

CONTROL OF AGGREGATE ELECTRIC WATER HEATERS FOR LOAD
SHIFTING AND BALANCING INTERMITTENT RENEWABLE ENERGY
GENERATION IN A SMART GRID ENVIRONMENT

by

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A thesis submitted in partial fulfillment
of the requirements for the degree

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in

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ABSTRACT

The majority of electrical energy in the United States is produced by fossil fuels, which release harmful greenhouse gas emissions and are non-renewable resources. The U.S. Department of Energy has established goals for a smart electric power grid, which facilitates the incorporation of clean, renewable generation sources, such as wind. A major challenge in incorporating renewable energy sources onto the power grid is balancing their intermittent and often unpredictable nature. In addition, wind generation is typically higher at night, when consumer demand is low.

Residential electric water heaters (EWHs), which currently account for 20% of the U.S. residential daily energy demand, are the largest contributors to the morning and evening peaks in residential power demand. The simulations in this thesis tested the hypothesis that controlling the thermostat setpoints of EWHs can shift EWH electrical energy demand from hours of higher demand to hours of lower demand, provide a large percentage of the balancing reserves necessary to integrate wind energy generation onto the electric power grid, and economically benefit the customer, while maintaining safe water temperatures and without significantly increasing average daily power demand or maximum power demand of the EWHs.

In the experimental simulation, during on-peak hours for demand, when electricity prices are high, the thermostat setpoints of EWHs were set to the minimum, in order to consume minimal energy. The result was that the vast majority of EWH demand occurred during off-peak hours, a significant improvement over the base case (normal operation in which no setpoint control was implemented). During off-peak hours, the thermostat setpoints of EWHs were controlled by the utility in order to provide balancing reserves necessary to maintain power system stability when wind generation is included in the system. The EWHs were able to provide the balancing reserves desired by the utility a majority of the time. In this combined control method, the customer benefitted financially by saving in electrical energy costs when compared to the base case, the EWH water temperatures always remained within safe limits. There was only a small increase in the total energy consumption, but the peak power demand did not change.

INTRODUCTION, BACKGROUND, AND MOTIVATION

Overview

The first portion of the introduction will introduce the present sources of electrical energy generation in the U.S., and their advantages and disadvantages. The following section will present the concept of an electrical power grid, called “smart grid”, which endeavors to alleviate the disadvantages of the modern generation sources and use patterns of electrical energy, by increasing the penetration of renewable generation sources and shifting consumer energy demand from hours of higher demand to hours of lower demand. Integral to the smart grid is a concept called “demand response”, in which consumer appliances may participate by allowing their electrical energy use to be increased or decreased at any given time. Demand response, and its various methods, will be presented in order to justify the significance of the research presented in this thesis.

Electrical Energy Generation in the U.S.

In 2009, the total electrical energy demand in the U.S. was 3,575 billion kWh, and 88% of the electrical energy was generated by three sources – coal, natural gas, and nuclear [1]. Figure 1 shows the proportion of electrical energy generation by fuel source in 2009.

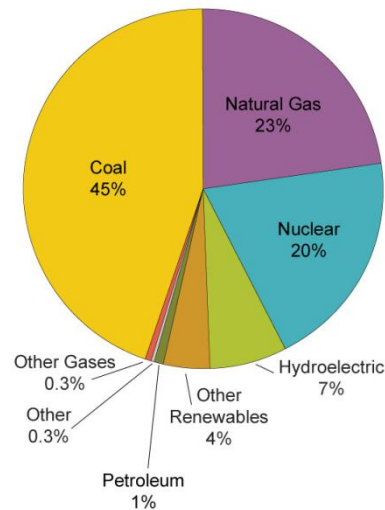


Fig. 1: U.S. Electric Power Industry Net Generation by Fuel, 2009 [2].

Base load plants are typically nuclear or coal, although in the Pacific Northwest region of the U.S., hydroelectric generation may also be used for the base load. The base load is the minimum amount of power that consumers will demand. In 2009, fossil fuel combustion in the U.S. produced 5,377.3 teragrams of carbon dioxide, 8.1 teragrams of methane, and 36.7 teragrams of nitrous oxide [3]. The greenhouse effect of these emissions will be discussed in a later section.

Coal

Coal is a non-renewable resource that takes millions of years to form. Dead plant matter is compressed by the layers of water, rock, and dirt that accumulate on top. This extreme pressure, as well as the earth's heat, slowly causes the dead plant matter to turn into coal [4]. Coal is extracted from the earth through mining operations. In 2009, coal mining operations produced 71.0 teragrams of methane emissions.

Energy from coal is extracted through the process of combustion. Burning coal causes energy to be released in the form of heat. This thermal energy heats steam, which creates pressure and turns a turbine, therefore converting to mechanical energy. The turbine operates an electrical generator, finally converting the energy to electrical energy which can be transmitted and distributed on the power system. Coal combustion is the largest source of energy in the United States. In 2009, coal accounted for 45% of the nation's electrical energy. In 2009, carbon dioxide emissions from coal totaled 1.841×10^9 metric tons.

Natural Gas

Natural gas is rich in methane. It is formed over the same time frame and under similar conditions as coal. Unlike coal, natural gas exists in small, odorless bubbles, trapped in the earth. Natural gas is the second largest source of electrical energy in the United States. In 2009, it provided 23% of the nation's electricity. Natural gas generation plants function in the same way as coal plants – using combustion to obtain electrical energy. In 2009, carbon dioxide emissions from natural gas totaled 1.2009×10^9 metric tons.

Nuclear

In 2009, nuclear generation plants provided 20% of the electrical energy in the U.S., making it the third largest source. Nuclear fission (the splitting of a uranium atom in two) releases thermal energy, which heats water into steam, and powers a turbine generator, much like in fossil fuel powered plants. Unlike fossil fuel generation, nuclear

generation produces minimal amounts of harmful greenhouse gas emissions. However, the byproduct of nuclear generation is highly radioactive unspent fuel, of which 2,000 metric tons are produced every year, which must be securely stored and constantly monitored [6]. Nuclear radiation can be extremely harmful to humans and the natural environment. In 1986, a meltdown occurred at a nuclear plant in Chernobyl, Soviet Union, releasing 50 tons of radioactive material, and causing many people to die from cancer or other radiation-caused illnesses. In 2011, an earthquake near Japan's Fukushima-Daiichi nuclear plant caused a tsunami, which damaged the plant and caused harmful radiation to leak into the environment.

Hydroelectric

Hydroelectric generation plants use the kinetic energy of moving water to turn the blades of a turbine, and produce electrical energy. In 2009, hydroelectric generation supplied 7% of the electrical energy in the U.S. Unlike fossil fuel combustion, hydroelectric energy generation does not produce large levels of greenhouse gas emissions. Hydroelectric is a renewable energy source, unlike fossil fuels and nuclear generation. The building of dams on rivers to produce hydroelectric energy result in flooding of low-lying areas, and disruption of natural flow cycles that change with the seasons, and block the flow of sediment which would normally prevent erosion of estuaries and beaches downstream.

Petroleum

Petroleum generation plants function in the same way as natural gas and coal power producing plants. In 2009, petroleum accounted for 1% of the electrical energy generation in the U.S., and emissions from petroleum totaled 2,166.7 teragrams.

Fossil Fuel Combustion Emissions and Anthropomorphic Global Warming

Burning fossil fuels, such as coal and natural gas, produce the greenhouse gases carbon dioxide, methane, and nitrous oxide [7]. Figure 2 shows the amounts of carbon dioxide generated by the different sources of electrical generation.

Carbon dioxide, methane, and nitrous oxide prevent solar radiation from exiting the earth's atmosphere, thus increasing the temperature of the atmosphere, surface, and ocean. Scientists in the International Panel on Climate Change estimate that there is a 90% chance that the majority of the global warming in the last 50 years is a result of human activities that produce greenhouse gas emissions. As human energy consumption continues to increase, greenhouse gas emissions will also increase, and therefore contribute to an increase in the earth's temperature. Figure 3 shows projections for the temperature of the earth, until the year 2100.

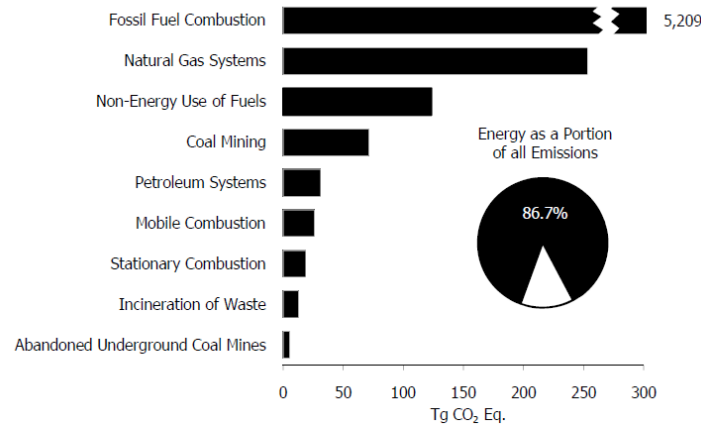


Fig. 2: 2009 Greenhouse Gas Emissions from Production of Electrical Energy in the U.S. [3].

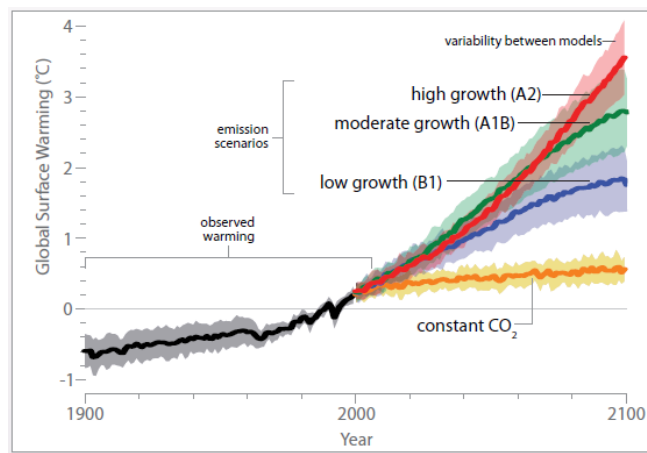


Fig. 3: Temperature Projections to the Year 2100, Based on Range of Emission Scenarios and Global Climate Models [8].

The impacts of global climate change are diverse. An increased temperature will increase health-related deaths, infectious diseases, and respiratory illnesses due to poor air quality. Agricultural effects of temperature increase include decreased crop yields, increased irrigation demand, and more difficult pest management. Changes in precipitation due to climate change will decrease the health and productivity of forests, and also change their composition in terms of biodiversity. Water quality and water supply will both decrease.

Rises in sea levels due to melting polar ice caps will result in erosion and inundation of land in coastal areas, and an increased cost to those who try to protect lands in these danger zones. Changes in temperature, precipitation, and rising sea levels will all impact wildlife, resulting in decreased biodiversity and shifts in species habitat ranges.

Wind Generation

Approximately 1% of U.S. electricity is generated by wind turbines [4]. The kinetic energy of moving air turns the turbine blades, converting it to mechanical energy, which drives an electric generator and thereby produces electrical energy. Wind generation, unlike coal, natural gas, and nuclear, is a scalable generation source, meaning that it can be used for virtually any application, as well as distributed throughout the electric power grid. Wind energy is typically produced on wind farms, of which the largest is Roscoe Wind Farm in Roscoe, Texas. It is rated at 781.5 MW, and comprises 627 wind turbines [9]. The largest wind turbine to date has a nameplate capacity of 7.5 MW [10], and there exist turbines small enough for virtually any application where wind is available.

Wind generation is an alternative to the non-renewable, greenhouse gas emitting fossil fuel sources such as coal, natural gas, and petroleum, and is free of the health and environmental risks and high cost associated with nuclear generation. Wind is a free and renewable resource. Costs associated with wind power generation are manufacturing wind turbines and transmission equipment, installing, and maintaining this equipment. Unlike fossil fuel combustion, wind generation does not produce carbon dioxide or other

harmful greenhouse gas emissions. In addition wind generation does not require the mining operations necessary to extract coal, natural gas, and petroleum.

It has been estimated that wind energy has the potential to supply more than 40 times the current worldwide electrical energy demand, and more than five times the global demand for all forms of energy [11]. In the contiguous U.S. alone, wind energy has the potential to supply 16 times the current energy demand. One disadvantage of wind generation is its intermittent nature. The generation of electrical power by the utility and the consumer demand for electrical power must remain in balance at all times. The current method is for the utility to provide the balancing reserves – spinning and non-spinning. Spinning reserves are power-generating reserves that the utility operator can ramp up in the case that demand exceeds generation, or ramp down in the case that generation exceeds demand. Non-spinning reserves are off-line generation capacity that the utility operator can dispatch and are able to provide the needed balancing reserves within five to 15 minutes [12]. Spinning reserves are typically provided by fossil fuels.

The intermittent nature of wind can create problems for power systems when wind penetration exceeds 20%. Beyond this percentage, the balancing reserves possessed by most utilities may not be able to accommodate the large fluctuations in wind power generation [13]. As wind penetration increases, the reliability of the power system can only be maintained by increasing the amount of available reserve [14], which is illustrated in Figure 4.

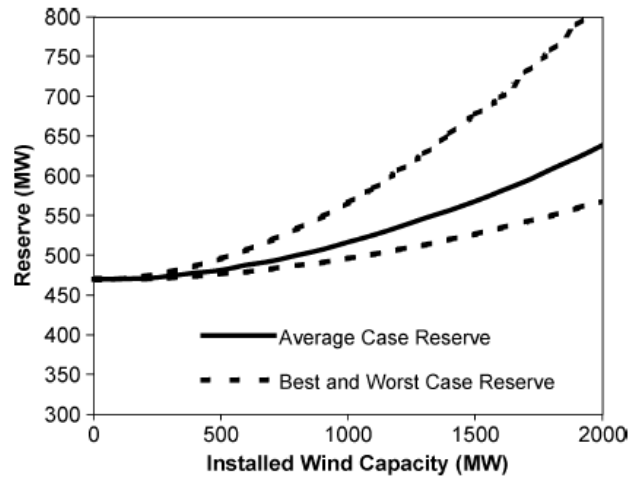


Fig. 4. System Reserve Level for the Average, Best- and Worst-Case Scenarios for a Forecast Horizon of 3 Hours Versus Installed Wind Capacity for a Reliability Criterion of Three Load Shedding Incidents per Year [14].

Another disadvantage of wind generation is that it is non-dispatchable, meaning that generation cannot be turned up at the request of utility operators. Power generation plants that run on fossil fuels such as coal and natural gas can be adjusted so that their output matches demand. Their output may be turned up or down at any time by the plant operator. Wind power generation is not adjustable in this manner – power is only available for use when the wind is blowing. Figure 5 shows an average daily wind profile.

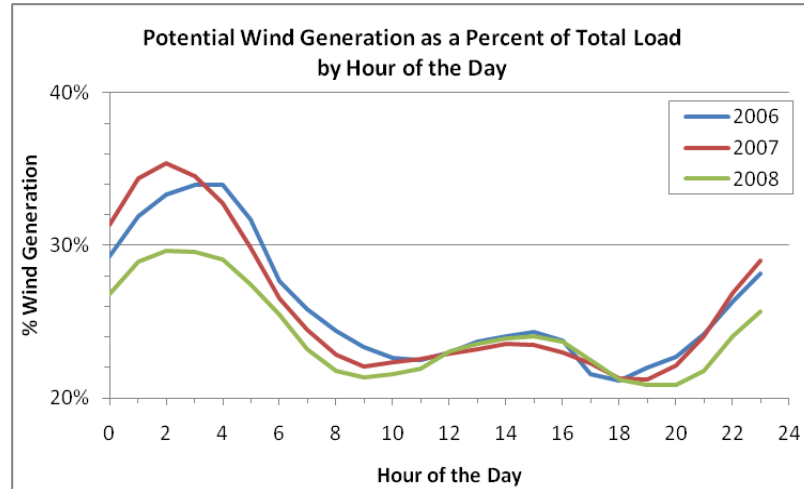


Fig. 5: Average Daily Wind Data Over a Three-Year Period for a Midwest Utility [15].

Potential wind generation is highest at night, during off-peak hours for demand.

Unneeded energy generated during this time may be wasted, or generation may be curtailed by turning some wind turbines off. Therefore, shifting demand from on-peak to off-peak hours would allow energy generated from wind to be used in place of other sources.

