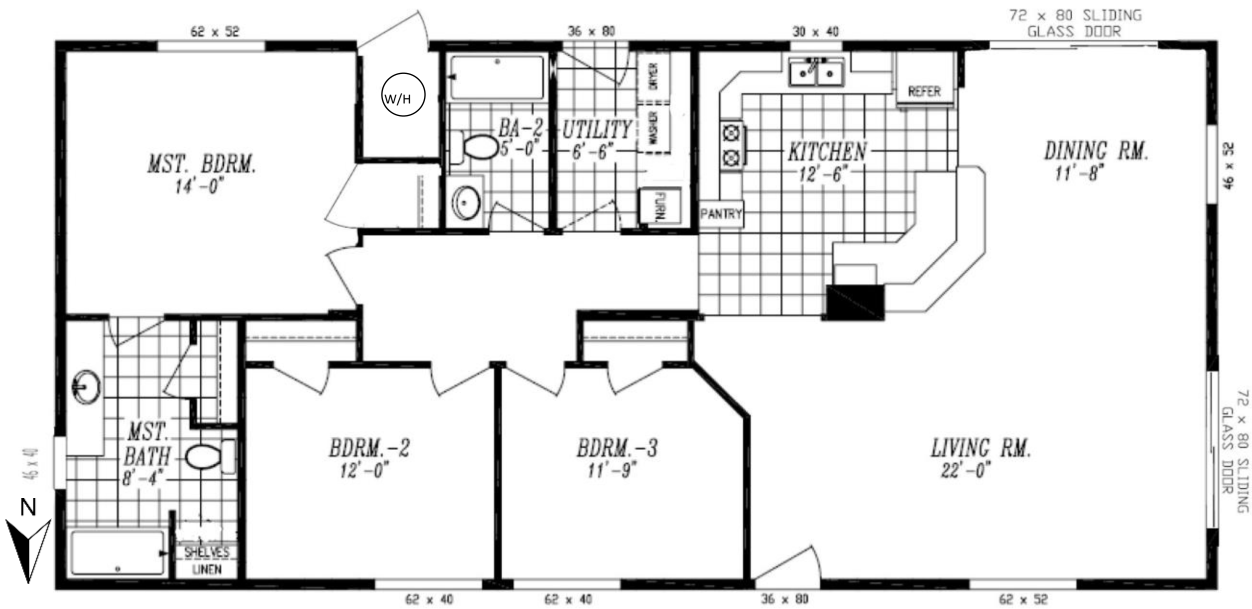

Figure 2.1. Floor Plan of the Lab Homes as Constructed

The unique nature of this side-by-side comparison means the homes experience the same weather at any given time. This allows comparisons of energy efficiency measures in the experimental home with baseline measures in the baseline home under identical environmental (indoor and outdoor) conditions, identical simulated occupancy, and cold water supply temperatures—all over the same time period. In addition to providing accurate information about energy consumption and savings associated with a specific technology, the independence of the comparison data from weather-related factors, such as outdoor air temperature and wind speed and their effects on savings, to be evaluated as independent variables rather than confounding variables.

2.1.1 Electrical Measurements

In each home, Campbell Scientific data loggers provide ample resolution for measuring simulated house loads (to be explained further in ensuing sections) and the power consumption of the system being studied. Electrical measurements for this experiment include whole house, external HPWH, electric furnace, furnace fan, Taco heat exchanger, and Seisco backup water heater energy use. All data were captured at 1-minute intervals.

2.1.2 Temperature and Environmental Sensors

The PNNL Lab Homes are equipped with many temperature and environmental sensors. Permanent space temperature sensors are located throughout the homes, and the hallway temperature sensor, nearest to the thermostat, is used in most experiments to help verify that the thermostat is meeting the space conditioning set point correctly. Typical sensors that are used in hot water-related experiments include insertion thermocouples to determine inlet and outlet water temperatures, as well as turbine flow meters to determine the flow rate of the water (to ensure water draw volume is the same between both homes). Specific measurements and locations for this experiment will be discussed further in section 2.2.2.

2.1.3 Simulated Occupancy

A focus of this experiment was to simulate "typical" space conditioning and domestic hot water (DHW) load profiles, as well as high and low load profiles, and determine if this combination system can meet the loads. The space conditioning set point, the water draw profiles, and the water draw set point were changed in the experimental home. The range of space conditioning set points was 80°F, 71°F, and 65°F. The water draw set points varied between 125°F and 135°F (Wilson et al. 2014, Lutz and Melody 2012).

In this experiment, other occupancy loads such as lighting and equipment were also simulated using the Building America House Simulation Protocols (Wilson et al. 2014). Those extraneous load profiles are described in more detail in Appendix A.

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. The three water draw profiles are shown in Figure 2.2, Figure 2.3, and Figure 2.4. The middle or "typical" water use profile is consistent with the draw profiles designed by the Northwest Energy Efficiency Alliance (NEEA) in 2016 and used by Ecotope in lab testing of this system (Larson et al. 2016). The low and high water use profiles alter the volume of that profile, while trying to maintain similar use patterns.

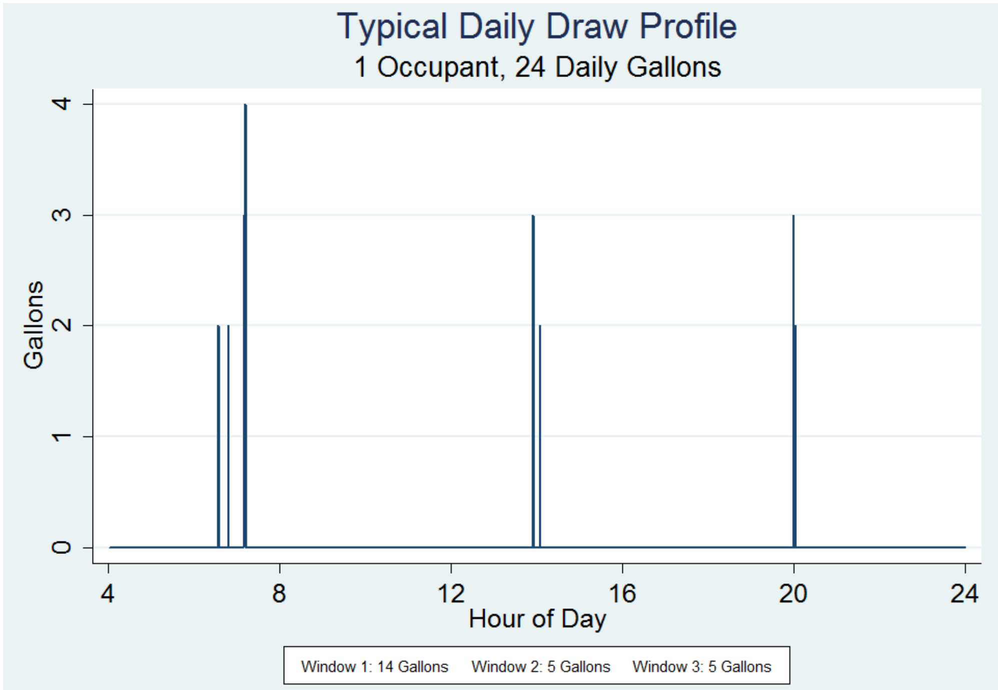

Figure 2.2. Low-Use Water Draw Profile

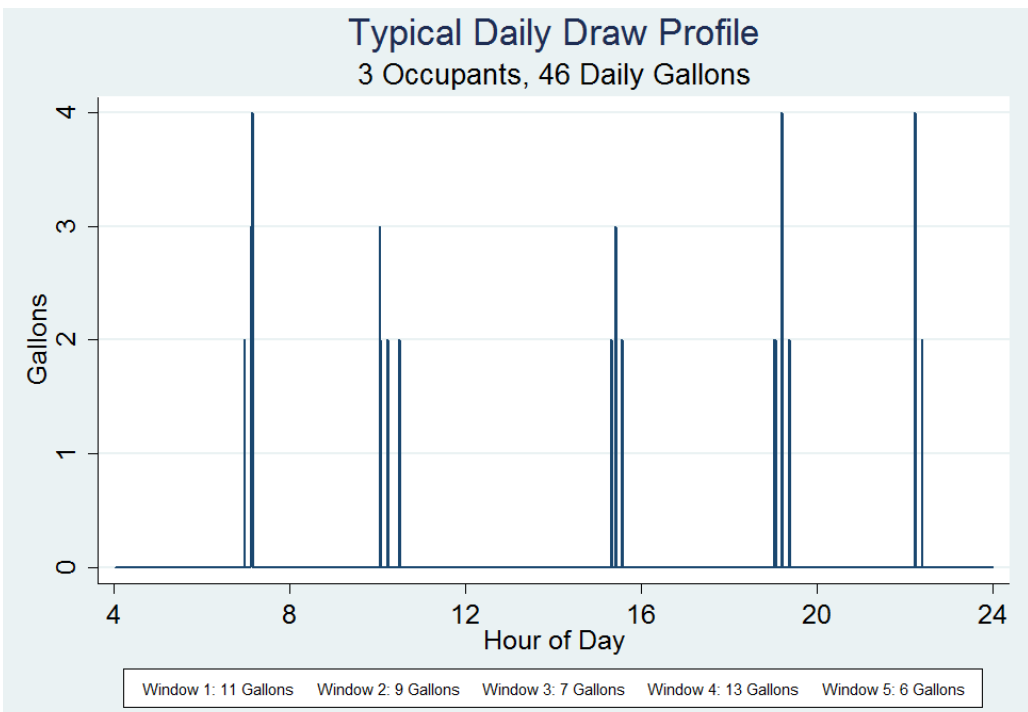

Figure 2.3. Middle-Use or "Typical" Use Water Draw Profile

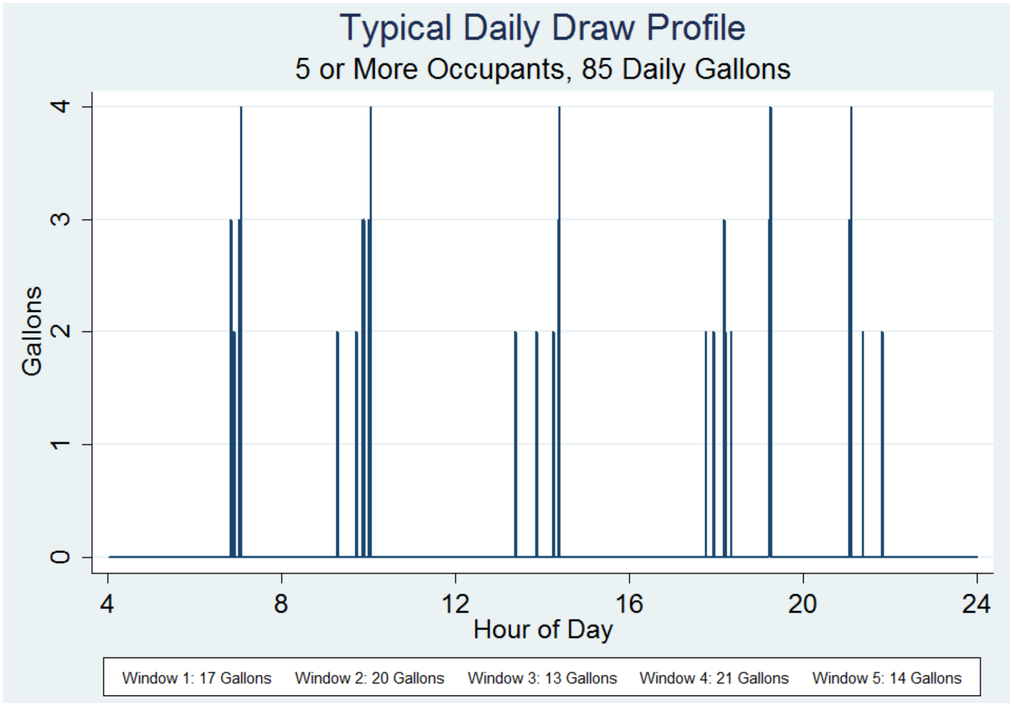

Figure 2.4. High-Use Water Draw Profile

The units had no factory-installed DR control at the time of the experiment[1], so DR schedules were implemented through the use of 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.

2.2 Combination CO_2 Heat Pump Water Heater and Space Conditioning System

System components, system integration and inline measurements, system controls, and installation challenges are described in this section.

2.2.1 System Components

The combination system consists of the Sanden Split-System HPWH, a Taco water-to-water heat exchanger, a water-to-air heat exchanger, and an air handler with a typical furnace fan. Each of the individual components is described in detail below.

The Sanden Split-System HPWH (model GAUS-315 EQTA) installed in both Lab Homes had two main components: a storage tank (Figure 2.5) and an outdoor unit (Figure 2.6). The storage tank was an insulated, 83-gallon tank designed for operation within the conditioned or semi-conditioned (e.g., garage) envelope of a home.

[1] The use of the standardized communication protocol CTA 2045 was explored by Sanden International as an integrated feature for these water heaters, but it was not developed as a workable protocol at the time these experiments took place. The company is committed to developing a state-of-the-art integrated DR control strategy in the next generation of its U.S. product line.

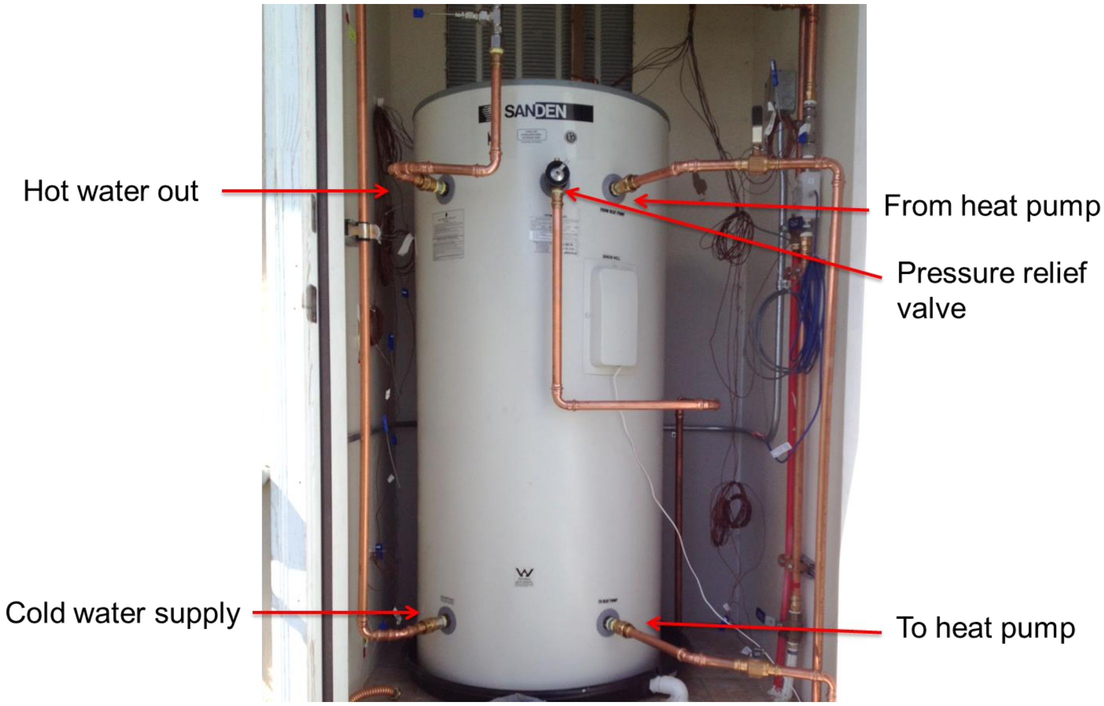

Figure 2.5. Sanden Water Heater Tank Installed in Lab Home Water Closet

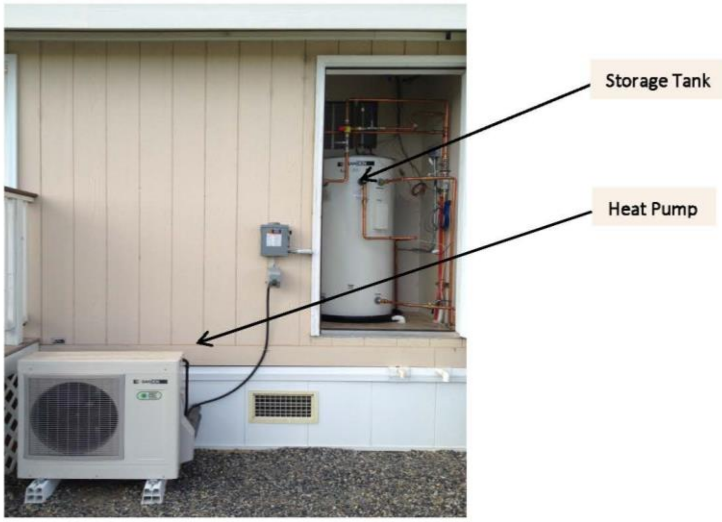

Figure 2.6. Sanden Split-System Heat Pump Water Heater as Installed in PNNL Lab Homes

The outdoor unit includes the compressor, evaporator, gas cooler, pump, and associated controls. The split-system design allows the source of heat to be the outside air, which eliminates any negative effects related to indoor cooling or noise. 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 a CO_2 transcritical refrigeration cycle because of its relatively high efficiency in producing hot water and its low environmental impact—it has a global warming potential of 1. This unit also uses an inverter-driven compressor and variable frequency evaporator fan to achieve even higher efficiencies. The Sanden water heater relies only on the heat pump and does not have backup resistance heating elements.

The storage tank has a thermostat located about one-third of the way from the bottom of the tank that 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 compressor constantly attempts to maintain the rated 4.5 kW heating output regardless of outdoor temperature. It has been documented that as the outdoor temperature decreases, the compressor power draw increases (Larson 2013). The output temperature at the tank is set to 149°F.

The Seisco (SH-7) on-demand water heater was not in the original design plan, but was later added based on preliminary data from field experiments associated with this project. The purpose was to generate backup heat for the system if the DHW design temperature was not being met. This hydronic heater can provide water temperatures from 90 to 145°F as set by the user. The on-demand water heater will cycle on when the supply temperature is less than the internal set point of the Seisco. This component would be recommended in a typical field installation to ensure all hot-water demands are met, but to minimize experimental error and reduce the total number of variables within the system it was not used in this experiment.

The Taco XPB-1 controls the heat delivery, circulates supply and load fluids, and has a heat exchanger that transfers heat from the hot-water heater to the space heating loop. The Taco has a constant speed pump, which continually operates when a heating load is triggered. The constant speed pump moves water through the water coil installed above the furnace fan and back to the heat exchanger to reheat the working fluid. The unit also contains a variable speed pump that cycles the water from the Sanden storage tank to the heat exchanger on the supply side of the heat exchanger.