Smart Grid

The U.S. Department of Energy identifies seven objectives of the future electric power system, called the smart grid [16]. These objectives are:

1. Enabling informed participation by customers
2. Accommodating all generation and storage options
3. Enabling new products, services, and markets
4. Providing the power quality for the range of needs in the 21st century economy

5. Optimizing asset utilization and operating efficiently
6. Addressing disturbances through automated prevention, containment, and restoration
7. Operating resiliently against all hazards.

The experiments in this thesis focus on Objectives 1 and 2. Objective 2 includes the incorporation of wind generation on the electric power grid, in order to replace polluting, non-renewable fossil fuel-based generation. It is necessary to account for the intermittency of wind generation with balancing reserves, and it is also necessary to have the ability to store the wind energy generated during off-peak demand hours, when wind generation is typically higher. One possible way to accomplish these tasks is through demand response. Instead of changing the amount of generation, the utility can send control signals to consumer devices, indicating whether the devices' power demand should be increased or decreased.

Electric water heaters (EWHs) are good candidates for demand response. There also exist other methods, which will be introduced in "Demand Response Research – State of the Art". Thermostat setpoint control of residential electric water heaters (EWHs) is one method of demand response. EWHs are used in residences to heat water for showers, baths, dishwashing, clothes washing, and cleaning.

In 2008, of the four economic sectors in the United States, industry used 31% of the total energy used; next was transportation at 28%, then residential at 22%, and commercial at 19% [17]. EWHs accounted for 20% of the electrical energy consumed by the average U.S. household in 2005, as illustrated in Figure 6 [18].

Figure 7 illustrates that the peak demand times for EWHs occur at nearly the same time as for residences, mainly because the residential demand shape is heavily influenced by EWH use. In addition, as evidenced by Figure 7, EWHs account for greater than 20% of the residential energy consumed during times of high demand. Therefore, if the peak demand of EWHs could be shifted from on-peak hours to off-peak hours, the total residential demand curve would also shift.

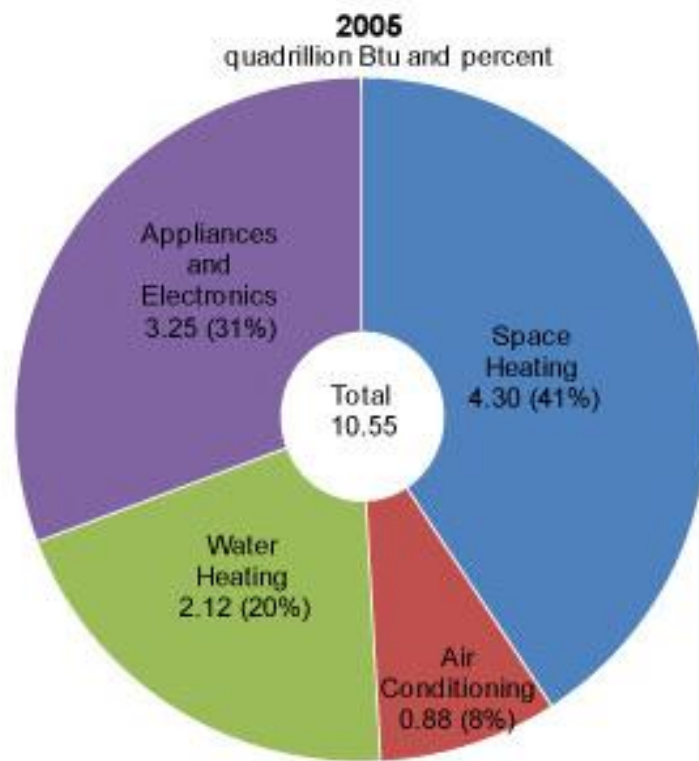


Figure 6: Total Energy Use in U.S. Homes.

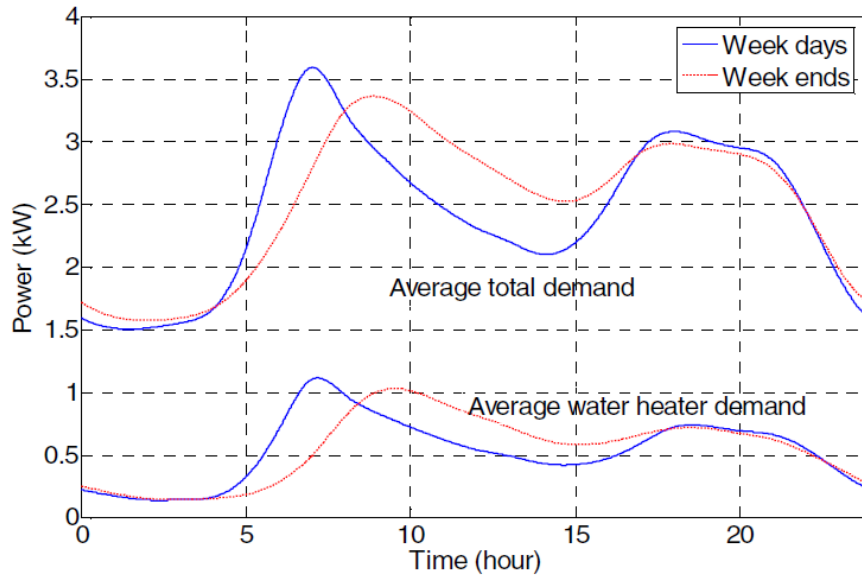


Fig. 7: Total Power Demand and EWH Power Demand of an Average U.S. House [19].

Peaks in power demand require the utility to compensate by generating power with peaking power plants. This dispatchable generation source is typically powered by fossil fuels, which are non-renewable and produce harmful greenhouse gases. EWHs have the potential to shift demand from on-peak to off-peak hours in order to flatten the demand profile and accommodate wind generation, and to provide the balancing reserves needed to account for the intermittency of wind generation.

Steffes Corporation analyzed the economic and environmental benefits of using EWHs for demand response [20]. When there is excess wind generation, the generation must either be curtailed, or maintained at the same level and the excess wasted.

Electric Water Heater Functionality

An electric water heater has a thermostat setpoint, and a deadband. The temperature of the water inside of the tank must be maintained within the range of the

thermostat setpoint minus the deadband. If the thermostat setpoint is 130°F and the deadband is 10°F, the water temperature must remain between 120°F and 130°F. If the temperature decreases to 120°F, the heating element turns on, in order to raise the temperature of the water. The heating element remains on until the water temperature reaches 130°F, at which time the heating element turns off. The water temperature is allowed to decrease until it reaches 120°F, at which point the heating element turns on again.

Figure 8 shows a typical residential electric water heater. Once hot water has been drawn from the tank, the tank refills with cool water. This cool water mixes with the hot water inside the tank, and causes the overall temperature of the water inside of the tank to decrease. The hot water inside the tank may decrease in temperature due to incoming cold water, and also due to conduction losses to the surrounding environment. An EWH tank has a certain amount of thermal insulation (R value), but this insulation is not 100% efficient.

There are several demand response methods by which the utility can control the thermostat setpoint control of EWHs, which will be explored in the following section. Objective 1 for the DOE's smart grid, enabling informed participation by customers, implies that in addition to allowing utility-based control of devices, the customer must also be allowed the choice of how and when to respond to control signals from the utility. The Power System Engineering Research Center (PSERC.org) states that it is necessary to have two-way communication between the customer and the utility, and for

customers to be able to respond to utility signals such as price, in order to incorporate renewable generation sources onto the electric power grid [22].

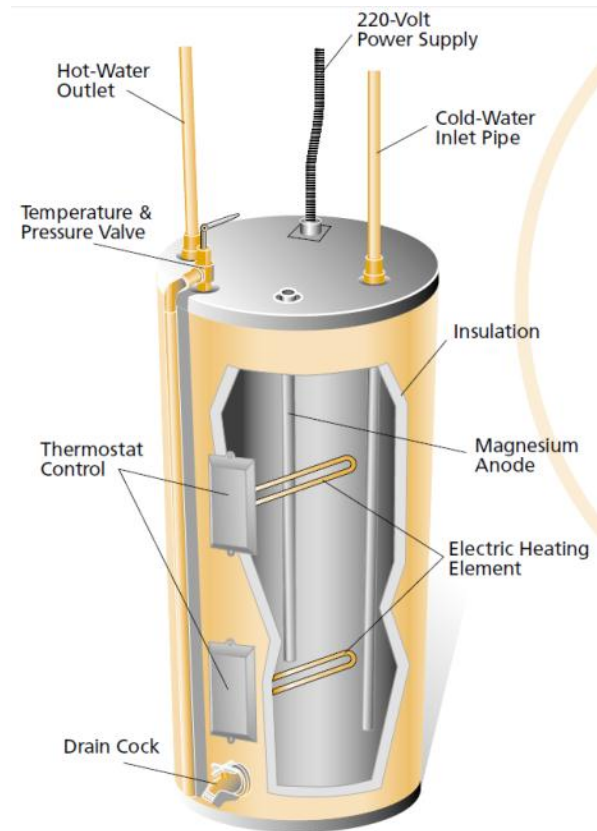


Fig. 8: Residential Electric Water Heater [21].

Demand Response Research – State of the Art

Before delving into the methods and results of demand response experiments, it is necessary to make the distinction between the various terminologies used in the different research experiments. Smart grid and demand response are relatively new technologies, and so many concepts relating to these technologies have myriad names or phrases with virtually the same meanings. Demand response is sometimes referred to as load control

or demand side management. The word demand is sometimes replaced with load, and response is sometimes replaced with management or control.

Within the demand response category is dynamic demand response (DDR). The term dynamic is sometimes replaced with real-time, both meaning that decisions are made as soon as new information becomes available. This method is used primarily for providing the reserves necessary to balance generation and demand. A different method of demand response is the adjustment or curtailment of loads based on prior knowledge of peak hours for demand and price. This method is used primarily for load shifting, sometimes with the added benefit of economic advantage for the consumer.

Load Shifting Using Fuzzy Logic Control of Applied Voltage to EWHs

Fuzzy logic based demand side management of residential EWHs was used to shift EWH power demand from on-peak hours to off-peak hours [23]. The power demand of an EWH is directly proportional to the square of the heating element voltage. Therefore, the power consumption of an EWH can be controlled by controlling the applied voltage. The power demand was controlled by adjusting the voltage of each EWH's 4.5 kW heating element, assuming that the voltage could be set to any level in the continuum between fully on and fully off.

The EWHs were distributed into four different groups for the purpose of control. Fuzzy logic was employed to select the voltage level applied to each group of EWHs. The four inputs to the fuzzy logic decision-making controller were the water temperature of the EWH, the maximum and minimum temperature specified by the customer, and the

power demand of the distribution system. It was generally desired to apply lower voltages during on-peak hours for demand, and higher voltages during off-peak hours. The voltages of all EWHs were controlled at all times, so that the peak power demand of each group of EWHs was shifted to a different time during the off-peak hours for demand. This resulted in successful time distribution of EWH power demand throughout the day, and leveling of the demand curve for the distribution system.

Load Shifting Using Voltage Control of Residential EWHs During On-Peak Hours

Previous studies have shown that the total power consumed by residential EWHs during on-peak hours can be reduced by controlling the voltage applied to the EWH heating elements [24]. Using a model with 1000 EWHs, voltages of 0.95, 1, and 1.05 per unit (PU) were applied to the EWH heating elements. Each EWH had a setpoint of 130°F and deadband of 10°F. The hot water demand of all EWHs had a mean of that of an average EWH on a typical weekday and a standard deviation of 1.17 gallons/hr. The tank volumes were randomized with a mean of 40 gallons, standard deviation 6.27, and range approximately 20 to 65 gallons. The thermal resistance of the tank, initial ON/OFF state, and initial water temperature inside of the tank all had a random uniform distribution. The temperature of the cold water entering the tank, temperature of the ambient environment, thermostat setpoint, deadband, and heating element power all remained constant for the duration of the simulation.

Figure 9 shows the results of applying different voltages to the EWH heating elements during peak hours. The hours between 7 and 11 represent the morning peak. Using the purple curve at 1.00 PU as a baseline for comparison, the voltage of 0.95 PU

successfully reduced the peak power consumed, and also shifted some demand to off-peak hours.

In this experiment, reducing the voltage applied to EWH heating elements provided both load shifting and peak shaving. The daily total energy demand was not significantly changed, and the temperatures of all EWHs remained within the deadband, thereby maintaining customer comfort.

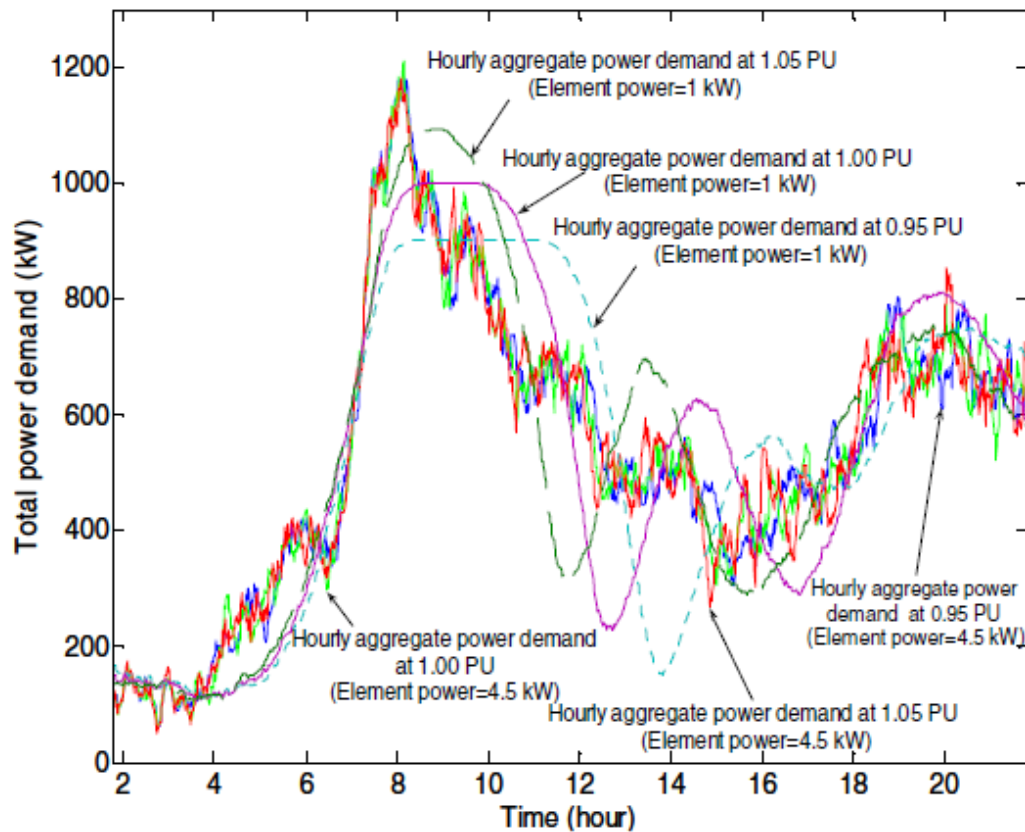


Fig. 9: Total Power demand of 1000 EWHs at Different Voltages [24].

Methods of Using Thermostatically Controlled Appliances for Load Shifting and Peak Shaving

Thermostatically controlled appliances (TCAs) are 85% the total GFA-compatible load on the US power system [25]. TCAs include heating, ventilation, and air

conditioning (HVAC) systems, refrigerators, and EWHs. Two different methods of controlling the power consumption of TCAs were explored in this study – curtailment and setpoint control.

In the curtailment method, EWHs were turned off during on-peak hours. At the end of the on-peak period, when the EWH loads were switched back on, there was a surge in the power consumed. In the setpoint control method, the setpoints of EWHs were reduced during on-peak hours. The setpoints were then raised during off-peak hours in order to pre-heat the water, so that the EWHs would not turn on during off-peak periods. In this case, the power consumed by the EWHs experienced an even larger spike than the curtailment method, which would stress distribution feeders.

In order to reduce the magnitude of the spike in power, two methods were evaluated. The first, randomizing the turn-on times of the EWHs, would require an extra communication instrument between the EWH and the controller, at a relatively high cost. The second method, incrementally increasing the setpoint temperature, would require a timer to be installed on each thermostat, at a relatively low cost. This method was simulated, and the power surge was successfully reduced to a level safe for the grid to handle. Figure 10 shows the EWH power consumption.