2.2.2 System Integration and Inline Measurements

In this study, a combination space and water heating system was installed in both homes. Mark Jerome of CLEAResult and Ken Eklund from Washington State University designed the system based on experience they had installing similar systems in the field. A diagram of the installed system is shown in Figure 2.7. The expansion tank was added after high pressures were discovered in system once the water was heated.

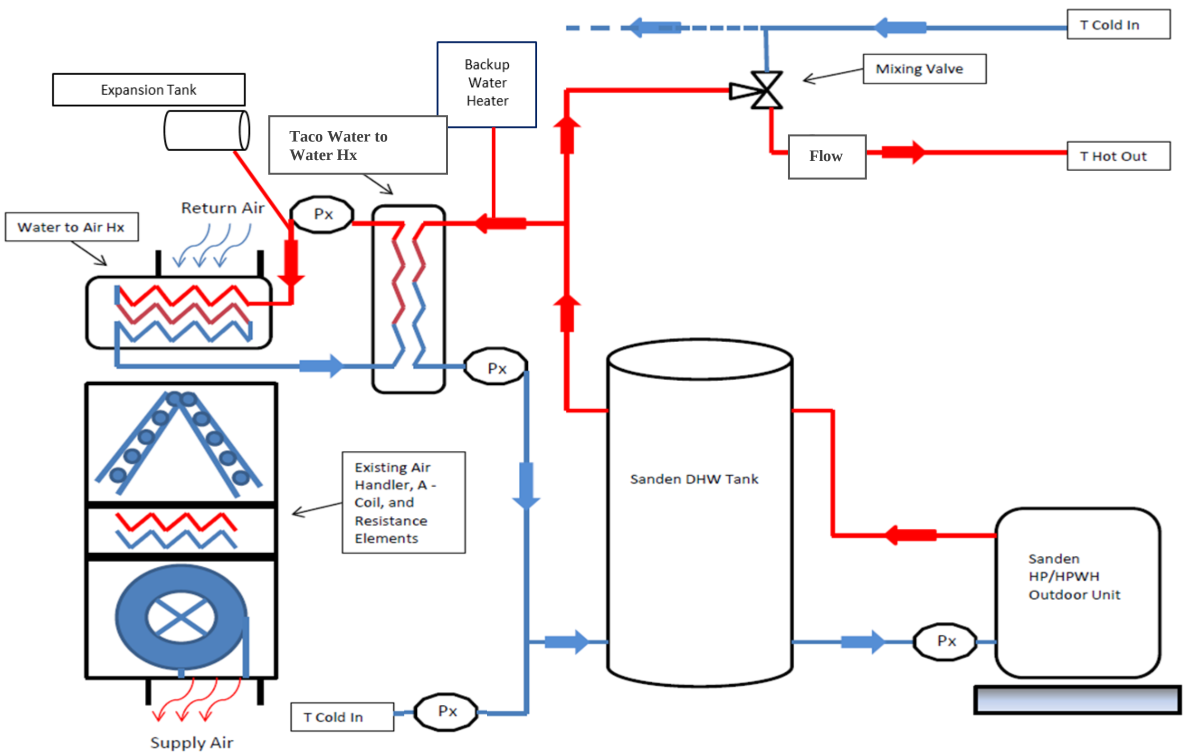

Figure 2.7. Diagram of Combi Installation in the PNNL Lab Homes

In this system, cold city water (measured with an insertion thermocouple immediately as it enters the home and referred to in Figure 2.7 as "T cold in") enters the water heater tank and is passed through to the outdoor unit, which heats the water in the CO_2 gas cooler, and is then returned back to the top of the tank in a closed loop system. The tank is set to hold the water at 149°F, which is ideal for space conditioning use. In a DHW draw, the water flows to the thermostatic mixing valve, where cold city water is mixed with the hot water to temper the water to the desired DHW supply temperature (measured with an insertion thermocouple immediately following the mixing valve and referred to in Figure 2.7 as "T Hot Out"). The hot water flow rate is also measured after the thermostatic mixing valve using a turbine flow meter that is in line with the hot water pipe (marked "Flow" in Figure 2.7). Water pressure was regulated with check valves in four locations to ensure proper flow and to help with installation commissioning and diagnostics (check values shown as ovals with "Px" in Figure 2.7).

During a call for space heating, hot water is pumped into the Taco water-to-water heat exchanger by the variable sped supply pump (Figure 2.8). The expansion tank provides additional pressure relief for the system because it is operating at a much higher temperature to meet the space conditioning needs. The variable speed pump in the Taco heat exchanger regulates the temperature by varying the heat delivered to the heat exchanger, thus regulating the temperature of the heating loop fluid that supplies the furnace.

The constant speed pump feeds the working fluid to the water-to-air heat exchanger, which was built as a custom add-on to the electric forced air furnace in each home. In this closed loop system, cold water exiting the heat exchanger is passed back through the Taco unit and re-heated until the space heating load is met. On the supply side, the variable speed pump returns the water from the heat exchanger to the water heater storage tank. This water is warmer than the city water, which reduces the efficiency of the system as a whole, which operates best at cold inlet temperatures.

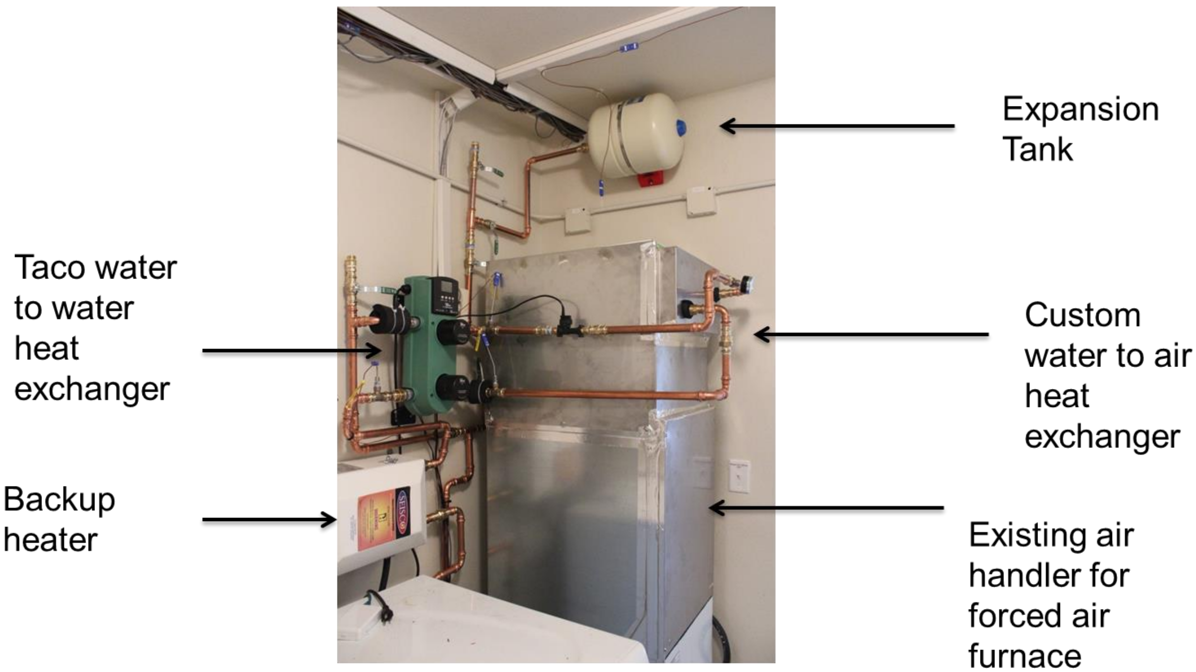

Figure 2.8. Picture of Indoor Combi Installation in the PNNL Lab Homes

The air side of the combination system consists of the water-to-air heat exchange coil and the furnace fan. When a heating demand is triggered, the furnace air handler cycles on to draw in air across the water coil. Heat is transferred from the coil to the air that is distributed throughout the Lab Homes via the supply ducts underneath the home. Once the thermostat is satisfied, the fan cycles off, but water may flow for a short period of time after the fan has shut off. Once the thermostat calls for heat again, the flow from the heat exchanger will start and the fan will cycle on as well.

2.2.3 System Controls

Control of the combination system depends on input variables from the local thermostat, exterior temperature sensor, and the Taco XPB-1 heat exchanger. The versatility of the heat exchanger allows for differing control architectures within the system. The two main control profiles (Figure 2.9) are described below.

- Setpoint Mode: Coupled to the thermostat, the Taco heat exchanger cycles off and on as the thermostat calls for heat. The tempered hot water temperature exiting the Taco unit is set within the heat exchanger. Upon meeting the space conditioning setpoint, the heat exchanger will continue to operate until the water coil has cooled below the target tempered temperature. The unit will remain idle until heat is called for again. This mode was used for the majority of the experiment (as explained in section 2.2.4).

- Outdoor Reset Mode: This mode requires the use of an outdoor air temperature sensor. The amount of heat introduced to the space is dependent on the thermostatic set point, the instantaneous outdoor air temperature, and the warm weather shutdown point. The assumed lowest outdoor air temperature and defined warm weather shutdown point are programmed into the heat exchanger. Depending on the outdoor air temperature and thermostat set point, the tempered water temperature is adjusted to meet the heating load by operating the variable speed pump over short or long durations.

  See Figure 2.9 for more detailed information about the control architecture for each heat exchanger mode.

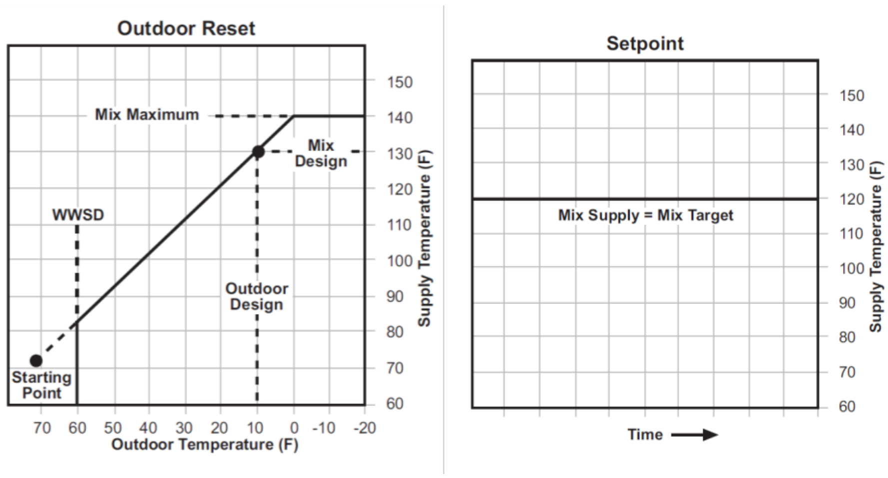

Figure 2.9. Various Control Strategies of the Taco Heat Exchanger

2.2.4 System Installation Challenges

As with any experiment, installation, commissioning, and execution challenges arose. These challenges are discussed here so that anyone trying to install a system like this may avoid similar pitfalls.

During installation of the system, the challenge noted was the volume of space required to simply install all of the required equipment. The water heater tank required piping to the outdoor unit as well as to the home. The sensors and mixing valve that were added to this space made for a tight fit in the water heater closet of these manufactured homes. The water heater tank was also connected to the furnace, which was in the utility room of the home. This space also housed the Taco water-to-water heat exchanger, the water-to-air heat exchanger, the expansion tank, and the control system. All of these devices took up most of the open wall space in the utility room and required some careful planning to ensure successful installation.

The water-to-water heat exchanger was added to the system to regulate the temperature of the water delivered to the water-to-air heat exchanger in the furnace. Upon installation of the Taco unit, staff noticed that the pump on the unit was leaking due to excess pressure; so the expansion tank was added. The factory setting of the Taco unit in one home was set to “outside air reset control.” This setting meant that the Taco system would not operate when the outside temperature was high enough to eliminate the need for heat. Once this system was adjusted properly, hot water was delivered to the furnace at the same time the furnace turned on. In the other home, the Taco was running continuously, even when the water heater was off and there was no call for heat. Further investigation revealed that the dipswitch of this Taco heat exchanger needed to be reconfigured.

Other issues to be aware of are the need to confirm that all parts are included in the original unpacking of the system, and to invest in high-quality mixing valves. In this case, a pressure relief valve was missing on one system, and the effects caused by a faulty mixing valve were difficult to diagnose— an avoidable problem if we had used a new, high-quality mixing valve from the beginning.

Lastly, in an experiment of this nature, with two side-by-side experiments running simultaneously, it is important to have both systems operating as similarly as possible. With this custom design and all of the components involved, it was difficult to get both systems to run similarly, let alone simultaneously. A lower quality mixing valve was part of the problem and made it difficult to ensure that both homes consistently had the same delivered hot-water temperatures.

3.0 Experimental Plan

The research questions associated with this experiment are:

1. During cold weather, does the system meet average space and water heating needs in the PNNL Lab Homes?
2. During cold weather, what is the impact on the system's ability to meet space and water heating needs when occupant-controlled variables such as thermostat settings, hot-water draws, and hot-water temperature settings are moved beyond average?
3. What is the DR capability of the system and the impact on its ability to meet average space and water heating needs in the PNNL Lab Homes during cold weather?
4. What is the DR capability and the impact on its ability to meet loads when occupant-controlled variables are moved beyond average?

All of these research questions focus on whether or not the combination system can meet both the space conditioning and water heating loads under various simulated occupant conditions. The research questions dictated the focus of the experiments, as well as their setup and execution. The advisory team for this experiment determined that both homes to would be equipped with the same combination systems. Throughout the experiment, the "baseline home" was run with typical occupancy use (see Section 2.1.3 for more detail), and the "experimental home" was run with various high- and low-use occupancy profiles to help determine the performance of the system under stressed conditions.

3.1 Stress Test Ranges

To understand the full performance of the combination system within the residential application, the proof of concept must include pushing the limits of the combination system technology. These limits include the internal thermostat set point, the DHW set point, and the total gallons of domestic hot water drawn per day in the experimental home. Table 3.1 details each of the stress tests that have been completed within this project.

Table 3.1. Stress Test Variables

Stress Test	Description
Thermostat Set Point Experiment	Adjust the internal thermostat set point High -80°F Medium – 71°F Low – 65°F
Domestic Water Temperature Experiment	Adjust the thermostatic mixing valve to supply DHW to: High – 135°F Low – 125°F
Water Draw Profile Experiment	Adjust the total volume of the hot-water draw profile to per day High – 85 gallons per day Low – 24 gallons per day

3.2 Demand Response Protocol

A DR schedule was generated to demonstrate the impact of turning off the system to reduce energy use during a peak period, or to force the system to recover during an oversupply period. The time period where the system was not allowed to operate was from 4–9 pm (Figure 3.1). Two DR sub-experiments were conducted, one to represent the reaction of the combi system under typical loads (46 GPD), and one to represent a higher load profile (85 GPD).

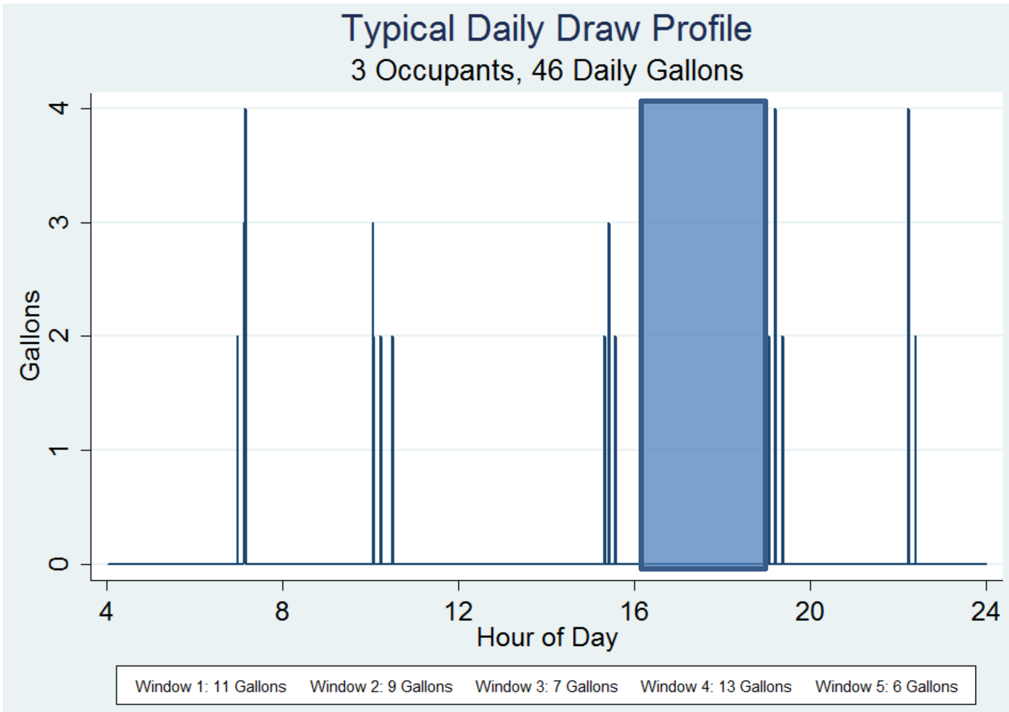

Figure 3.1. Demand Response Schedule Used in the PNNL Lab Homes

Table 3.2 shows the full range of parameters that were tested during this experiment. These parameters were chosen by the project team and its advisors to represent a range of realistic conditions that a combi system like this might experience in field conditions.

Table 3.2. Test Scenarios for the CO_2 Combination System

Test Name	Baseline/Control Home				Experimental Home					Test Time
	Heating System	Heat Load	Water System	Water Load	Heating System	Heat Load	Water System	Water Load	DR/ DHW Temp	
Combi Baseline	Sanden HP	71°F	Sanden HP	46 GPD	Sanden HP	71°F	Sanden HP	46 GPD	None/ 125°F	3 days
Stress High Heat	Sanden HP	71°F	Sanden HP	46 GPD	Sanden HP	80°F	Sanden HP	85 GPD	None/ 125°F	3 days
Stress Low Heat	Sanden HP	71°F	Sanden HP	46 GPD	Sanden HP	65°F	Sanden HP	23 GPD	None/ 125°F	3 days
Stress High Water T	Sanden HP	71°F	Sanden HP	46 GPD	Sanden HP	71°F	Sanden HP	46 GPD	None/ 135°F	3 days
Stress High Flow	Sanden HP	71°F	Sanden HP	46 GPD	Sanden HP	71°F	Sanden HP	85 GPD	None/ 125°F	3 days

Stress Low Flow	Sanden HP	71°F	Sanden HP	46 GPD	Sanden HP	71°F	Sanden HP	23 GPD	None/ 125°F	3 days
DR 46 GPD	Sanden HP	71°F	Sanden HP	46 GPD	Sanden HP	71°F	Sanden HP	46 GPD	5 hr off/ 125°F	2 days
DR 85 GPD	Sanden HP	71°F	Sanden HP	46 GPD	Sanden HP	71°F	Sanden HP	85 GPD	5 hr off/ 125°F	2 days

4.0 Results

The experiment and analysis focused on answering the research questions. The results are provided after each research question in the section below. Graphs of experimental data are used to explain the responses to each research question. In all of the graphs, the green line represents outdoor air temperature, the purple markers represent data from the baseline home (always typical-use patterns) and the teal markers represent data from the experimental home (always the high-use patterns). The data points that form tall vertical lines represent the hot-water outlet temperature (measured at the hot-water outlet of the water heater) and the relatively flat lines with short spikes are the hallway air temperatures near the home thermostat (as measured by a thermocouple that was verified to be consistent with the thermostat).