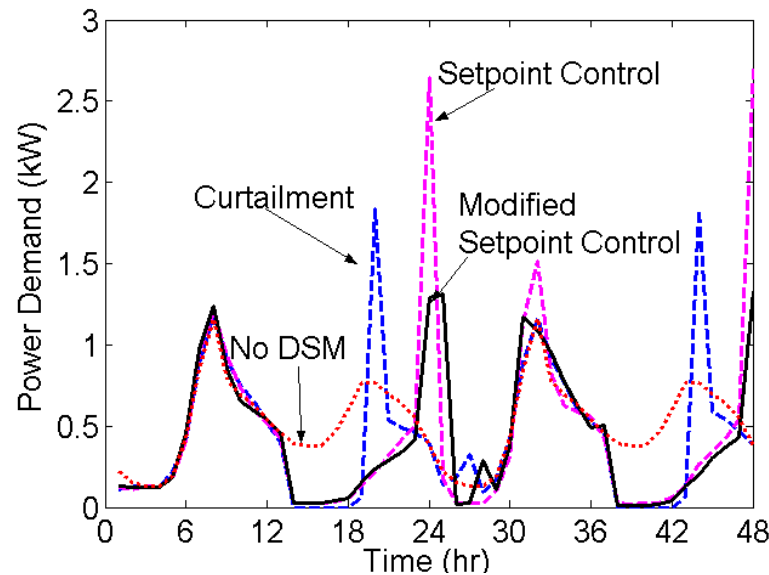


Fig. 10: Different Control Strategies for Residential EWHs [25].

The modified setpoint control shifts load from on-peak to off-peak times, and has the lowest peak power demand of the three control cases. Additionally, the modified setpoint control strategy was also the most economically advantageous to the customer, under the time-of-use pricing scheme employed.

Load Shifting Using Curtailment, No Control, and Setpoint Control for HVAC Systems

A Pacific Northwest National Laboratory (PNNL) study involving another type of thermostatically controlled device, the residential HVAC system, compared the load-shifting results of three different load control strategies – curtailment, no control, and setpoint control [26]. The simulation was run for a summer day, in which the average peak power demand hours for a residential HVAC system are 1pm to 7pm.

In the curtailment case, resulted in the greatest reduction in power demand during the target time interval, but the temperature was out of control during that time and

approached the outdoor air temperature. The no-control case resulted in minimal power reduction, only during the last two hours of the peak demand period. The setpoint control strategy resulted in much lower power demand than the no-control strategy, and higher power demand than the curtailment strategy. However, the customer comfort level was maintained throughout the day, and so the setpoint control strategy was chosen as most effective.

Adjusting Grid-Friendly Appliance ON/OFF States for Under-Frequency Control

Because frequency deviation from the normal operating frequency of 60 Hz is an indicator of an imbalance between generation and demand, adjusting the demand based on frequency can provide balancing reserves for the utility [27]. Grid-friendly appliances (GFAs) have the ability to change their power demand based on a control signal by the utility or an internal controller, in order to benefit the power grid. This study explored the use of GFAs for reduction of demand in the cases of under-frequency events on the electric power grid, indicating that demand exceeds generation.

This study aggregated 1000 GFAs into a model. Each GFA was assigned a unique frequency threshold below 60 Hz which would trigger the GFA to turn off, and thus stop consuming power. These trigger frequencies were randomly distributed, so that not all GFAs would turn off at the same time. Each GFA was also randomly assigned a unique frequency threshold, between its trigger frequency and 60 Hz, at which it would be released into the on state. The release threshold was higher than the trigger threshold, to ensure safe recovery of frequency. After each under-frequency event was successfully

corrected, GFAs were assigned new trigger and release thresholds, to ensure that the same devices were not always turning off first.

The response of GFAs to different types of under-frequency events was tested, using turn-on time delays of 2 seconds, 10 seconds, and 50 seconds. It was found that all methods were successful at alleviating frequency problems within 0.05 Hz of the desired frequency. However, problems were encountered when the frequency experienced large oscillations. In those cases, the 50-second turn-on time responded the best, because the GFAs did not all turn back on before the next under-frequency event occurred. With a greater range of randomization times for the GFAs, the under-frequency control was more successful.

Frequency Control Using Refrigerators for Dynamic Demand Control

In a simulation environment, a large number of refrigerator loads were aggregated, and connected to a traditional power system in place of spinning reserve [28]. These refrigerators were equipped with the ability to turn off when frequency decreased, and remained off until a maximum safe temperature limit was reached. When the frequency deviated from 60 Hz, the rate of frequency change was decreased significantly by the refrigerator loads as compared to the case in which traditional spinning reserve was used, as was the need for dispatchable generation sources to correct for frequency imbalance. When wind generation was added to the system, the amount of traditional spinning reserve needed to correct for frequency deviations was reduced by 50% due to the reserve supplied by the frequency-responsive refrigerators.

Use of Dual-Fluid Energy Storage of Intermittent Solar Energy

This study explored the use of a dual fluid energy storage (DFES) system to balance the intermittency of solar energy generation [29]. Solar, like wind, can have large fluctuations in generation. These fluctuations require the use of balancing reserves in order for solar generation units to be incorporated onto the electric power system. DFES is proposed, as an alternative to conventional fossil fuel-based balancing reserves. In the DFES method, two fluids are used. A compressible fluid, air, is used to store energy. The solar energy drives a pump, which compresses the air in an enclosed chamber.

When energy is needed on the power grid, the stored energy in the compressed air is used to push the incompressible fluid, water, through a hydroelectric turbine, thereby generating electrical energy. Simulations showed that this method was successful creating demand to balance high solar energy generation. However, the process of extracting the energy was highly inefficient at higher power levels, at which much of the energy would be lost. The DFES system was most efficient at extracting energy at slower rates, and thus would be a useful supplement to traditional balancing reserve methods, but not a suitable replacement.

Use of Residential Smart Appliances for Peak-Load Shifting and Spinning Reserves

A PNNL report analyzed the costs and benefits of using residential smart appliances for demand response, from the perspective of the utility [30]. The smart

appliances studied were refrigerators, freezers, clothes washers, clothes dryers, room air-conditioners, and dishwashers. The report defined savings as a reduction in the cost of producing electrical power due to two actions – load shifting from on-peak to off-peak hours, and curtailment as a means of providing spinning reserves. The cost was the credit that the utility would return to the customers, in order to compensate for an increase in power consumption with these smart appliances providing load shifting and spinning reserves.

The study found that using smart appliances for load shifting and spinning reserves would result in savings to the utility, even when crediting customers back for the extra power consumed by the appliances when providing these services. This would eventually translate to customer savings as well, when the utility sets their new rates. The study also found that the majority of savings were caused by using smart appliances to provide spinning reserves. Although this proved the viability of using smart appliances for demand response to benefit both the utility and the consumer, EWHs were not among those analyzed.

Customer Participation in Demand Response Programs

A study of seven utilities which employ demand response programs in the U.S. and Canada found a high correlation between providing economic incentive to customers and customer participation [31]. Utilities achieved between 6.5% and 23% reduction in energy use during on-peak hours, and customer satisfaction in the demand response programs averaged 82%. When demand was reduced or curtailed, customers did not notice changes in comfort level due to demand response.

The Pacific Northwest GridWise Testbed Demonstration Projects by PNNL also found high levels of customer satisfaction with demand response programs, and customers did not notice interruptions in the operation of their frequency-responsive devices [32]. When pricing signals were employed in the project, customers adjusted thermostat setpoints to lower settings when the price for electricity was higher, which provided economic benefit to the customer and helped to flatten the system's daily load profile.

Willingness to Pay More for Renewable Resources

The National Renewable Energy Laboratory (NREL) compiled market research data from multiple utilities from across the USA, and found that customers have favorable attitudes toward renewable resources, and many are willing to pay more for electricity generated by renewable sources [33]. More than 75% of study participants were willing to pay at least 5% more in order to obtain all their electricity from renewable sources, and 33% of participants would be willing to pay 25% more for this service.

Areas in Need of Further Research

This section will analyze the opportunities for future research in the demand response field, based upon the research in [23]-[32], which was presented above. The model aggregating a large number of refrigerators responded to the desired balancing reserve signal created when wind energy was integrated onto the system, but did not include load shifting or pricing for consumer economic benefit. A few models explored load shifting and price signal response together, but only involved a single EWH or HVAC system; not high numbers of aggregated devices. In the dynamic demand

response under-frequency balancing study with 1000 GFAs, the experiments lasted a maximum of 3.5 minutes, and therefore the long-term effects of providing balancing reserves could not be seen, and economic benefit was not accounted for.

The longest simulations were two days long, and involved load reduction based on prior knowledge of on-peak demand hours, but no dynamic response to desired balancing reserve signal from the utility. The experiment involving dynamic demand response to the desired balancing reserves created by the utility and also analyzed customer benefit had only 200 EWHs. The signal for desired balancing reserves was update on a relatively large time frame – every 10 minutes – although the utility from which the data was taken also deploys desired balancing reserves as often as every 30 seconds.

Experiments which included cost analysis were from the utility perspective only. An important component of smart grid is customer participation, which is not possible without economic benefit. Therefore, experiments are needed which compare the economic benefit to the customer when participating in demand response, compared to non-participation.

There is a need for dynamic demand response simulations involving large numbers of grid-friendly devices, which respond to both time-of-use pricing for load shifting and short sampling period desired balancing reserve signals from a utility for balancing renewable generation, and are analyzed for performance in those areas as well as on the basis of economic benefit to the customer. The simulations in this thesis attempted to fill this gap in research. The goal was to control the thermostat setpoints of

1000 aggregated EWHs. EWHs responded to a time-of-use pricing signal during on-peak hours, in order to shift consumer electrical energy demand from on-peak to off-peak hours. During off-peak hours, EWHs responded to a 30-second desired balancing reserve signal which includes wind generation. This model was compared to a no-control case, as well as each of the two control strategies alone, with additional goals of economically benefitting the customer, while maintaining safe water temperatures and without significantly increasing average power demand or peak power demand.

ELECTRIC WATER HEATER MODEL DEVELOPMENT AND EXPERIMENT METHODS

The Individual Electric Water Heater Model

If an EWH is in the ON state, it consumes 4.5 kW of power, and consumes no power in the OFF state. The temperature of hot water in the EWH tank can be obtained as a function of time by Equation 1 [34].

$$T_h(t) = T_h(\tau)e^{-\left(\frac{1}{R'C}\right)(t-\tau)} + \{GR'T_{out} + BR'T_{in} + QR'\}[1 - e^{-\left(\frac{1}{R'C}\right)(t-\tau)}] \text{ [Eq. 1]}$$

In this equation, the following variables represent:

τ : initial time (hours);

T_{in} : incoming cold water temperature (°F);

T_{out} : ambient environment temperature (°F);

$T_h(t)$: the water temperature inside EWH at time t (°F);

Q : the electric energy input rate; $Q=3.4121*10^3*P$ (BTU/hour);

P : heating element power (kW), 4.5 when the EWH is ON, zero when the EWH is OFF;

R : tank insulation thermal resistance (hour*ft²*°F/BTU);

SA : tank surface area (ft²);

Volume: the capacity of the tank (gallons); (note: a cylindrical-shaped tank is used with the ratio of cylinder height to its base radius=4, so SA is determined by volume, though it does not appear in (1));

G : ratio of surface area to thermal resistance; $G = \frac{SA}{R}$;

$F(t)$: hot water flow rate [gallons/hour];

$K(t)$: gallons/hour per kW; at the rated voltage of 1 PU, one kilowatt of electric power can heat at most K gallons of water from $T_{incoming\ cold\ water}$ to $T_{setpoint}$ in one hour; see equation below

$$B = 8.34 * F(t) * C_p;$$

8.34: density of water (lbs/gallon);

C_p : the specific heat of water (1.00 BTU/ISO/ (lbs*°F));

$$C = volume * 8.34 * C_p;$$

$$R' = \frac{1}{G + B};$$

The maximum temperature of water delivered to the consumer is 116°F. If the temperature of the water in the EWH tank is less than or equal to 116°F, it is considered safe for consumer use [35]. If the temperature of water inside of the EWH tank is less than or equal to 116°F, all of the hot water demanded by the consumer is supplied by the EWH tank. The value of the hot water flow rate, F , from the EWH tank is then equal to the consumer water demand rate at a given time, F_{demand} , defined below.

$$F_{demand}(t) = P_{avg}(t) * K \quad [\text{Eq. 2}]$$

$$F(t) = F_{demand}(t) \quad [\text{Eq. 3}]$$

$P_{avg}(t)$: average residential EWH power demand (kW)

K : gallons/hour per kW

Each EWH has a maximum hot water flow rate at rated voltage, for a specific thermostat setpoint. This rated capacity is $F_{max,rated} = P_{heating\ element} * K$, and had units of gallons/hour. At the rated voltage of 1 PU, one kilowatt of electric power can

heat at most K gallons of water from T_{in} to $T_{setpoint}$ in one hour. The value of K , neglecting convection losses, is [34]:

$$K = \frac{1000 \frac{J}{s} * 3600 \frac{s}{hour}}{1.0545 * 10^3 \frac{J}{BTU_{ISO}} * 1.00 \frac{BTU_{ISO}}{^{\circ}F * lbs} * (T_{setpoint} - T_{in}) * 8.34 \frac{lbs}{gallon}} \quad [Eq. 4]$$

The setpoint temperature, $T_{setpoint}$, of each EWH is variable, and so the value of K also varies, as it is dependent upon the EWH setpoint. Table 1 shows different EWH capacities at different setpoints, and illustrates the relationship between setpoint and K .

Table 1: Electric Water Heater Capacity at Different Voltages and Different Thermostat Setpoints [24].

Temperature set-point ($^{\circ}F$)		130		125		120	
Voltage (PU)	Real Power (kW)	Constant K (Gallons/hour per kW)	Capacity F_{max} (Gallons/hour)	Constant K (Gallons/hour per kW)	Capacity F_{max} (Gallons/hour)	Constant K (Gallons/hour per kW)	Capacity F_{max} (Gallons/hour)
0.95	4.06		23.74		25.57		27.70
1.00	4.5	5.85	26.31	6.30	28.34	6.82	30.70
1.05	4.96		29.00		31.23		33.84

Note: The constants are based on a common incoming cold water temperature of 60 $^{\circ}F$.

It may seem odd that the equation for hot water flow rate relies on the average residential power demand, which ranges from zero to about 1.5 kW, not the power demand of the EWH heating element, 4.5 kW. The average power demand is simply used to shape the water demand curve, so that water demand has the same peaks and valleys as power demand. Using the power demand profile of an average EWH on a typical weekday [19], and multiplying this power by the constant, K , the average EWH hot water demand curve is obtained. This is shown in Figure 11.

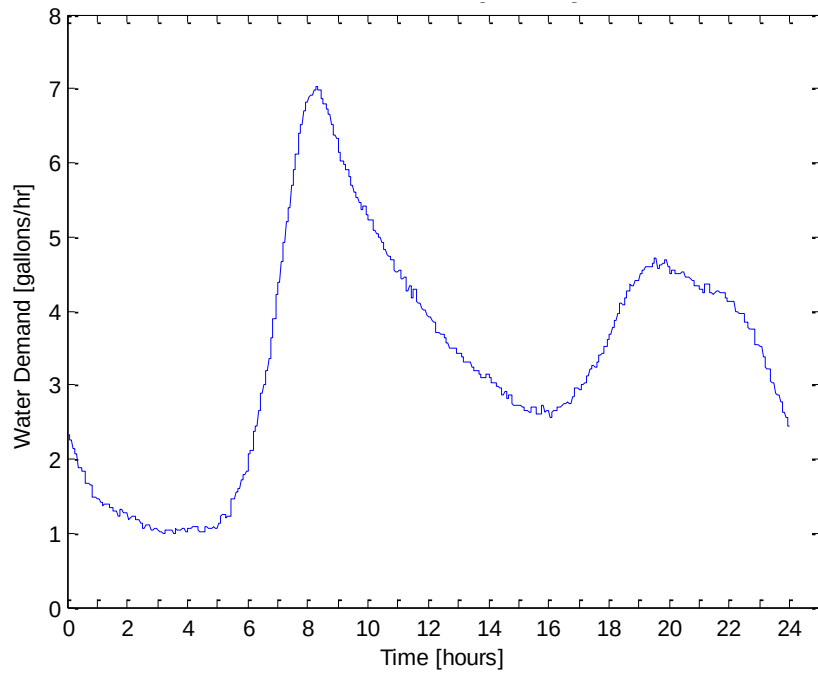


Figure 11: Water Demand of a Single, Average EWH [34].

For the average EWH shown in Figure 11, the minimum hot water flow rate (water demand) is 1 gallon/hour at approximately 4 AM, and the maximum hot water demand is 7 gallons/hour at approximately 8:30 AM.

In the original model used in [24], the EWH thermostat setpoints did not change, and so the temperature of the water in the EWH tank was always less than or equal to 130°F. The model used in these experiments differs in that the temperature of the water in the EWH tanks is now allowed to increase as high as 160°F, and decrease as low as 116°F. Severe scalding can occur at temperatures above 130°F. As water temperature increases, the time for scalding to occur decreases logarithmically, to 5 seconds for water at 140°F and just 0.5 seconds for water at 160°F [35]. If the present temperature of the water in the EWH tank is greater than 116°F, the water flowing out of the EWH is considered too hot for consumer use. Before reaching the consumer, the outflowing

water will be mixed with the appropriate amount of cool water from a thermostatic mixing valve (TMV), of temperature $T_{in} = 60^{\circ}\text{F}$, in order to ensure that the delivered water temperature is 116°F . In this case, not all of the water used by the consumer is supplied by the EWH tank. The hot water flow rate from the EWH tank is then determined as follows. For extra distinction between hot water from the EWH tank and cool water from the TMV, in the following equations, let F_{hot} represent the variable F , which was used in Equations 1 and 3.

$$F_{hot} + F_{cool} = F_{demand} \quad [\text{Eq. 5}]$$

F_{hot} : water flow rate in gallons/hour from the EWH tank

F_{cool} : water flow rate in gallons/hour from TMV, which has a temperature T_{in}

According to the Second Law of Thermodynamics, the two water sources, EWH tank hot water and TMV cool water, will mix into thermal equilibrium if the following equation is satisfied [36], where the heat lost by the hot water is equal to the heat gained by the cool water, and the net work done by the system is zero:

$$Q_{hot} = Q_{cool} \quad [\text{Eq. 6}]$$

Q_{hot} : heat lost by hot water from EWH tank

Q_{cool} : heat gained by cool water from TMV

Each heat variable is defined by the equations:

$$Q_{hot} = Cp * m_{hot} * \Delta T_{hot} \quad [\text{Eq. 7}]$$

$$Q_{cool} = Cp * m_{cool} * \Delta T_{cool} \quad [\text{Eq. 8}]$$

m_{hot} : mass of hot water

m_{cool} : mass of cool water

ΔT_{hot} : temperature decrease in hot water

ΔT_{cool} : temperature increase in cool water

The water temperature changes are equal to

$$\Delta T_{hot} = (T_h(t) - T_{mixed}) \quad [\text{Eq. 9}]$$

$$\Delta T_{cool} = (T_{mixed} - T_{in}) \quad [\text{Eq. 10}]$$

T_{mixed} : temperature of water after hot and cool water are mixed together; always equal to 116°F

The thermal equilibrium equation can be equivalently written as follows:

$$Cp * m_{hot} * (T_h(t) - T_{mixed}) = Cp * m_{cool} * (T_{mixed} - T_{in}) \quad [\text{Eq. 11}]$$

The specific heat of water, Cp, is assumed to be the same for both sides of the equation, because the specific heats only differ by 0.1% even in the most extreme case when the hot water temperature is 160°F [37], and therefore cancels. Instead of working with mass, it is more useful to work with flow rate, in gallons/hour.

$$F_{hot} = \frac{V_{hot}}{\Delta t} \quad [\text{Eq. 12}]$$

$$F_{cool} = \frac{V_{cool}}{\Delta t} \quad [\text{Eq. 13}]$$

V_{hot} : volume of hot water in gallons, needed from the EWH tank

V_{cool} : volume of water in gallons, needed from the TMV

Δt : time elapsed

The equations for volume of water relate to mass as follows

$$V_{hot} = \frac{m_{hot}}{\rho} \quad [\text{Eq. 14}]$$

$$V_{cool} = \frac{m_{cool}}{\rho} \quad [\text{Eq. 15}]$$

ρ : density of water

Solving for mass of water

$$m_{hot} = F_{hot} * \rho * \Delta t \quad [\text{Eq. 16}]$$

$$m_{cool} = F_{cool} * \rho * \Delta t \quad [\text{Eq. 17}]$$

Substituting into Equation 11

$$F_{hot} * \rho * \Delta t * (T_h(t) - T_{mixed}) = F_{cool} * \rho * \Delta t * (T_{mixed} - T_{in}) \quad [\text{Eq. 18}]$$

The same time elapses while both the hot and cool water are flowing, and so Δt cancels from both sides.

The density of water is only 2% lower at 160°F than at 60°F, the most extreme possible difference between hot and cool water sources that could possibly occur in this simulation environment [38]. This translates to an overall variation in hot water flow rate of just 0.6%, and is such a small difference that the density of water will be assumed as a constant, and cancels from both sides of the above equation.

Thus, the following thermal equilibrium equation is obtained

$$F_{hot} * (T_h(t) - T_{mixed}) = F_{cool} * (T_{mixed} - T_{in}) \quad [\text{Eq. 19}]$$

Solving Equations 5 and 19 for F_{cool} yields

$$F_{cool} = F_{demand} - F_{hot} \quad [\text{Eq. 20}]$$

$$F_{cool} = F_{hot} * \frac{(T_h(t) - T_{mixed})}{(T_{mixed} - T_{in})} \quad [\text{Eq. 21}]$$

Setting Equations 20 and 21 equal to each other, a new equation is achieved, in which the dependent variable is F_{hot}

$$F_{hot} * \frac{(T_h(t) - T_{mixed})}{(T_{mixed} - T_{in})} = F_{demand} - F_{hot} \quad [\text{Eq. 22}]$$

Solving for the hot water flow rate from the EWH tank, F_{hot} , yields

$$F = F_{demand} * \frac{T_{mixed} - T_{in}}{T_h(t) - T_{in}} \quad [\text{Eq. 23}]$$

Bear in mind that the hot water flow rate is time-dependent, as well as different for each individual EWH, because it depends on the EWH's present temperature.

Figure 12 shows the temperature characteristic of a single EWH, with initial temperature of 60°F, the incoming cold water temperature. The lower and upper thermostat setpoints are 120°F and 130°F respectively. A constant flow rate of 25 gallons/hour is assumed for this entire simulation, insulation thermal resistance of 15 [hour*ft²*°F/BTU] (the mean from the aggregate model), and tank volume of 50 gallons.

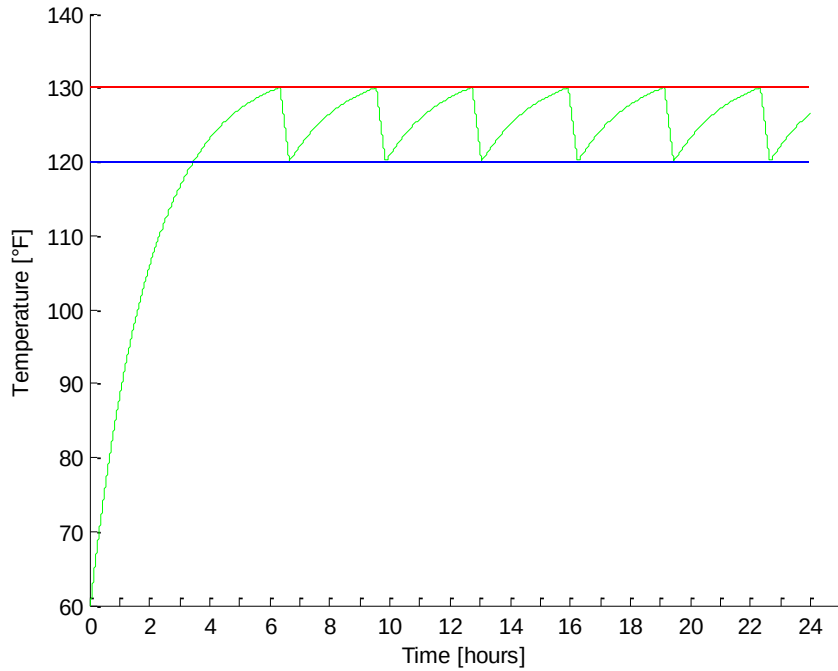


Fig. 12: EWH Temperature Characteristic, Tank Volume 50 Gallons.

Decreasing the tank volume causes the rate of heating to increase considerably. In Figure 12, the water took slightly longer than six hours to heat from 60°F to 130°F, with a 50-

gallon tank. With a 40-gallon tank, the water now heats from 60°F to 130°F in slightly less than five hours, as shown in Figure 13.

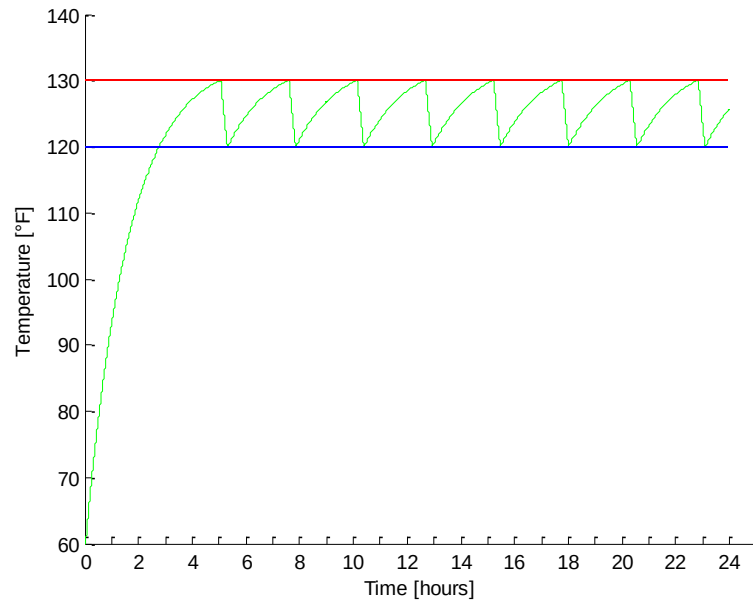


Fig. 13: EWH Temperature Characteristic, Tank Volume 40 Gallons.

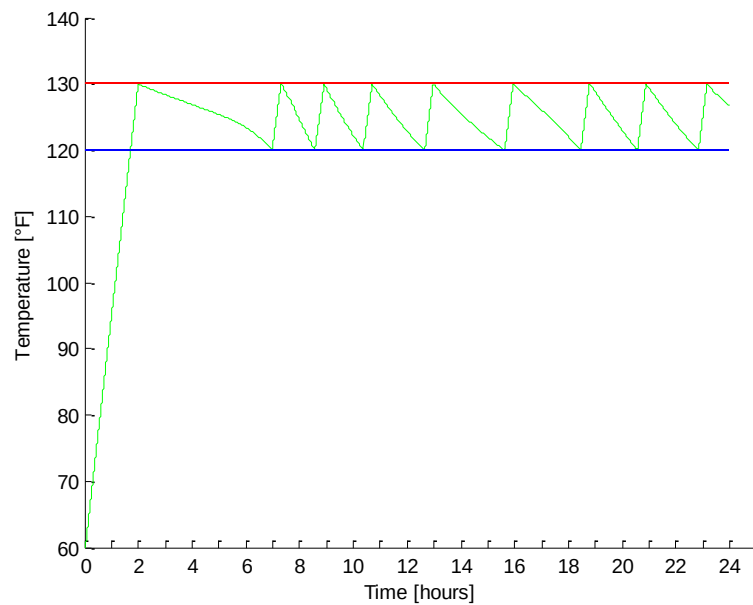


Fig. 14: EWH Temperature Characteristic, Using Average Water Demand Flow Rate.

In reality, the demand flow rate does not remain a constant 25 gallons/hour, but varies throughout the day. When the varying hot water demand is applied to the simulation, in place of 25 gallons/hour the realistic EWH temperature characteristic, shown in Figure 14, is obtained.

The Aggregate EWH Model

The aggregate EWH model comprises 1000 EWHs. Each EWH has slightly different parameters (such as tank volume and water demand), and therefore will respond slightly differently to thermostat setpoint control. The same matrix of values for F_{demand} was used for each experiment, meaning that EWH number 1 had the same F_{demand} curve for all experiments. The curve for EWH number 1 was different from the F_{demand} curve corresponding to EWH number 2, but EWH number 2 had the same F_{demand} demand curve in all experiments, and so on, for all 1000 EWHs in the aggregate model. The variable F_{demand} had a different value for each EWH at each 5-second period, and the average of all EWHs' F_{demand} values was the curve shown in Figure 11, above.

Distribution of Simulation Parameters

Tables 2, 3, and 4 show the different parameter values used in the simulation [34]. These parameters were based on data from actual EWHs whenever possible.

Table 2: Parameters Having a Random Normal Distribution for the 1000 EWH Population.

Parameter	Value
Tank volume (and tank surface area)	Mean 40 gallons, standard deviation 6.27, range approximately 20 to 65 gallons

Table 3: Parameters Having a Random Uniform Distribution for the 1000 EWH Population.

Parameter	Value
Thermal resistance of tank insulation, R	10 to 20 hour* $\text{ft}^2 \cdot ^\circ\text{F}/\text{BTU}$
Initial ON/OFF state	Approximately half ON, half OFF
Initial water temperature inside of the tank	120°F to 130°F

Table 4: Parameters that Remained Constant Throughout the Duration of the Simulation.

Parameter	Value
Temperature of cold water entering the tank, T_{in}	60°F
Temperature of the ambient environment, T_{out}	70°F
Thermostat setpoint, T_{setpoint}	130°F
Deadband, D	10°F
Heating element power in ON state, P	4.5 kW
Heating element power in OFF state, P	0 kW

The hot water demand of each EWH, randomly distributed about the average, is shown in Figure 15.

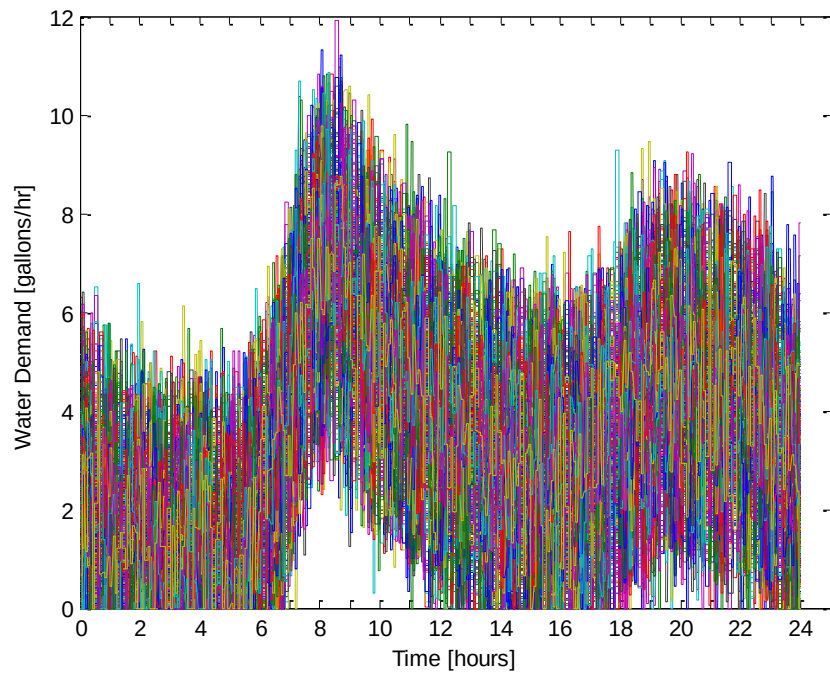


Fig. 15: Water Demand Rate of 1000 EWHs.

Figure 16 shows the temperature response of ten EWHs randomly selected from the model, with initial water temperature equal to that of the cold water entering the tank, 60°F. If all water in each tank were to have an initial temperature of 60°F, it would take approximately two hours for the water to reach the thermostat setpoint. After that, the EWH power consumption cycles between the ON and OFF state approximately 15 times in one day, in order to keep the temperature within the desired 10°F deadband.