4.1 Answers to the Research Questions

1. During cold weather, does the system meet average space and water heating needs in the PNNL Lab Homes?

Answer: Yes, the system meets average space and water heating loads in these homes, as long as the outdoor temperature is above 40°F (conservatively). Figures 4.1 and 4.2 show how the system reacts to a typical-use case scenario, under varying outdoor air temperature conditions. Figure 4.1 shows that when water draws occur during periods during which outdoor temperatures are above 40°F, the system has no problem meeting both the space conditioning and DHW outlet temperature. Figure 4.2 shows that when there is a water draw during a period when outdoor temperatures drop below 40°F, the system meets the space conditioning set temperature, but falls short of meeting the DHW outlet temperature (only reaching about 95°F compared to the set point of 125°F). This clearly shows the limits of this system under typical-use patterns and indicates why a demand heater on the DHW line would be helpful in this situation.

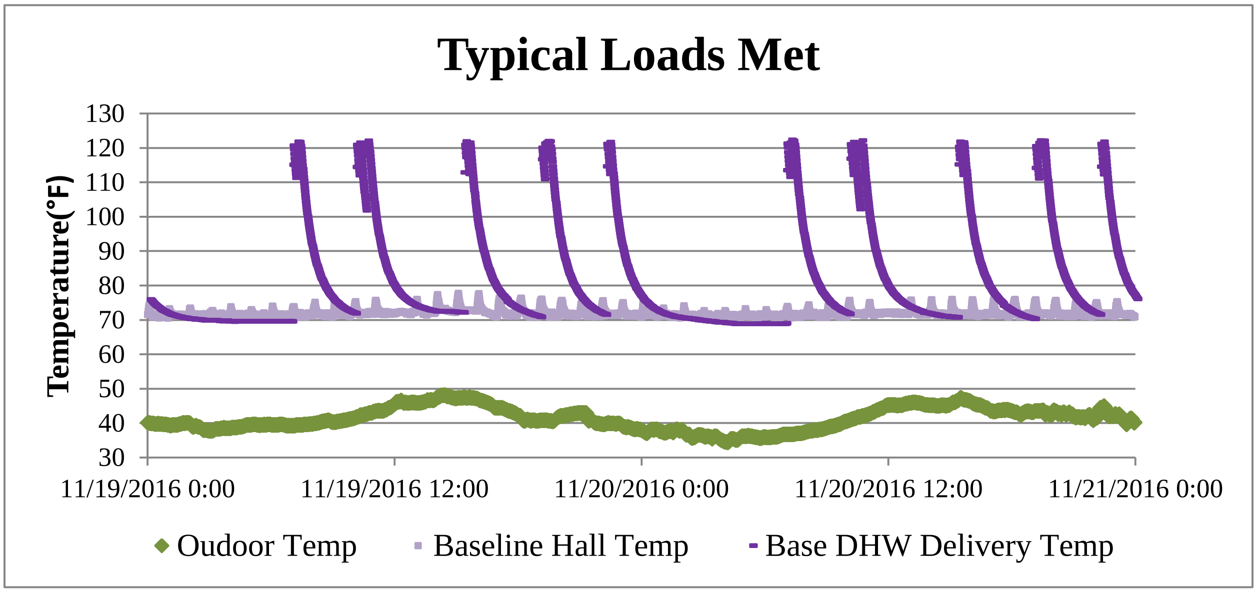

Figure 4.1. Space Conditioning and DHW Loads Met (71°F space temperature set point, 46 GPD water draw volume, and 125°F DHW set temperature)

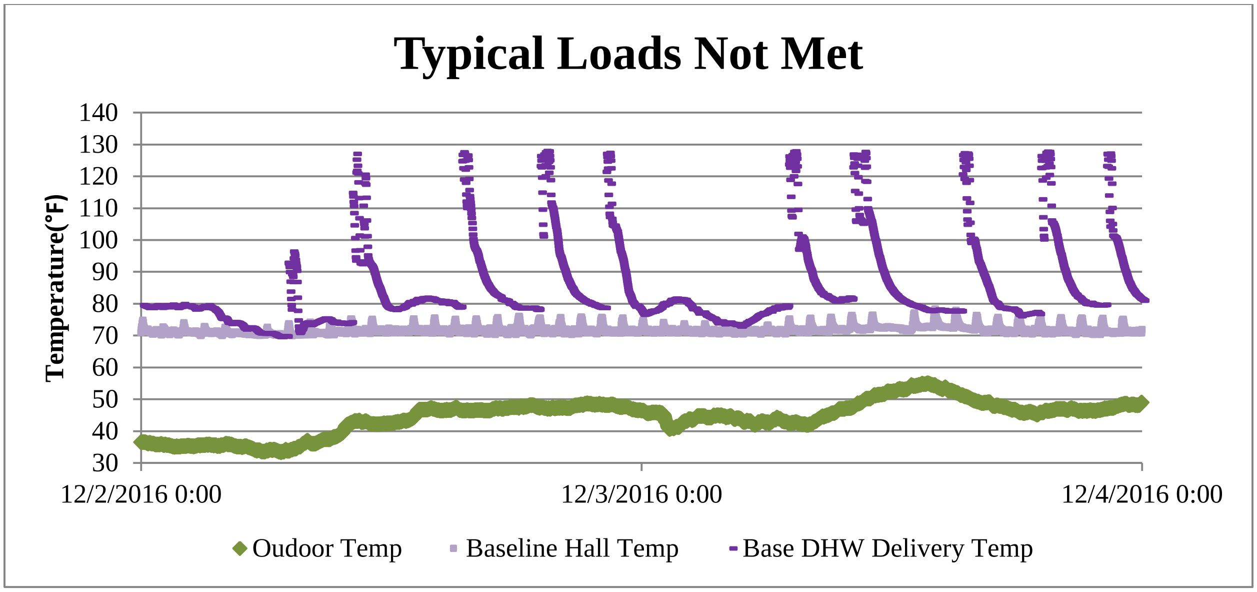

Figure 4.2. DHW Was Not Met when Outdoor Temperatures Were Below About 40°F (71°F space temperature set point, 46 GPD water draw volume, and 125°F DHW set temperature)

2. During cold weather, what is the impact on the system's ability to meet space and water heating needs when occupant-controlled variables such as thermostat settings, hot-water draws, and hot-water temperature settings are moved beyond average?

Answer: The system was able to meet all space conditioning and water heater loads, even with high-use patterns, as long as the outdoor temperature was above 40°F. Figure 4.3,Figure 4.4, and Figure 4.5 show the results from the corresponding experiments. Figure 4.5 shows that the system has trouble meeting the DHW set point when the space set point temperature is high and the outdoor temperature is below 40°F. It is interesting to notice that in each of the cases below, the space set point temperature is reached, which means that the system is prioritizing that load over the DHW outlet temperature (Figure 4.3 and Figure 4.5 show the effects of solar gains on the indoor space temperature on November 12 and December 1 respectively. Solar gains are visible and similar in both homes, due to the hall temperature rising above set point on those days.)

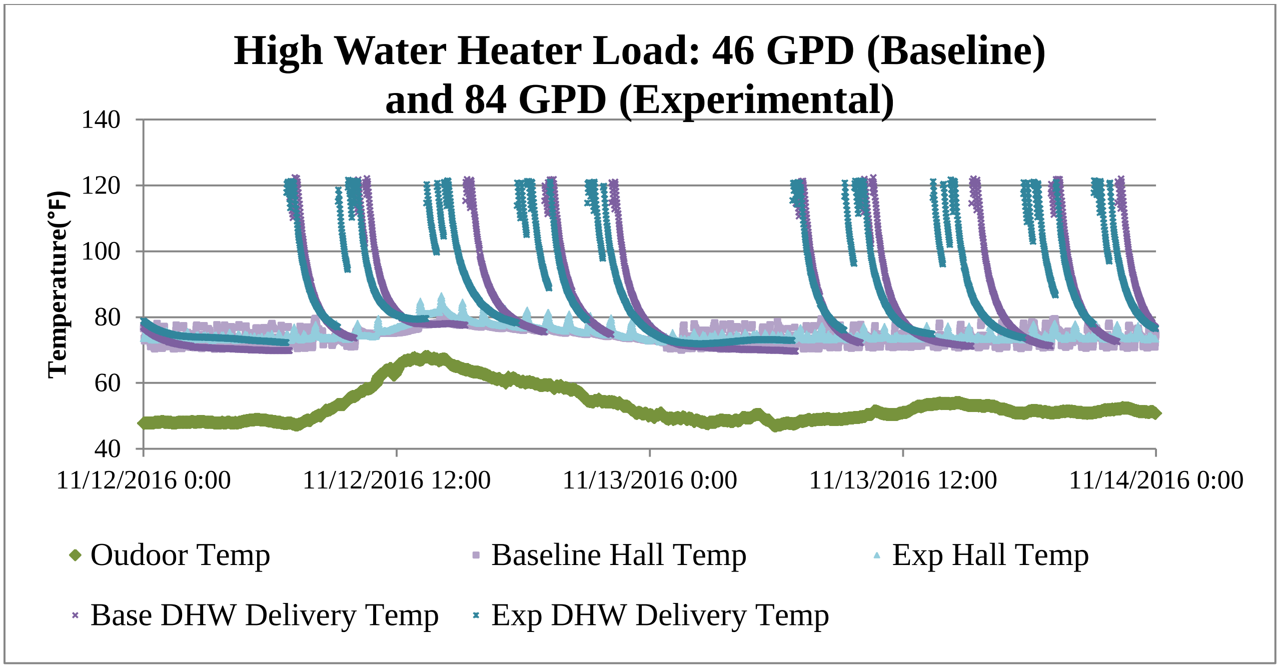

Figure 4.3. Typical and High Water Load Results (71°F space temperature set point with 125°F DHW set temperature)