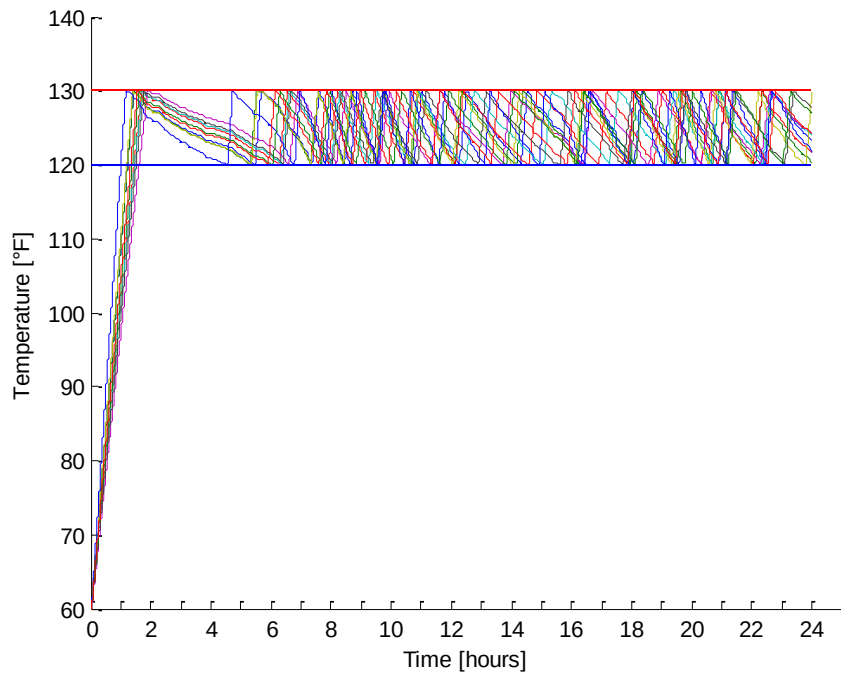


Fig. 16: EWH Temperature Characteristic of Ten Representative EWHs in 1000-EWH Model.

Notice that each EWH has a slightly different temperature characteristic. This is due to the fact that each EWH has a different demand flow rate, tank insulation thermal resistance, surface area, and temperature at each time. These differences are representative of the differences in EWHs used by residential consumers, based on aggregate model data in [24].

Verification of Aggregate Electric Water Heater Model with New Five-Second Sampling Period

The original model had a sampling period of 1 minute. The code was modified to have a sampling interval of 5 seconds, to facilitate easy comparison with results of new experiments. The simulation was run for two days, with all EWH thermostat setpoints held constant at 130°F, in order to verify that the program produces consistent results for each simulation day.

Figure 17 shows the water temperature of all EWHs in the model for the 2-day period. The water temperature is maintained within the desired deadband of 120°F to 130°F, and the temperatures always have a good diversity – not all increasing or decreasing at the same time, and distributed evenly throughout the entire deadband at all times. The temperature diversity will become increasingly important when balancing reserve desired by the utility and time-of-use pricing signals are employed in later experiments.

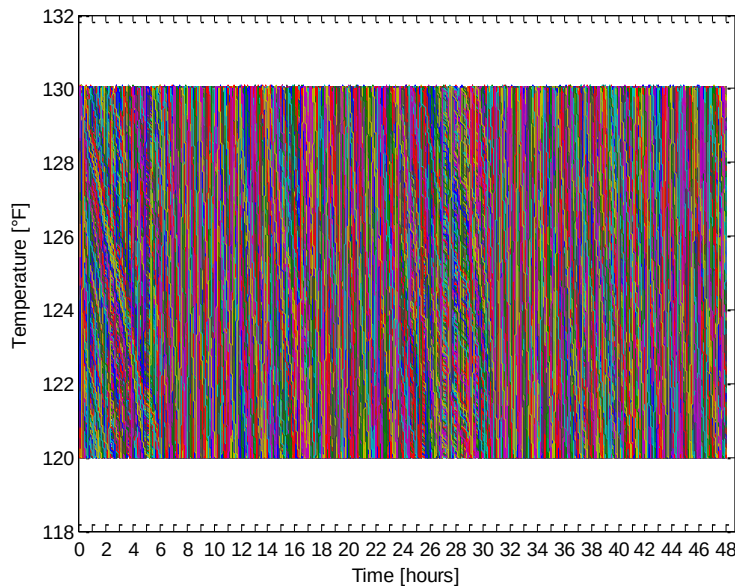


Fig. 17: Outgoing Water Temperature of Each EWH.

Power. The power consumed by a single EWH was calculated every 5 seconds, using the following equation:

$$P_{demand}(t) = P * onoff(t) \quad [\text{Eq. 24}]$$

$onoff(t)$: represents the ON/OFF state of the EWH; if the EWH is ON, then

$onoff(t) = 1$; if the EWH is OFF, then $onoff(t) = 0$

The total power consumed by all EWHs was also calculated for each period in the following fashion:

$$P_{demand,total}(t) = \sum_{all\ EWHs} P_{demand}(t) \quad [\text{Eq. 25}]$$

Figure 18 shows the power consumed by all EWHs in the model. Note that the power demand profile in this figure is the same shape as the water demand profile in Figure 18 above. When hot water is extracted from the EWH tank for consumer use, it is replaced with cool water. This incoming cool water must be heated by turning on the EWH heating element.

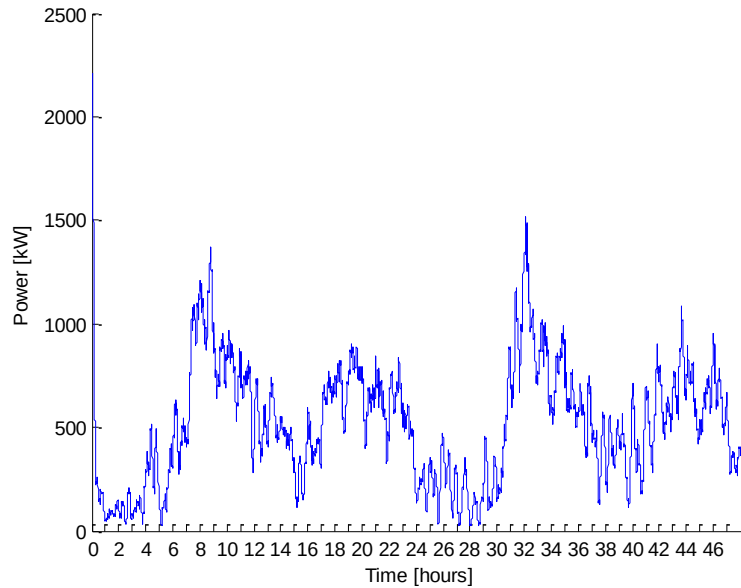


Fig. 18: Total Power Demand of 1000 EWHs.

Energy. The cumulative energy consumed by all EWHs in the model was computed each period, by finding the integral of the total power demand from the first period through the present period, with respect to time:

$$E_{demand,cumulative,total}(t) = \int_1^t P_{demand,total}(t)dt \quad [\text{Eq. 26}]$$

Figure 19 shows the total energy consumed by all 1000 EWHs in the model, for a 2-day period. Note that because power is the rate of energy consumption, when power demand is low, such as in the middle of the night, the cumulative energy increases more slowly. When power demand is high, such as around 8 AM, the cumulative energy increases more quickly.

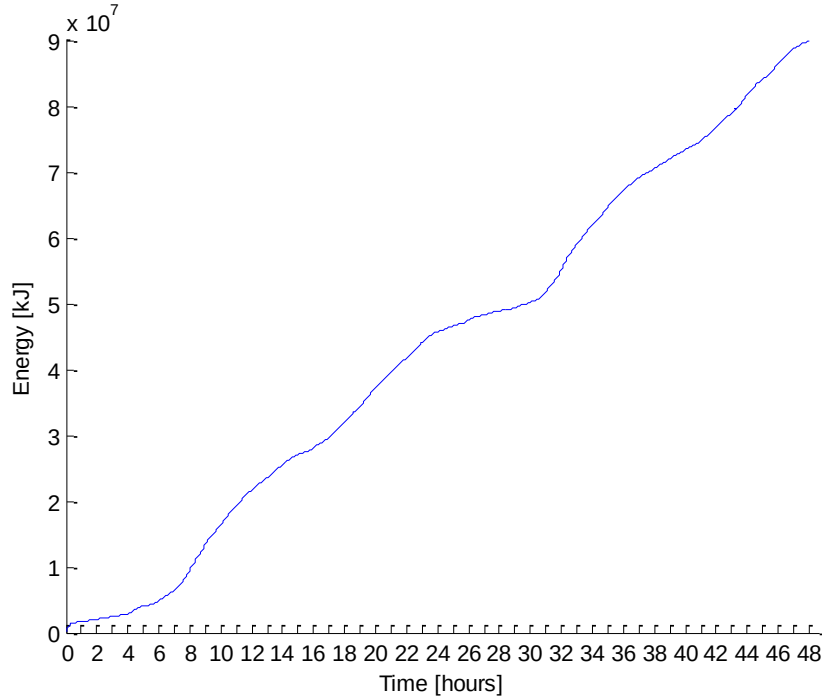


Fig. 19: Total Energy Demand of 1000 EWHs.

The results obtained here, for temperature, power, and energy, are consistent for each simulation day. The results are also consistent with those obtained in [24], thus verifying that the conversion to the new 5-second sampling period was performed correctly.

Difference Between ACE and Balancing Reserve Signals for Demand Response

A desired balancing reserve signal, also called an inc/dec signal, is generated by the utility every thirty seconds. This signal is essentially a representation of the mismatch between power generation and demand. When generation exceeds demand, there is a need for more demand or a decrease in reserve. This is a decrease, or “DEC” signal. Likewise, when demand exceeds generation, an increase in reserve is required. This is an increase, or “INC” signal.

The desired balancing reserve signal differs from the area control error (ACE) signal commonly used by utility companies. The desired balancing reserve signal only accounts for the instantaneous difference between the amount of power being generated by the utility, and the amount of power being consumed. The ACE signal depends on the difference between the scheduled and actual interchange, the difference between the desired and actual frequency of the grid, equipment error, and the area’s total inadvertent interchange accumulations during the last hour. The Western Electricity Coordinating Council calculates the ACE signal as follows [39]:

$$ACE = (NI_A - NI_S) - 10\beta (F_A - F_S) - T_{ob} + I_{ME} + \frac{\pi_{primary}^{on/off\ peak}}{(1-Y)*H} \quad [Eq. 27]$$

In the above expression:

ACE: Area Control Error in MW. Negative values denote a condition of undergeneration and positive values denote over-generation.

NI_A : net actual interchange in MW

NI_S : scheduled net interchange in MW

F_A : actual system frequency in Hz

F_S : scheduled system frequency in Hz, normally 60 Hz

T_{ob} : scheduled interchange in MW

I_{ME} : manually entered value (in MW) to compensate for known equipment error

$\frac{\Pi_{primary}^{on/off\ peak}}{(1-Y)*H}$: WECC automatic time error correction term

The desired balancing reserve signal was used for the experiments presented in this thesis due to its availability from BPA, although the EWH thermostat setpoint control algorithm could also be applied using the ACE signal in place of desired balancing reserve, depending on the preference of each individual utility.

EWH Thermostat Setpoint Control Based on Desired Balancing Reserve Signal

This section will introduce the concept of the Matlab algorithm, in which the thermostat setpoints of electric water heaters (EWHs) are adjusted in real time order to minimize mismatch between generation of power by the utility and consumer demand. The power generation includes wind generation.

There are 1000 EWHs in the model. Each EWH begins the simulation at a temperature randomly chosen between 120°F and 140°F. Each EWH is also assigned a random state at the simulation start – either ON or OFF – with even distribution, just as in the base case model. If an EWH is in the OFF state, it does not consume any power, and cools according to Equation 1 for $T_h(t)$ explained above.

Additionally, each EWH is assigned a random initial thermostat setpoint, between 120°F and 145°F. This setpoint determines the maximum and minimum temperatures that the EWH may reach. This range of temperatures that the EWH must maintain is called a deadband. Each EWH's setpoint may be adjusted by the utility at any time. In this program, each EWH must maintain a temperature within the deadband of 10°F. The size of this deadband is large enough so that the EWHs are not constantly switching ON and OFF. Changing the load less often makes the load more predictable to the utility operator, who also deploys the desired balancing reserve signal.

The lower limit of the deadband, called the lower temperature setpoint, is 10°F lower than the EWH thermostat setpoint. If an EWH's temperature becomes greater than the upper thermostat setpoint, the EWH turns OFF in order to cool and return to the deadband. If an EWH's temperature becomes less than the lower temperature setpoint, the EWH turns ON in order to heat and return to the deadband.

In this program, the desired balancing reserve, or inc/dec, is the number of kilowatts of reserve or demand that needs to be created, in order for generation to equal demand. This signal includes wind generation. The desired balancing reserve signal is a square wave, with a new desired balancing reserve every 30-seconds. A new set of

calculations is performed by the algorithm every five seconds. These calculations include comparing the desired balancing reserve to the balancing reserve created (called the needed balancing reserve, or inc/dec needed), and also includes calculating new thermostat setpoints for EWHs if the needed balancing reserve is nonzero. The goal is to achieve the desired amount of increase or decrease in demand by the end of the thirty-second period.

The amount of balancing reserve needed is calculated every 5-second period, by taking the difference between the balancing reserve desired, and the balancing reserve that has been created since the beginning of the 30-second interval. The balancing reserve created is calculated as follows:

$$P_{incdec\ created}(t) = -(P_{total\ EWH\ power}(t) - P_{total\ EWH\ power}\left(\left\lfloor \frac{t}{6} \right\rfloor * 6\right))$$

[Eq. 28]

$P_{incdec\ created}(t)$: balancing reserve that has been created since the beginning of the 30-second period

$P_{total\ EWH\ power}(t)$: total power consumed by all EWHs at the present 5-second period

$P_{total\ EWH\ power}\left(\left\lfloor \frac{t}{6} \right\rfloor * 6\right)$: total power consumed by all EWHs at the beginning of the 30-second period, when the desired balancing reserve signal was first deployed

The needed balancing reserve is calculated as follows:

$$P_{incdec\ needed}(t) = P_{incdec\ desired}(t) - P_{incdec\ created}(t) \quad [\text{Eq. 29}]$$

$P_{incdec\ needed}(t)$: Amount of balancing reserve that still needs to be created in order to meet the desired balancing reserve

$P_{incdec\ desired}(t)$: desired balancing reserve for the 30-second period

In order to calculate the number of EWHs that need to be turned ON or OFF, it is necessary to calculate how many EWHs are about to turn ON or OFF in the next 30-second period by reaching their upper thermostat setpoint or falling to their lower temperature setpoint. This is done by comparing each EWH in the ON state to its thermostat setpoint, and each EWH in the OFF state to its lower temperature setpoint. Each EWH has slightly different parameters, and the temperature change is dependent on demand flow rate, present temperature, surface area, and insulation thermal resistance, as per Equation 1. However, surface area and insulation thermal resistance are not necessarily known parameters to the utility. With each smart grid compatible EWH, there exists the possibility to test the amount of temperature change per 5-second period, at different water temperatures between 116°F and 160°F, in both the ON and OFF state. The utility can digitally store this data for each EWH. Temperature change in one 5-second period can be easily retrieved for each EWH, based on present hot water flow rate from the EWH tank, present EWH temperature, and ON/OFF state, thus not requiring knowledge of the physical tank parameters. In addition to knowing how many EWHs are about to change state anyway, it is also necessary to know which EWHs these are, so that they are not selected as EWHs which are available to be changed.

The net difference between the number of EWHs turning ON or OFF, in order to satisfy the desired balancing reserve, is computed by first finding the absolute value of the balancing reserve needed, then dividing this by the power per EWH, and rounding this down to the nearest whole number.

$$N_{change}(t) = abs(round\left(\frac{P_{incdec\ needed}(t)}{P_{single\ EWH}}\right)) \quad [Eq. 30]$$

$N_{change}(t)$: number of EWHs to change at time t

$P_{incdec\ needed}(t)$: balancing reserve still needed, in order to meet the desired balancing reserve for the present 30-second period

$P_{single\ EWH}$: power consumed by one EWH in the ON state; 4.5 [kW]

abs: absolute value

round: Round to the nearest whole number, to ensure that a whole number of EWHs is changed. If the balancing reserve needed is less than half the power of one EWH (less than 2.25 kW), then zero EWHs will need to be changed. This deadband prevents oscillations in the number of EWHs turning ON and OFF.

Desired Balancing Reserve Less Than Zero

If the balancing reserve needed is negative, then more DEC is required. This means a decrease in reserve, and therefore an increase in demand. Therefore, the utility control must ensure that the number of EWHs turning ON in the next 5-second period needs to be $N_{change}(t)$ greater than the number of EWHs turning OFF.