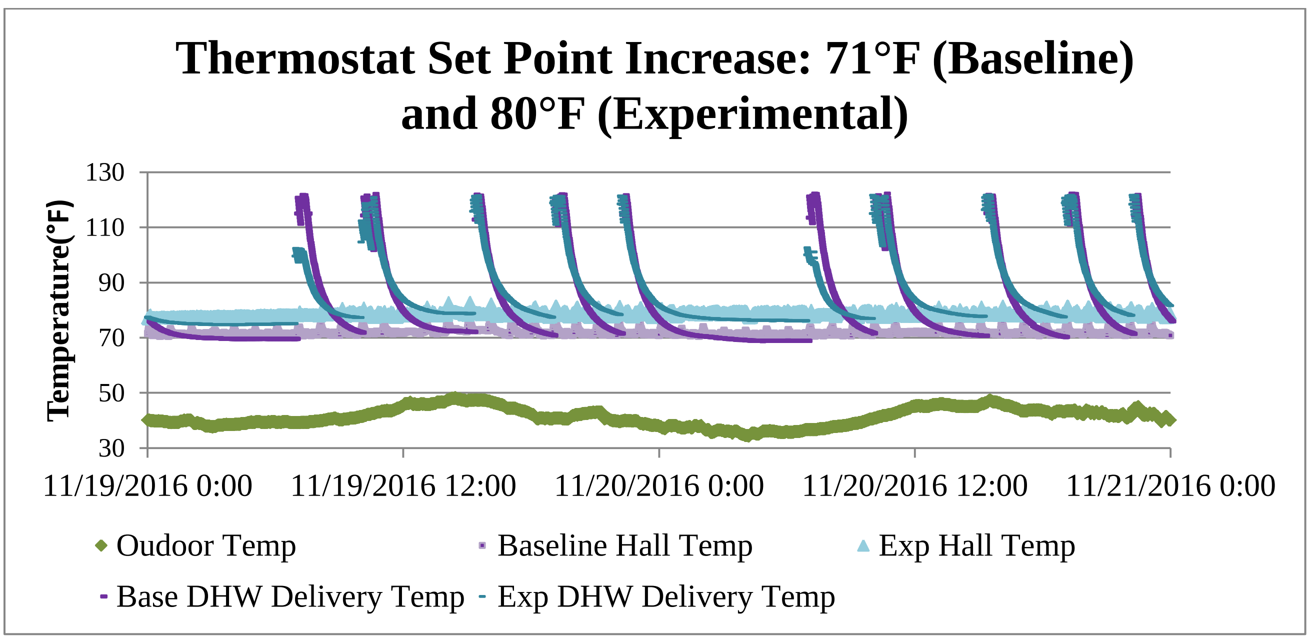

Figure 4.4. Typical and High Thermostat Set Point Results (46 GPD Water draw profiles with 125°F DHW set temperature)

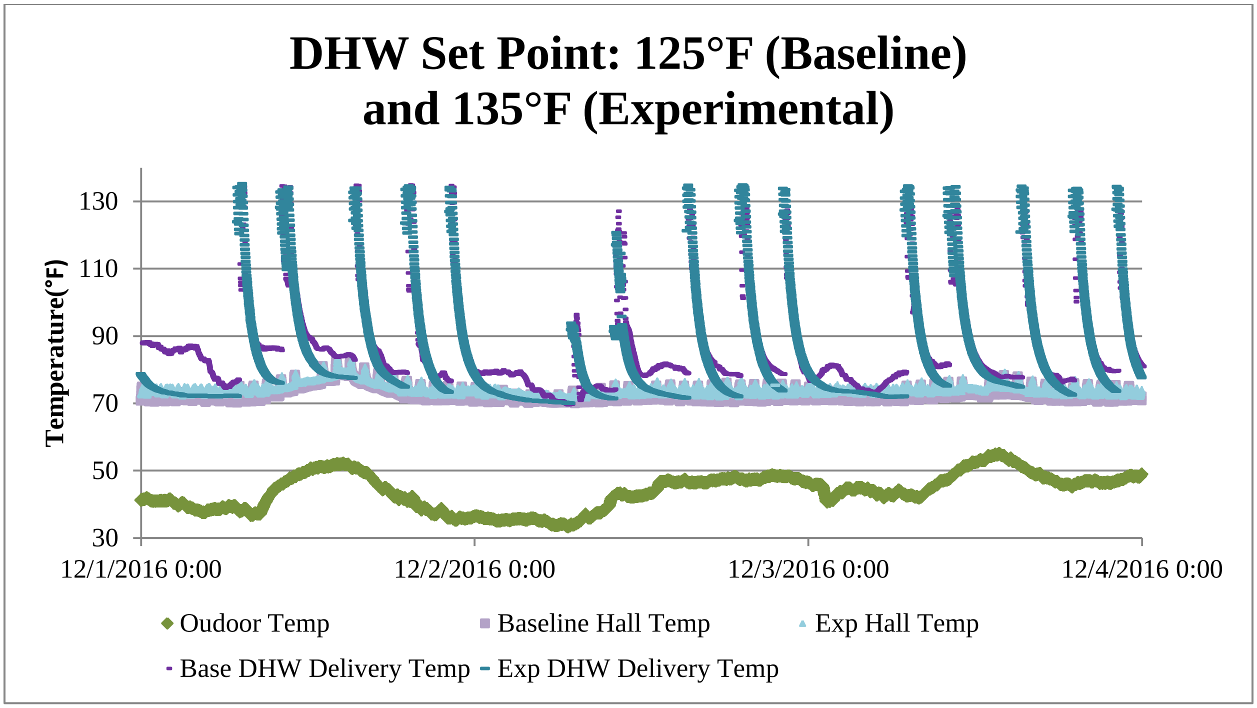

Figure 4.5. Typical and High DHW Set Point Results (71°F Space Temperature Set Point with 46 Gallons Per Day Water Draw Profiles)

3. What is the DR capability of the system and the impact on its ability to meet average space and water heating needs in the PNNL Lab Homes during cold weather?

Answer: In this experiment, the baseline home had typical occupancy loads, while the experimental home used high water volume draws. Both homes were subjected to one DR event per day between 4–9 pm when the heat pump was not allowed to cycle on (shown graphically with grey bars).

For these typical loads, the outdoor temperature affected the overall DHW delivery temperature, but the DR event did not substantially affect the space temperature near the thermostat in the hallway. The combi system was able to meet the space conditioning set temperature, and a DHW outlet temperature of about 100°F, at typical occupancy loads (see control/baseline home results in Figure 4.6) with outdoor temperatures down to about 25°F. A different control strategy could either prioritize the hot-water system over the space conditioning system, or use a backup electric water heater to make up the difference in delivered hot-water temperature.