The number of “EWHs needed” is positive if this number of EWHs needs to be turned ON, and negative if this number of EWHs needs to be turned OFF in order to meet the needed balancing reserve. The following equation calculated the number of EWHs needed:

$$N_{needed}(t) = N_{change}(t) + \left(N_{turning\ ON}(t) - N_{turning\ OFF}(t) \right) * sign(P_{incdec\ needed}(t)) \text{ [Eq. 31]}$$

$N_{needed}(t)$: Number of EWHs that need to be turned ON or OFF, to meet the needed balancing reserve

$N_{turning\ ON}(t)$: Number of EWHs turning ON by the end of the present 5-second interval, by falling to their lower temperature setpoint

$N_{turning\ OFF}(t)$: Number of EWHs turning OFF by the end of the present 5-second interval, by reaching their thermostat setpoint

sign: Literally, the sign of the balancing reserve needed, either positive or negative

Desired Balancing Reserve Greater Than Zero

If the balancing reserve needed is positive, then more INC is required. This means an increase in reserve, and therefore a decrease in demand. Therefore, the utility control must ensure that the number of EWHs turning OFF in the next 5-second period needs to be $N_{change}(t)$ greater than the number of EWHs turning ON.

The number of “EWHs needed” is positive if this number of EWHs needs to be turned ON, and negative if this number of EWHs needs to be turned OFF in order to meet the needed balancing reserve. In the following equation for EWHs needed, all variables are the same as stated previously.

$$N_{needed}(t) = N_{change}(t) + \left(N_{turning\ ON}(t) - N_{turning\ OFF}(t) \right) * (-sign(P_{incdec\ needed}(t)))$$

[Eq. 32]

Desired Balancing Reserve Equal to Zero

If the balancing reserve needed is zero, then the net difference between the number of EWHs turning ON and OFF must be zero. If net EWHs are turning ON, then an equal number of EWHs must be turned OFF to compensate, so that no new balancing reserve is created. If net EWHs are turning OFF, then an equal number of EWHs must be turned ON. The following equation calculates the number of EWHs needed in the case where balancing reserve needed is zero:

$$N_{needed}(t) = N_{turning\ OFF}(t) - N_{turning\ ON}(t) \quad [\text{Eq. 33}]$$

The new setpoints generated during the present 5-second period should guarantee that $N_{needed}(t)$ of EWHs turn ON or OFF.

When the balancing reserve is less than half of the power of one EWH, therefore less than 2.25 kW, it is rounded to zero. This creates a deadband around balancing reserve equal to zero, so that the number of EWHs needed does not oscillate unnecessarily.

Electric Water Heaters Need to be Turned OFF

If N_{needed} is less than zero, then some EWHs need to be turned OFF. This must be done by lowering the appropriate number of EWH setpoints, and will create less demand, more reserve, and therefore more INC. Recall that the number of EWHs needed depends not only on the sign of the balancing reserve needed, but also on the number of EWHs turning ON or OFF automatically by the end of the present 5-second period. As the utility lowers the appropriate amount of EWH setpoints to create more INC, this

amount of INC will balance correctly with the amount of balancing reserve created by the EWHs that are automatically turning ON or OFF.

The new setpoints are chosen such that the thermostat setpoint is less than the present temperature. If the temperature of these EWHs is suddenly greater than the thermostat setpoint, the EWHs will turn OFF, and therefore stop consuming power. First, the program makes an array, containing all of the temperatures of the EWHs in the ON state, and which are not going to turn OFF anyway in the next 5 seconds, and thus are available to be turned OFF by changing the thermostat setpoint.

If the number of available EWHs in the ON state is greater than or equal to N_{needed} , then N_{needed} of these EWHs are chosen at random. Each of these N_{needed} random EWHs in the ON state is assigned a new thermostat setpoint, which will cause it to turn OFF. If the number of available EWHs in the ON state is less than N_{needed} , then all of these EWHs are assigned new thermostat setpoints, which will cause them to turn OFF. The following equation determines the new thermostat setpoint of each EWH to be turned OFF:

$$T_{new\ setpoint}(t) = T_{EWH\ temperature}(t) - \Delta T \quad [\text{Eq. 34}]$$

$T_{new\ setpoint}(t)$: newly generated thermostat setpoint

$T_{EWH\ temperature}(t)$: present temperature of the EWH

ΔT : This quantity ensures that the new thermostat setpoint is less than the present EWH temperature. In this program, the quantity ΔT is equal to 0.12°F, as this is the maximum temperature change that a water heater with the parameters used in these experiments can experience during a 5-second period. In the 5-second time interval that the calculations

are being made, the temperature of the EWH in the ON state will continue to increase. The number ΔT ensures that the new thermostat setpoint temperature will still be less than the EWH temperature at the end of the 5-second period, and thus still cause the EWH to turn OFF.

Figure 20 illustrates the manner in which the new thermostat setpoint for a single EWH is determined, when N_{needed} is negative, and therefore some EWHs must be turned OFF by lowering the thermostat setpoint.

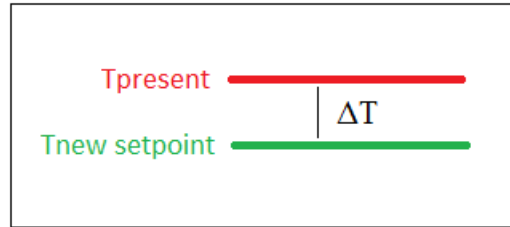


Fig. 20: Thermostat Setpoint Control to Turn EWH OFF.

Electric Water Heaters Need to be Turned ON

If N_{needed} is greater than zero, then some EWHs need to be turned ON. This must be accomplished by raising the appropriate number of EWH setpoints, and will create more demand, less reserve, and therefore more DEC.

The new setpoints are chosen such that the lower temperature setpoint is greater than the present temperature. If the temperature of these EWHs is suddenly less than the lower temperature setpoint, the EWHs will turn ON, and therefore begin consuming power. First, the program makes an array, containing all of the temperatures of the EWHs in the OFF state, and which are not going to turn ON anyway in the next 5 seconds, and thus are available to be turned ON by changing the thermostat setpoint.

If the number of available EWHs in the OFF state is greater than or equal to N_{needed} , then N_{needed} of these EWHs are chosen at random. Each of these N_{needed} random EWHs in the OFF state is assigned a new thermostat setpoint, which will cause it to turn ON. If the number of available EWHs in the OFF state is less than N_{needed} , then all of these EWHs are assigned new thermostat setpoints, which will cause them to turn ON.

If there are not enough EWHs in the OFF state, the utility must use other means of creating DEC. This may include decreasing or curtailing generation, or turning ON other, non-EWH, demand responsive consumer loads.

The following equation determines the new thermostat setpoint of each EWH to be turned ON:

$$T_{new\ setpoint}(t) = T_{EWH\ temperature}(t) + \Delta T + D \quad [\text{Eq. 35}]$$

$T_{new\ setpoint}(t)$: newly generated thermostat setpoint

$T_{EWH\ temperature}(t)$: present temperature of the EWH

ΔT : this quantity, 0.12°F, ensures that the new thermostat setpoint is less than the present EWH temperature

D: deadband; 10 °F

Figure 21 illustrates the manner in which the new thermostat setpoint for a single EWH is determined, when N_{needed} is positive, and therefore EWHs must be turned ON by raising the thermostat setpoint.

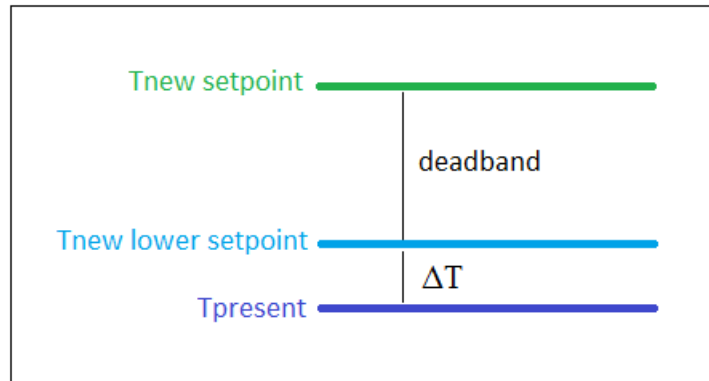


Fig. 21: Thermostat Setpoint Control to Turn EWH ON.

Summary

For each 30-second period, the utility calculates the mismatch between power generation and demand, wherein the power generation may include wind generation. This mismatch becomes a desired balancing reserve signal. The desired balancing reserve indicates how many kilowatts of consumer demand need to be turned OFF or ON, in order for generation and demand to properly match.

The utility then calculates how much balancing reserve has been created since the start of the 30-second period, and this is the balancing reserve created. The difference between the balancing reserve desired and the balancing reserve created gives the balancing reserve needed at the present 5-second period. If INC is required, then an increase in reserve is achieved by guaranteeing the appropriate decrease in demand. Likewise, if DEC is required, a decrease in reserve is achieved by guaranteeing an increase in demand.

The number of EWHs about to turn ON or OFF by reaching the limits of their deadbands are calculated, and used in calculating the number of EWHs needed to be

turned ON or OFF in order to achieve the needed increase or decrease in demand. If a net number of EWHs need to be turned OFF, then the thermostat setpoints of some randomly selected EWHs in the ON state, and not about to turn OFF anyway, are lowered by 0.12°F . This triggers the EWHs to turn OFF and stop consuming power. If a net number of EWHs need to be turned ON, then the thermostat setpoints of some randomly selected EWHs in the OFF state, and not about to turn ON anyway, are raised by 0.12°F plus the deadband of 10°F . This triggers the EWHs to turn ON and begin consuming power.

Explanation and Correction of a Previous Problem in Methodology

In previous programs, the setpoints of only the hottest (when balancing reserve is greater than zero) or coolest (balancing reserve less than zero) EWHs were adjusted. This was an attempt to keep all EWHs within the desired temperature range of 116°F to 160°F , without the temperatures being too extreme. However, the problem with this approach was that the EWHs' temperatures all tended toward the same $\sim 7^{\circ}\text{F}$ temperature band, and eventually all exhibited the same behavior. This response makes sense, because the EWHs with the most "extreme" or "diverse" temperatures were the ones forced to setpoints more similar to the average of the others, but was disadvantageous in terms of maintaining the diversity of temperatures within the EWH population.

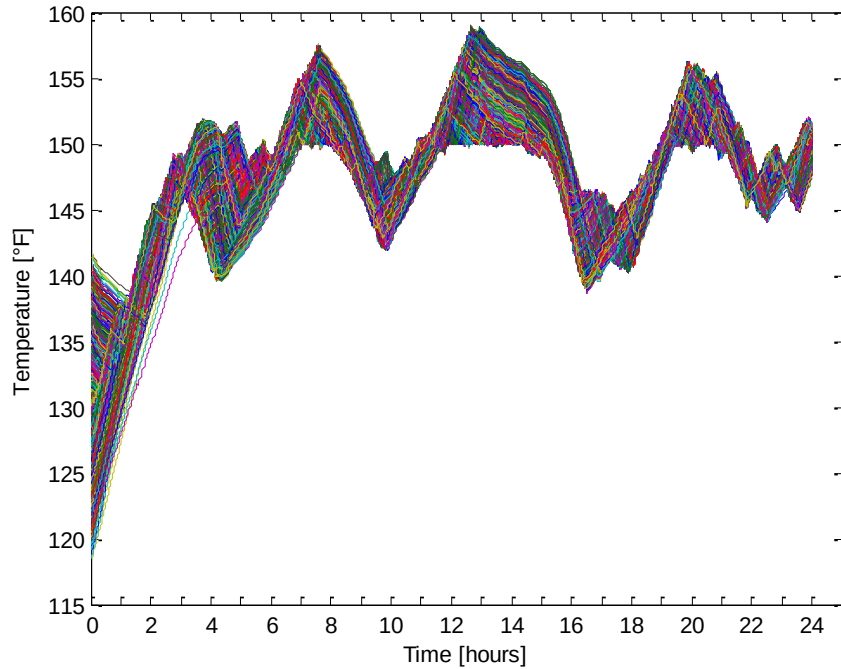


Fig. 22: Outgoing Water Temperature of Each EWH in Failed Experiment.

Figure 22 illustrates the two problems that arose when adjusting the setpoints of only the EWHs with the hottest or coolest temperatures:

1. At any given time, most EWHs' temperatures are within less than 10 °F of one another. This is a problem when all of the EWHs are close to the maximum upper temperature limit of 160 °F and the desired balancing reserve is negative, meaning that reserve must be decreased, demand must be increased, and therefore some EWH setpoints must be *raised*. In this case, there are not enough EWHs which's setpoints *can* be raised, because increasing the upper setpoint would exceed the maximum upper temperature limit. Thus, the desired balancing reserve can not be met.
2. There are times when all EWHs are in the same state, either all ON (heating), or all OFF (cooling). If all EWHs are ON at the same time, then demand can not be

increased, even if the desired balancing reserve is less than zero. Likewise, if all EWHs are OFF at the same time and the desired balancing reserve is greater than zero, demand can not be decreased, and so the desired balancing reserve can not be met.

The compounded effect of points 1. and 2. from above is illustrated in Figure 23.

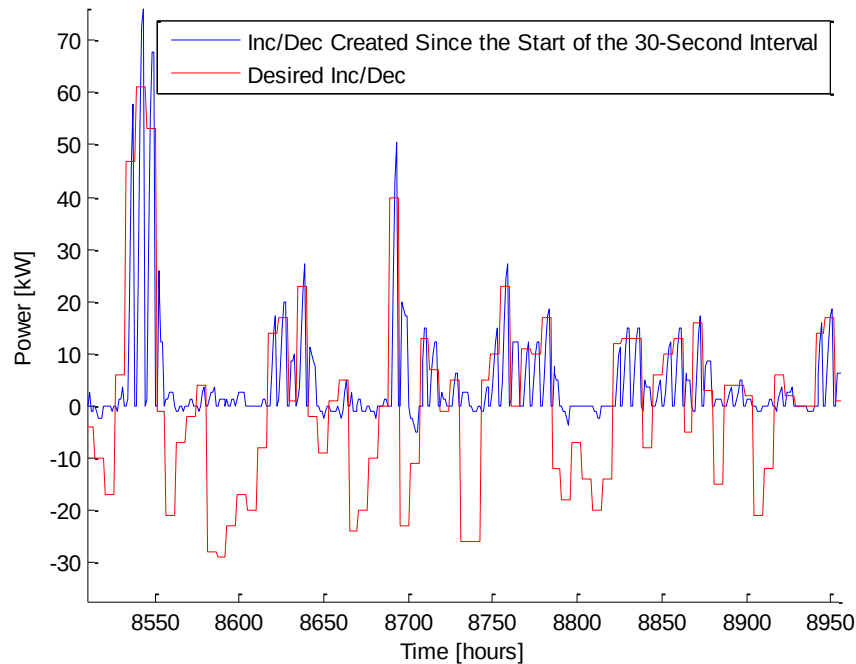


Fig. 23: Balancing Reserve Desired and Created, Failed Experiment.

The time span in this figure is about half an hour, beginning at approximately 11:52 am and ending at 12:26 pm. Notice that when the desired balancing reserve is positive, and therefore EWH setpoints must be lowered, the goal is always met. However, when the desired balancing reserve is negative, and therefore EWH setpoints must be raised, the goal is never even close to met. This is because there are not enough EWHs in the OFF state to be turned ON, and those that are OFF have upper setpoints very close to or already at 160 °F. Therefore, the technique of selecting random EWHs

from those available should allow the EWH population to have much greater diversity in both ON/OFF state and temperature.

Justification of Minimum and Maximum Allowable Water Temperatures

The upper limit of the optimal growth temperature range for *Legionella pneumophila* and *Legionella* bacteria is 116°F [40]. It is recommended that stored hot water be kept above this temperature. These *Legionella* bacteria can be the source of legionellosis, a disease which's wide range of symptoms can include high fever, vomiting, delirium, retrograde amnesia, renal failure, severe respiratory failure, and multi-organ failure leading to death [41]. Therefore, the minimum temperature limit for all EWHs is set to 116°F. With a deadband of 10°F, the minimum EWH thermostat setpoint is 126°F.

EWHs are an ideal living situation for sulfate-reducing bacteria [42]. The warm temperature of most EWHs is within the bacteria's growth range. Additionally, if the corrosion-retarding anode inside of the EWH tank is made of magnesium (as opposed to aluminum), this can supply extra electrons needed for the bacteria to perform the sulfate-reduction process. The result is the production of hydrogen sulfide gas, which has an offensive odor, is harmful to humans when concentrated in an enclosed area such as a basement or garage (where EWHs are typically stored), and corrodes pipes and other metal plumbing fixtures. These sulfate-reducing bacteria also generate a nutrient-rich substance to grow other forms of bacteria, which can clog drains and pipes. To prevent

the growth of sulfate-reducing bacteria, it is recommended to periodically allow the water temperature inside of the tank to increase to at least 160°F.

However, higher water temperatures also correspond to increased mineral buildup in the EWH tank and pipes [43]. As water is heated, the minerals suspended in the water are extracted, and settle at the bottom of the EWH tank. If the heating element is at the bottom of the tank, the mineral buildup can coat the heating element and act as an insulator, and thus decrease the efficiency of energy transfer from the heating element to the water. If enough mineral sediment builds up in the tank, this can decrease the volume of water that the tank can hold. Additionally, the mineral buildup can cause the bottom of the EWH tank to overheat, and therefore decrease the lifetime of the tank's protective glass lining. By maintaining a lower water temperature inside of an EWH tank, mineral buildup can be reduced, and the efficiency and lifetime of the tank can be increased. The minimum EWH thermostat setpoint temperature is 126°F, allowing a minimum water temperature of 116°F, above the ideal growth range for harmful *Legionella* bacteria strains. The maximum thermostat setpoint temperature, and therefore maximum water temperature, is 160°F, the minimum required to kill sulfate-reducing bacteria. The minimum was chosen in the interest of prolonging tank life and allowing maximum efficiency by decreasing mineral buildup that results from higher water temperatures.

Four Experimental Models for Simulation

The four experimental models are described below.

Case 0: No EWH Thermostat Setpoint Control

This case represents EWHs under normal operation, with no thermostat setpoint control. This is how EWHs behave in a non-smart grid environment with a flat-rate pricing scheme, or in a smart grid environment in which the customers choose not to participate in balancing reserve-based thermostat setpoint control demand response program. The results of this case will be used as a basis for comparison for Cases 1-4, to determine performance in the six areas of analysis listed at the end of this section.

Case 1: EWH Thermostat Setpoint Control Based on Balancing Reserves Desired by Utility

In this case, the balancing reserve signal from the utility is used for EWH thermostat setpoint control, as explained previously. The utility has full control over the thermostat setpoints of all EWHs. If this method were to be implemented in a smart grid environment, the customer would have to benefit economically from participation. However, if this method were of higher cost to the customer than Case 0, then the utility would have to provide an economic incentive to the customer in order to encourage participation.

Real Balancing Reserve Signal Source and Scaling. The source of the desired balancing reserve signal data is Bonneville Power Administration (BPA), and was originally supplied with units of MW. BPA estimates that in the region including Washington, Oregon, Idaho, and western Montana, there are 3.4 million EWHs. In the portion of this region specifically serviced by BPA, and to which the desired balancing

reserve signal is applied, there are approximately 40% of the region's EWHs, total of 1.36 million EWHs.

The reasonability of this estimate is verified in this paragraph. The BPA service area includes 12,561,595 residents [44], and the average US household size is 2.59 people [45]. This implies a total of 4.85 million residences in the BPA area. Approximately 40% of US residences use electricity to heat water [46]. Assuming 40% of the residences in the BPA service area have electric water heaters, this would be 1.94 million EWHs. However, some living arrangements, such as apartment buildings, have one very large EWH for multiple residences, and so the number of residential-size EWHs in the BPA service area would be smaller than 1.94 million. Therefore, BPA's estimate of approximately 1.36 million EWHs is reasonable.

In order to properly scale the desired balancing reserve signal for a population of 1000 EWHs, the following equation was used

$$Inc/Dec_{scaled} = \frac{Inc/Dec_{original}}{1.36 \times 10^6 [EWHs]} * 1000 [EWHs] \quad [Eq. 36]$$

This original desired balancing reserve signal is therefore scaled by a factor of $7.3529 * 10^{-4}$ to obtain the balancing reserve desired for the experiments in this study.

Correlation Between Balancing

Reserve Desired and Wind Generation. The desired balancing reserve data

provided by BPA also included the amount of wind power generation accommodated during each 30-second period. This wind power generation data could not be scaled by the same factor as the balancing reserve signal, because the wind power generation is not

directly proportional to the amount of reserves that need to be deployed. However, there is a strong correlation, which will be evaluated in the following paragraphs.

From the balancing reserve data provided by BPA, two different winter weeks of balancing reserve data were selected, in order to explore the correlation between wind power generation and balancing reserve desired. These weeks of data were chosen so that the first day was a Sunday and the last day was a Saturday, and so that one week had a larger average change in wind power generation per 30-second period, and the other had a smaller average change in wind power generation per 30-second period.

For the week with the larger average change in wind power generation per 30-second period, this average was 3.1301 MW. The total wind energy generated during this week was 1.4018×10^{11} MWh (or 5.0466×10^{11} GJ).

For the week with the smaller average change in wind power generation per 30-second period, this average was 2.3549 MW. The total wind energy generated during this week was 1.3937×10^{11} MWh (or 5.0174×10^{11} GJ).

Though both weeks had approximately the same total wind energy generation, one week had a much higher rate of change in power generation. The total wind energy generated during the week with the larger average change in wind power generation is 0.58% higher than in the week with the smaller average change in wind power generation, and the average change in power generation is 32.9% higher.

Figure 24 shows the wind power generation for each of the two weeks, accommodated by the original, unscaled balancing reserve desired. Note that in the curve corresponding to the week with the larger average change in wind power generation, the

changes are often rapid and severe in magnitude. The curve corresponding to the week with the smaller average change in wind power generation is relatively smooth, and the changes are generally neither rapid nor severe in magnitude.

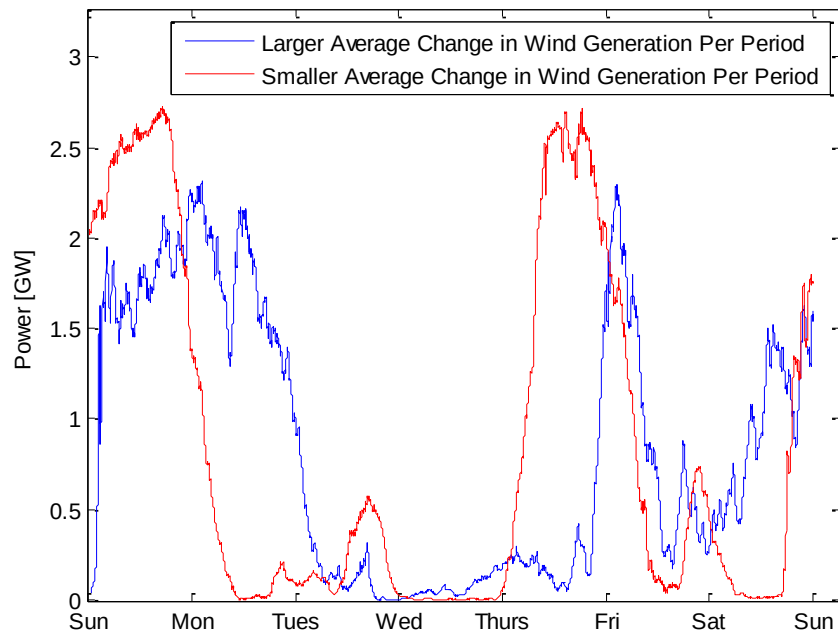


Fig. 24: Wind Power Generation During Period of Desired Balancing Reserve Signals.

Balancing Reserve Signal Overview. Figures 25 through 28 show the seven-day periods of balancing reserve data. The balancing reserve data has already been properly scaled for the 1000-EWH population. The blue figures are from the week with the smaller average change in wind power generation per 30-second period, and the red figures are from the week with the larger average change in wind power generation per 30-second period. Figure 25 shows the balancing reserves deployed during each week.

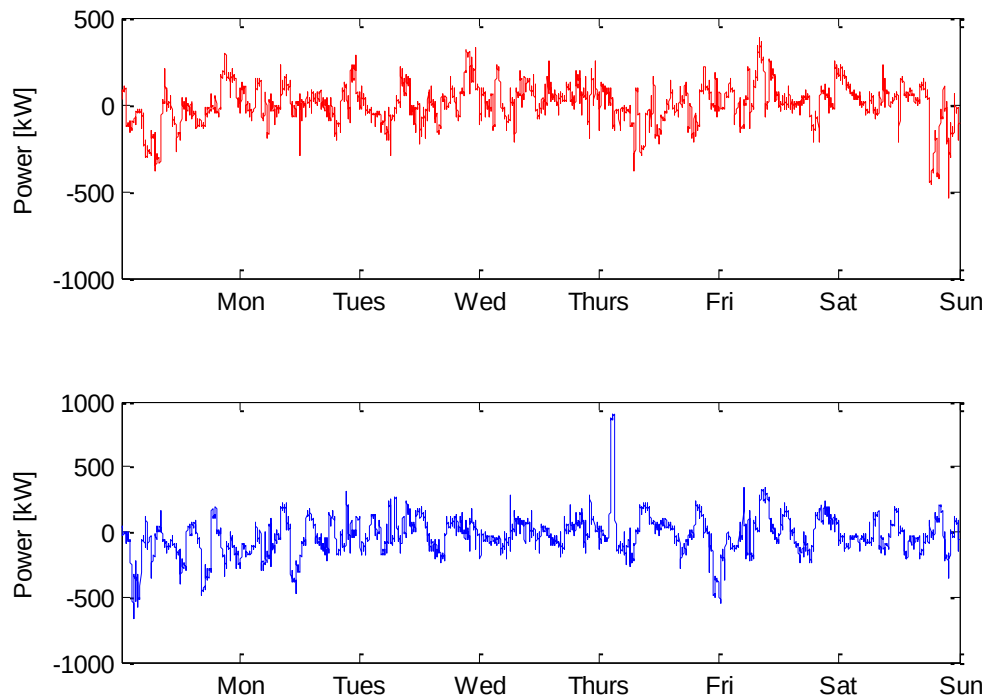


Figure 25: Balancing Reserve Deployed by Utility During Week with Smaller Average Change in Wind Generation per Period (Top), and Larger Average Change in Wind Generation per Period (Bottom).

In order to obtain the desired balancing reserve for each 30-second period, the difference between the balancing reserves deployed at the present period and the balancing reserves deployed at the previous period was calculated. Figure 26 shows the balancing reserve desired, corresponding to the balancing reserves deployed shown in Figure 25, above.

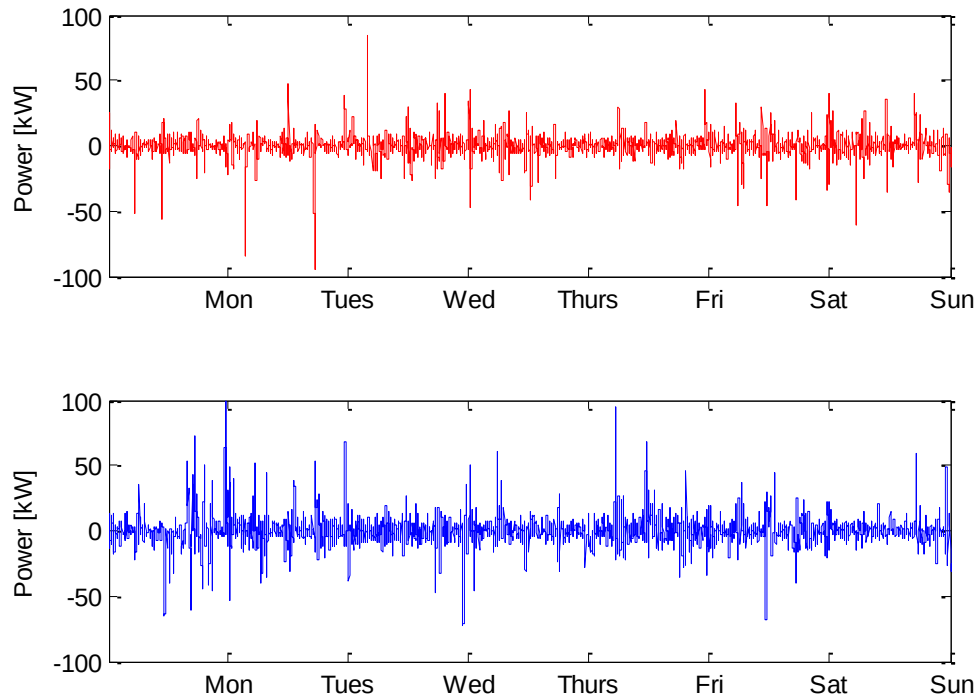


Fig. 26: Desired Balancing Reserve for Week with Smaller Average Change in Wind Generation per Period (Top) and Larger Average Change in Wind Generation per Period (Bottom).

A probability distribution function (PDF) for the magnitude of the balancing reserve desired was calculated, by rounding all balancing reserve data to the nearest five kW. These PDFs are shown in Figures 27 and 28. There is a high probability of the desired balancing reserve being less than or equal to 5 kW, and the probability of the desired balancing reserve at each 5 kW step after that decreases exponentially.

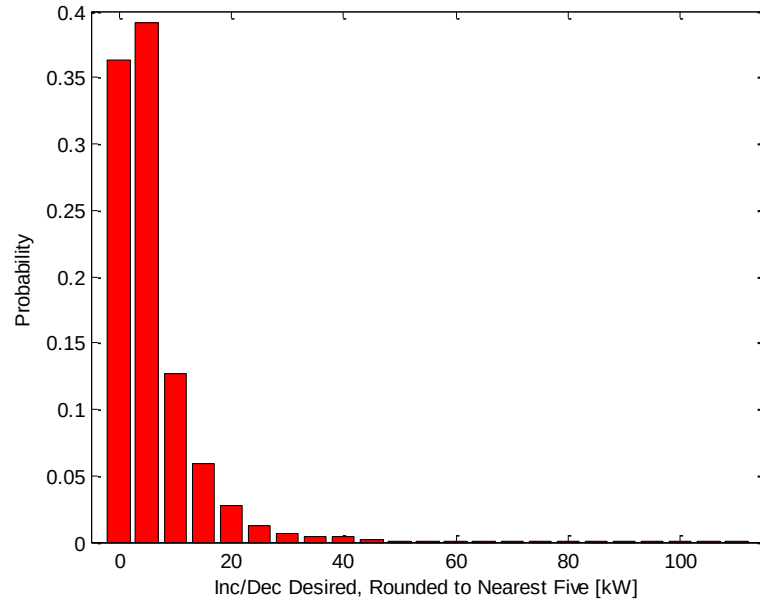


Fig. 27: Probability Distribution Function For Balancing Reserve Desired During Week with Smaller Average Change in Wind Generation per Period.

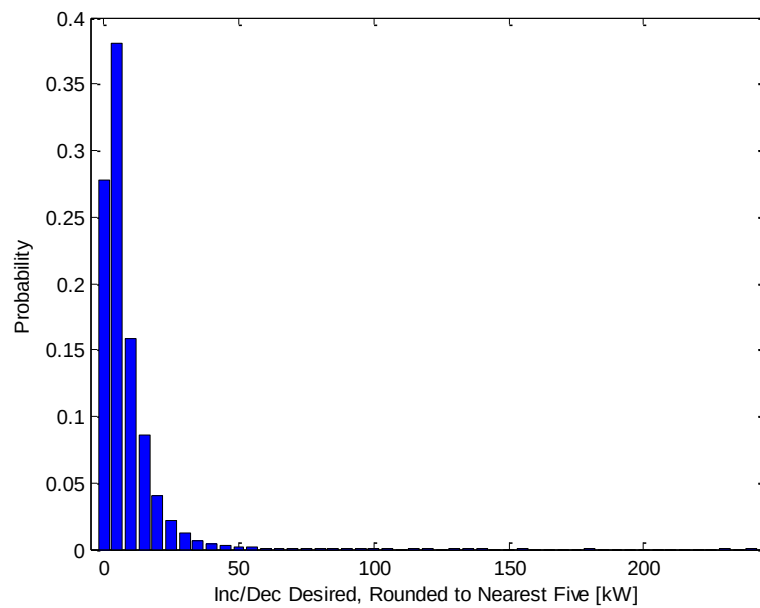


Fig. 28: Probability Distribution Function For Balancing Reserve Desired During Week with Larger Average Change in Wind Generation per Period.

The week with the larger average change in wind power generation had a range of 241.9 kW for the balancing reserve desired; 118% larger range than that of the week with

the smaller average change in wind power generation, which had a range of 111.0 kW (Figure 26).

The average balancing reserve desired per 30-second period was 6.0701 kW for the the week with the smaller average change in wind power generation, and 7.6800 kW for the week with the larger average change in wind power generation (Figure 28). The the week with the larger average change in wind power generation had a 27.6566% higher average balancing reserve desired (and therefore the same percentage difference in total balancing reserve desired for the week), meaning higher mismatch between generation and demand. This correlates very well to the 32.9% higher average wind generation per period.

The winter week with the 32.9% larger average change in wind power generation per 30-second period also had a 27.6566% higher average balancing reserve desired, and a 118% larger range. The balancing reserve data for this week was used for the experiments in this study, in order to test the algorithm's ability to accommodate highly variable wind conditions.