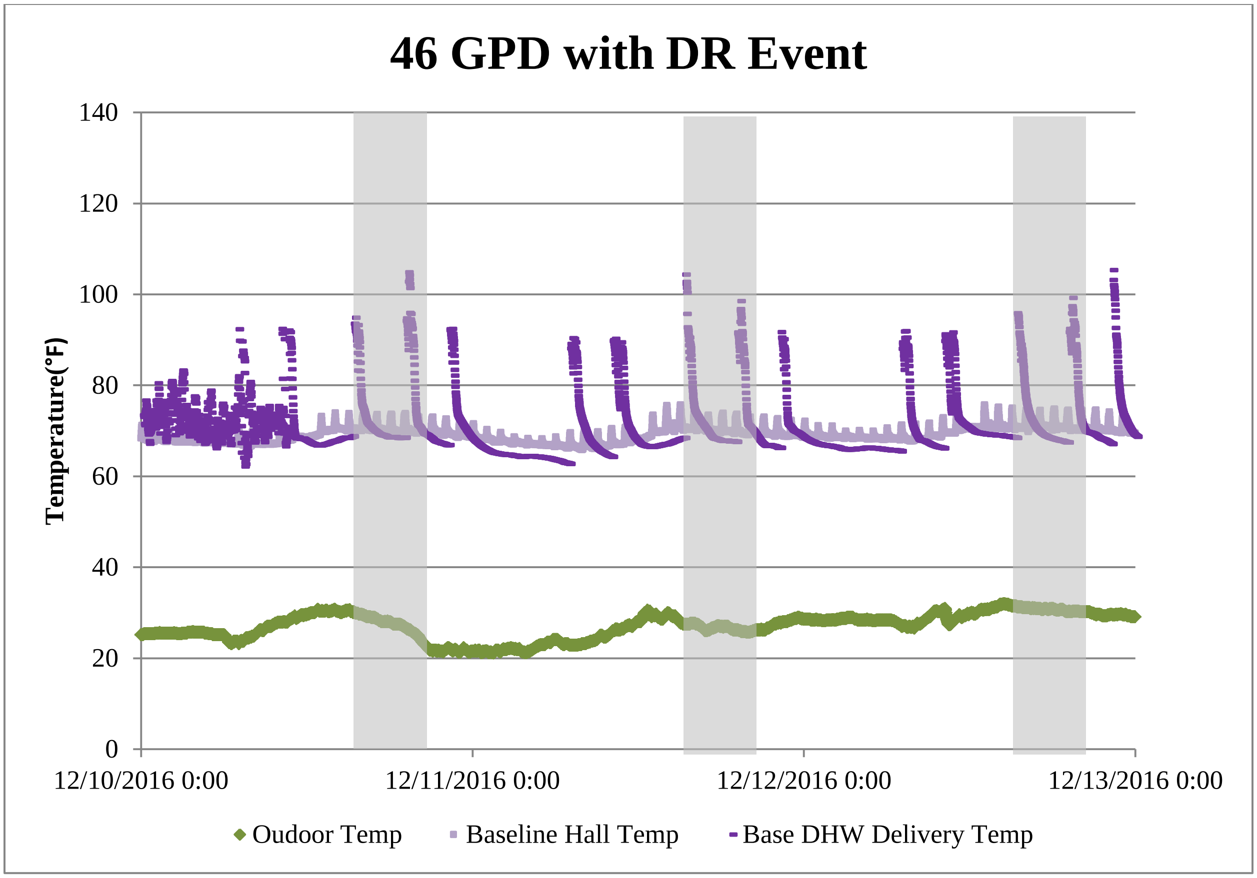

Figure 4.6. DR Results with Typical Use (71°F space temperature set point with 46 GPD water draw profiles and 125°F DHW set point)

4. What is the DR capability and the impact on its ability to meet loads when occupant-controlled variables are moved beyond average?

Answer: Figure 4.7 shows that when the water draw volume was increased to a high load of 84 GPD, the system struggled to meet both the space conditioning and DHW outlet temperatures. After a DR event, the space temperature dropped about 9°F to near 60°F, and the DHW outlet temperature could not rise above about 90°F, even during a water draw that was about 2 hours after the DR event was over.

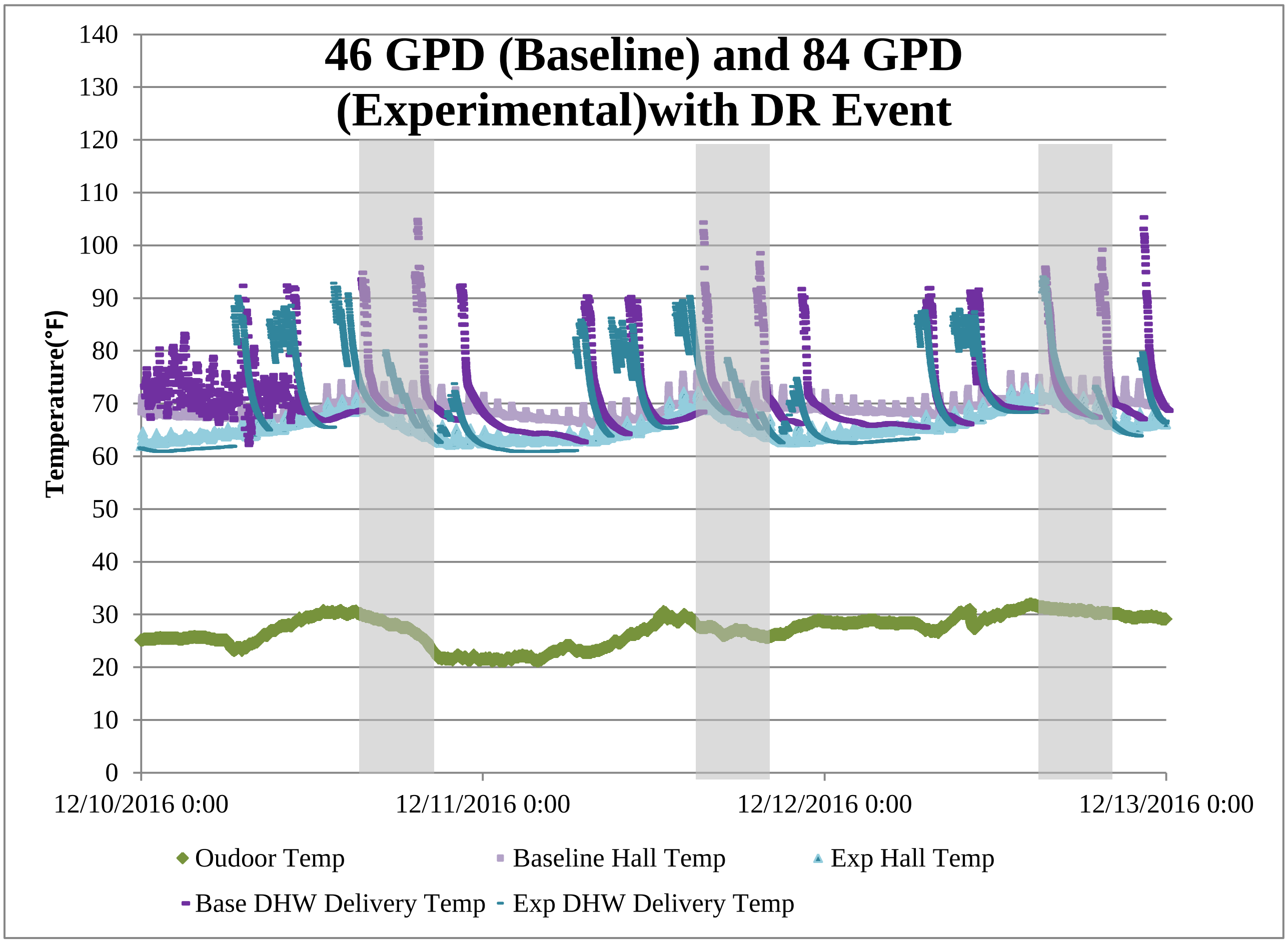

Figure 4.7. DR Results with Typical (46 GPD) and High (84 GPD) Water Use Profiles (71°F space temperature set point with 125°F DHW set point)

4.2 Conclusions

Overall, it appears that this system is capable of meeting even high occupancy use patterns as long as the outdoor temperature is above 40°F. The combi system is a bit more challenged during a DR event when the water heater is turned off for 5 hours. During the DR experiment, the outdoor temperature was never above 40°F. The results show that under this DR condition, with low outdoor temperatures, the space conditioning set point of 71°F can be met as long as the DHW water draw volume is kept at 46 GPD. However, the DHW temperature set point of 125°F is not met under these challenging DR conditions. (Unfortunately, due to the fact that the outdoor temperatures never rose above 40°F during this part of the experiment, it is unclear how the system would react during this type of DR event if it was above 40°F outside.) When there is a combination of high-use loads, low outdoor temperatures and a DR event, neither the space conditioning (71°F set point) nor the DHW outlet temperatures (46 GPD at 125°F set point temperature) are met.

Interestingly, it appears that the system that was installed in the PNNL Lab Homes prioritizes meeting the space conditioning set point over the DHW outlet temperature. This may or may not be desirable, depending on ease of integrating a backup electric resistance water heater with the system. The control strategy of the system could also be refined if the DHW outlet temperature was actually a priority.

Another key factor demonstrated by this research is that the heat output capacity of the heat pump should match the design load of the structure. In this case, either improving the efficiency of the home to bring the design load to the heat pump capacity or a larger heat pump that could meet the design load—or a combination of both—would allow operation down to colder temperatures without sacrificing comfort or performance. The total energy used by this combination system for “typical” loads (71°F space temperature set point, 46 GPD hot-water draw volume, and 125°F DHW set point) varies greatly based on the outdoor temperature. Each blue diamond in Figure 4.8 represents the total energy for that day at a given average daily temperature. The total energy includes the energy from the fan in the air handler, the water heater, and the Taco water-to-water heat exchanger. No energy from the backup water heater was included since it was disabled. The line of best fit is drawn as a reference point, but is only relevant for the data taken in the PNNL Lab Homes.

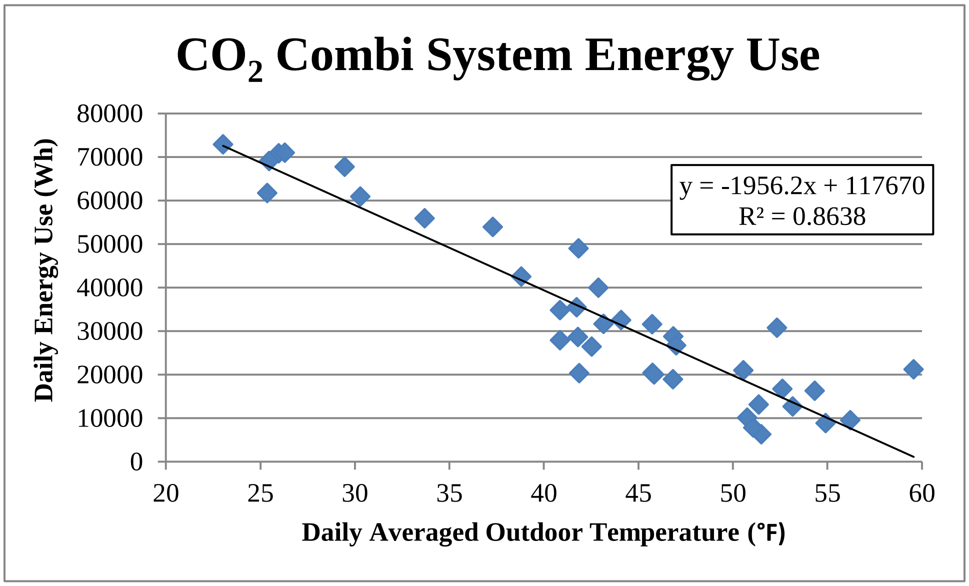

Figure 4.8. CO_2 Combi System Energy Used Compared to Outdoor Temperature

5.0 References

Note that some references in this section are cited in the Appendix A.

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Appendix A

Occupancy Simulation: Electrical Loads

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Occupancy Simulation: Electrical Loads

Controllable breakers were programmed to activate connected loads on schedules to simulate human occupancy. The bases for occupancy simulation were data and analysis developed in previous residential simulation activities (Wilson et al. 2014). The occupancy simulations and schedules developed here were derived specific to the home style, square footage, and an assumed occupancy of three adults. The per-person sensible heat generation and occupancy profiles were mapped from Wilson et al. was applicable to this demonstration.

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

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

Throughout the experiment, the heating, ventilation, and air-conditioning systems were operated identically in the two homes. The combi systems were set to maintain an interior set point of 71°F with no setback, in accordance with Building America House Simulation Protocols (Wilson et al. 2014).

Table A.1. Daily Occupancy Schedules and Simulated Load

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

Table A.2. Daily Lighting Schedules and Simulated Load

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

Table A.3. Daily Equipment Schedules and Simulated Load

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

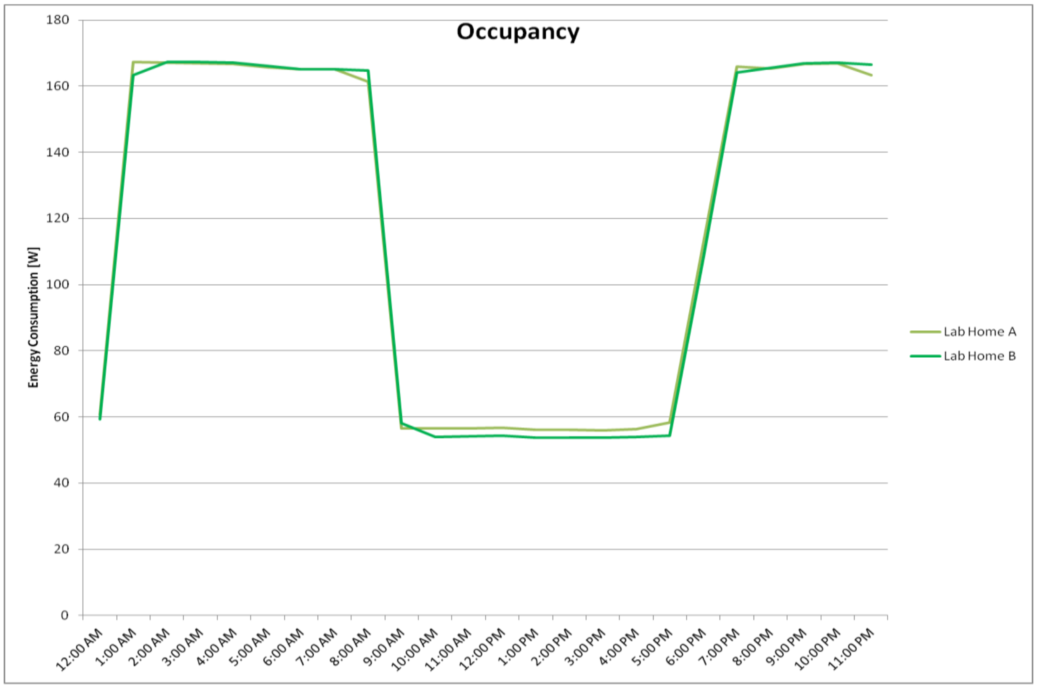

Figure A.1. Hourly Average Energy Consumption (W) Associated with Human Occupancy for an Example Day during the Baseline Period

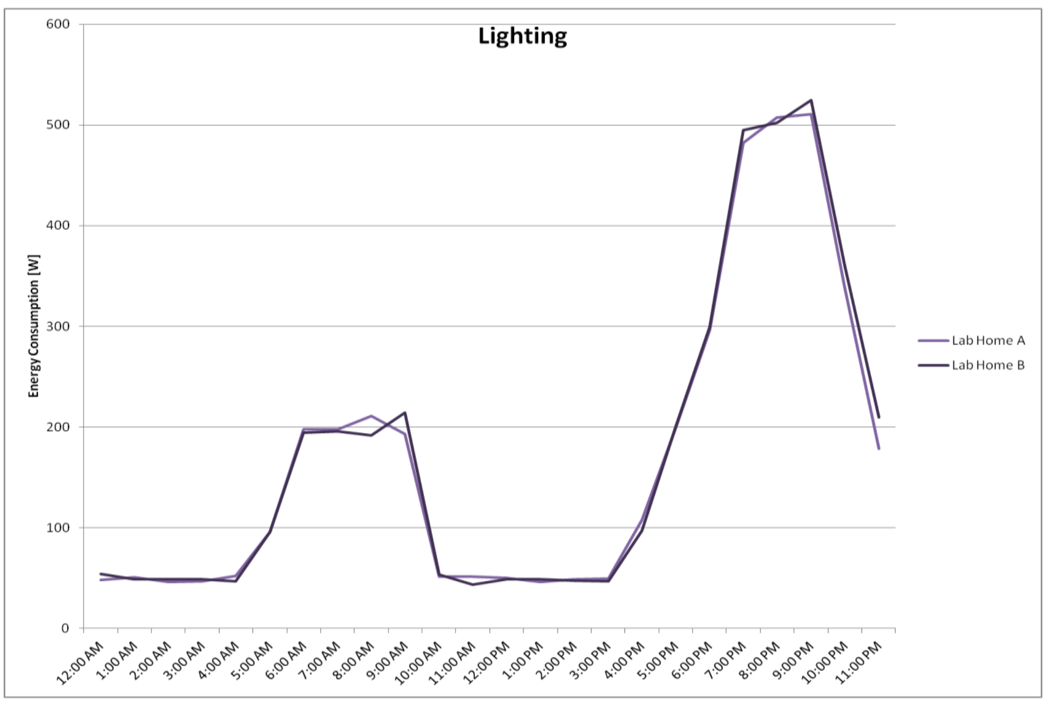

Figure A.2. Hourly Average Energy Consumption (W) Associated with Lighting for an Example Day during the Baseline Period

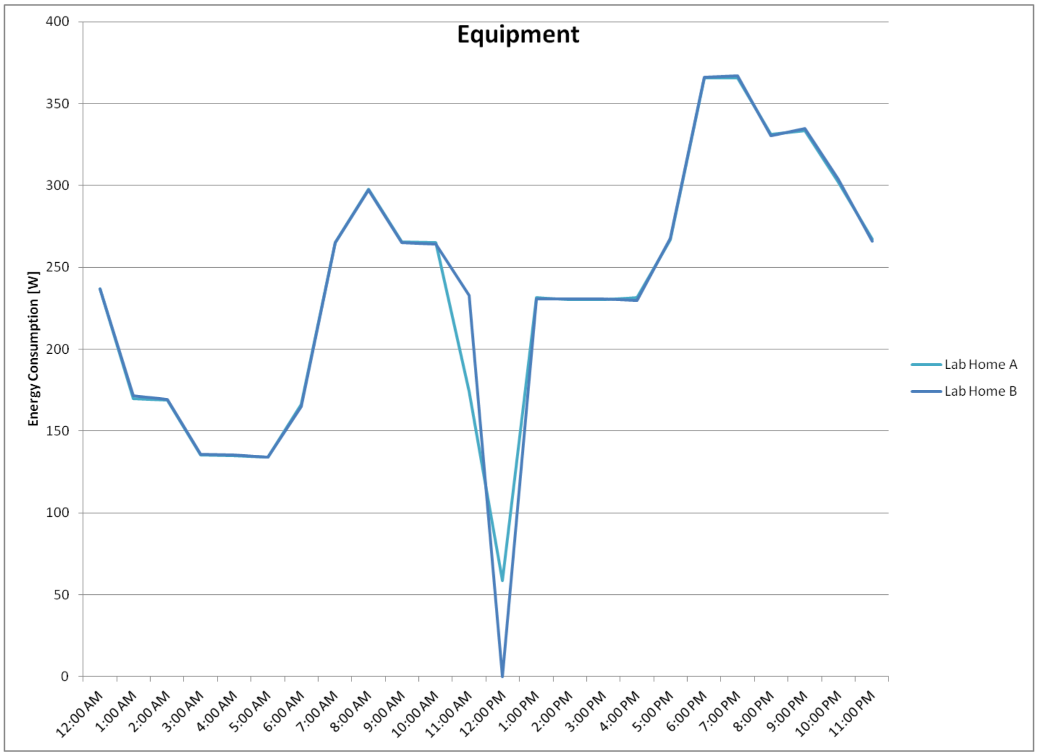

Figure A.3. Hourly Average Energy Consumption (W) Associated with Equipment Loads for an Example Day during the Baseline Period

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