Case 2: EWH Thermostat Setpoint Control Based on Time-of-Use Pricing

This case is a demonstration of how EWHs behave when a time-of-use pricing signal is deployed. The goal of the utility in this pricing scheme is to shift demand from on-peak hours to off-peak. The consumer's goal is to benefit economically over Case 0 in which there is no time-of-use pricing.

While the total amount of energy consumed by the EWH load in one day is important to the customer and the utility, it is also important when the energy is consumed. Time-of-use pricing is implemented by utilities, imposing higher prices during peak hours, and lower prices during off-peak hours. The goal is to encourage consumers to consume more during off-peak hours and less during peak hours, and therefore cause a flatter demand curve. Studies show that consumers are willing to change their habits in order to benefit financially [47].

Figure 29 shows the rate of energy consumption by a single typical residence, for a one-day period [19]. There are two peaks in use; the first is called the “morning peak”, and the second is the “evening peak”.

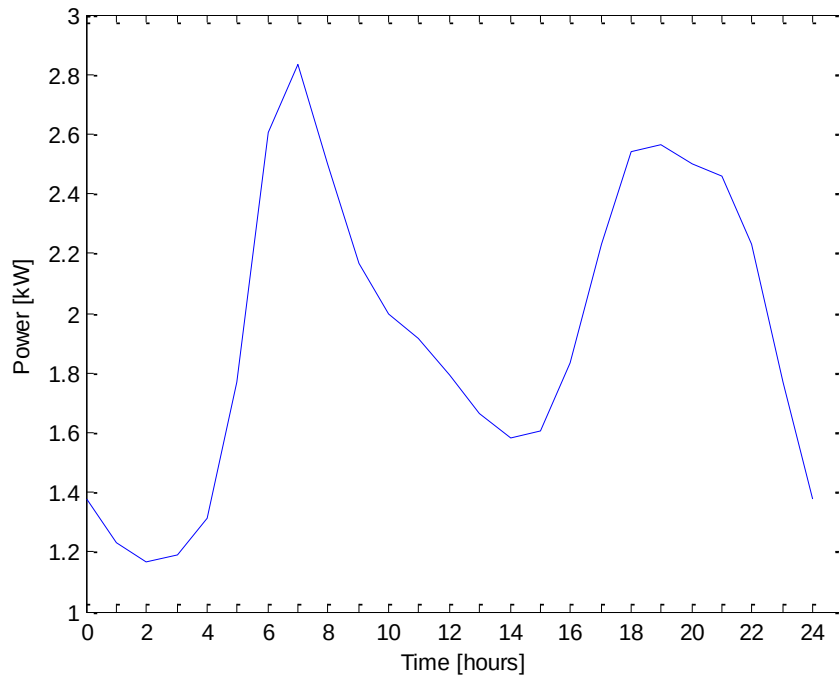


Fig. 29: Power Demand of a Single, Average Residence.

Different utilities in the Pacific Northwest region of the United States, near to BPA, define the on-peak and off-peak hours in a nearly identical fashion. For example,

examine Pacific Power in Oregon [48] and Portland General Electric [49]. Pacific Power provides data for both flat-rate and time-of-use pricing schemes, and so these two pricing schemes were chosen for these experiments, to model realistic consumer costs. Pacific Power's flat rate pricing scheme was chosen for this experiment. The Table 5 shows the electrical energy pricing rate [50].

Table 5: Rate for Electric Energy Consumed in Flat Pricing Scheme for Pacific Power [50].

Usage	Price
Basic charge	\$9.00/month
First 1000 kWh	8.9 ¢/kWh
Additional energy	10.719 ¢/kWh

Pacific Power's electricity pricing rate structure for time-of-use involves two components. The first is a basic charge. Table 6 shows the base rate based on kWh of energy usage in a month.

Table 6: Base Rate for Electric Energy Consumed in Time-of-Use Pricing Scheme for Pacific Power [50].

Usage [kWh]	Price [¢/kWh]
0-500	3.873
501-1000	4.590
1001 +	5.664

The second component of the time-of-use pricing scheme is a charge for using power during on-peak hours, and a credit for using power during off-peak hours. On-peak and off-peak hours are illustrated in Figure 30.



Fig. 30: On-Peak and Off-Peak Hours for Demand, for Pacific Power [50].

The different definitions of on-peak and off-peak times during summer and winter reflect the different energy usage patterns during those seasons. Figure 31 shows electricity demand for an entire system, including commercial, industrial, and residential sectors, for a single representative day in summer and winter. Note that the peak demand hours shown in Figure 31 correspond to the peak demand hours defined in Pacific Power's time-of-use pricing scheme detailed above.

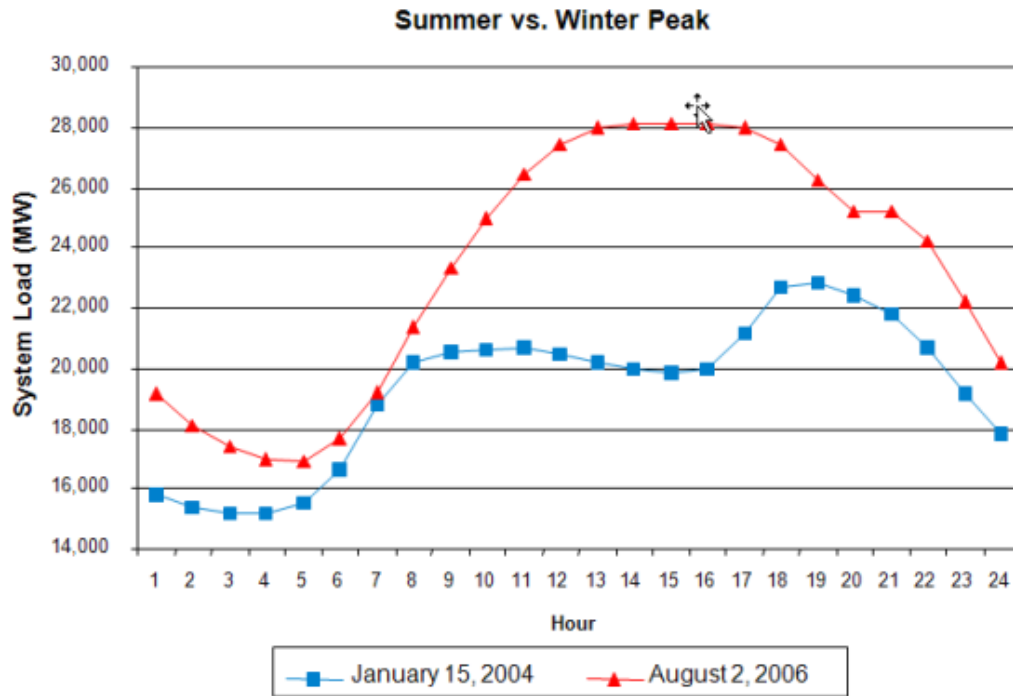


Fig. 31: Power Demand of an Entire Electric Power Distribution System [51].

Pacific Power's time of use rate adjustments for summer and winter are shown in Figure 32. The charge during the on-peak periods in winter will be \$0.03316/kWh, and the charge during the off-peak periods in winter will be \$0.02191/kWh.

Summer		On Peak Charge	Off Peak Credit
Residential (per kWh)	Rate schedule 4	\$0.06124	-\$0.01125

Winter		On Peak Charge	Off Peak Credit
Residential (per kWh)	Rate schedule 4	\$0.03316	-\$0.01125

Fig. 32: Time-of-Use Electricity Rate Adjustments for Pacific Power [50].

Figure 33 illustrates the time-of-use rate adjustments for seven days in winter, the season from which the balancing reserve data was used in the experiments.

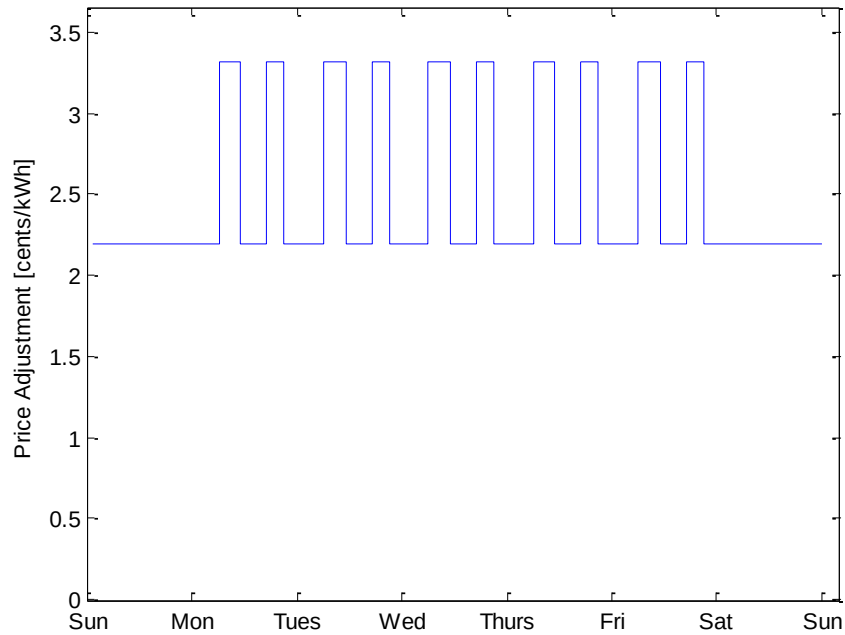


Fig. 33: Time-of-Use Electricity Rate Adjustment, Winter.

In the control scheme in Case 2, the customer has full control over the EWH. The main goal of the customer is to benefit economically. When the time-of-use pricing scheme is implemented, the customer responds by trying to consume as little energy as possible during on-peak hours. All thermostat setpoints are set to the minimum allowable temperature, 126°F, during on-peak hours.

In Case 2A, customers allow their EWHs to operate normally, as in Case 0, and so all thermostat setpoints are set to 130°F during off-peak hours. However, this may not allow EWHs to store enough thermal energy to make it through the on-peak hours without reaching the minimum temperature and thus turning ON and consuming power. In Case 2B, in order to ensure that the EWHs do not turn on during on-peak hours, which would increase the cost to the customer, the thermostat setpoints are set to 160°F during off-peak hours. When the on-peak period begins, all EWHs have a temperature between

150°F and 160°F. The goal is for the EWHs to remain in the OFF state during the peak periods, as their temperatures decrease toward 116°F, never reaching it and causing the EWHs to turn back ON.

Case 3: EWH Thermostat Setpoint Control
Based on Time-of-Use Pricing, and Balancing
Reserves Desired During Off-Peak Hours

The time-of-use pricing signal has highest priority of the two control signals, due to the customer's desire for economic benefit. During peak hours, EWHs opt out of balancing reserve-based setpoint control, and all setpoints are set to 126°F, the minimum allowable setpoint which ensures that the temperature of the water in the EWH tank never falls below 116°F. Thus, EWHs consume less energy when price for electricity is high. The balancing reserve-based thermostat setpoint control has the second highest priority. During off-peak hours, when price of electricity is low, all EWHs opt in to balancing reserve based setpoint control. All setpoints are maintained between 126°F and 160°F, thus allowing EWHs to store thermal energy needed to make it through the next on-peak period without reaching the minimum water temperature and turning ON.

Six Areas of Analysis of Experimental Results

The four experimental simulation cases tested the hypothesis that controlling the thermostat setpoints of electric water heaters can shift consumer electrical energy demand from on-peak to off-peak hours, provide a large percentage of the balancing reserves necessary to integrate wind energy generation onto the system, and economically benefit the customer, while maintaining safe water temperatures and without significantly

increasing average power demand or peak power demand. There were six areas of performance for which each of the four cases were evaluated.

Goal 1: Maintain Customer Comfort Level

The hot water supply must be available to support the customer's needs. The water within the EWH tank must always remain within safe temperature limits, between 116°F and 160°F. This was the highest priority goal, and was never allowed to be compromised.

Goal 2: Load Shifting from On-Peak to Off-Peak Hours

The ratio of total energy demand during on-peak hours to total energy demand during off-peak hours should be minimal, and lower in the control cases than in the no-control case. This was a high-priority goal. The pricing signal's main intent was to provide load shifting, with the added benefit of economic advantage for the consumer. Load shifting to off-peak hours would allow the EWHs to accommodate the wind generation that is typically higher at night, and thus also reduce the need for non-renewable, polluting fossil fuel generation.

Goal 3: Peak Load Equality or Reduction

Maximum power demand in the control cases should be less than or equal to the maximum power demand in no-control case. A large increase in peak power demand would be very undesirable. This would increase the need for availability of high-capacity

spinning reserves, thus costing money to the utility, and causing more fossil fuel-based greenhouse gas emissions.

Goal 4: Total Energy
Demand Equality or Reduction

The total energy consumed in the control cases should be less than or equal to the total energy demand in the no-control case. A large increase in total energy demand would be very undesirable. This would increase the level at which base load power plants must operate, thus an economic disadvantage to the utility, as well as an environmental disadvantage, as base load power plants are typically non-renewable, polluting fossil fuel or nuclear powered.

Goal 5: Economic Benefit to Customer

The total cost to customer in the control cases should be less than or equal to the total cost in the no-control case. This was a mid-priority goal, which correlates to reduction of demand during on-peak hours.

Goal 6: Provide Desired Balancing Reserves

This was a high-priority goal, preceded in importance only by Goals 1 and 2. The balancing reserves created in the control cases should match the balancing reserves desired by the utility with minimal error. This would replace some of the balancing reserves currently provided by fossil fuel based spinning reserve, and also account for the intermittency of wind power generation, allowing wind generation sources to be utilized on the power grid.

RESULTS OF FOUR SIMULATION CASES

Case 0: No EWH Thermostat Setpoint Control

In Case 0, the thermostat setpoints of the EWHs remained constant at 130°F. Therefore, the water temperatures remained between 120°F and 130°F. No balancing reserves were supplied in this case, and the flat-rate pricing scheme was used.

Goal 1: Maintain Customer Comfort Level

The hot water supply was always maintained within reasonable and safe operating limits. The thermostat setpoint was always set at 130°F. The water temperature inside the EWH tank had a minimum of 120°F and a maximum of 130°F. Figure 34 shows the temperatures of all 1000 EWHs in the model, for the entire week-long simulation period.

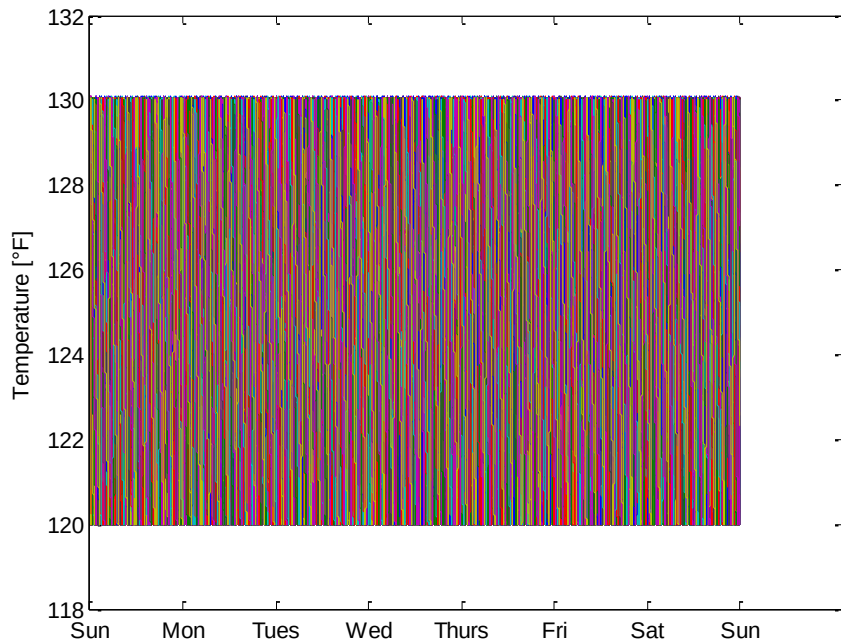


Fig. 34: Outgoing Water Temperature of Each EWH, Case 0.

The thermostat setpoints remained set to 130°F for all EWHs for the entire duration of the simulation.

Goal 2: Load Shifting from On-Peak to Off-Peak Hours

The power demand profile of the 1000 EWHs for the 7-day period is shown in Figure 35a. The total energy consumed by all EWHs in the 7-day period was 273.37 GJ (or 75.936 MWh). Evaluating the on-peak and off-peak demand based on the winter pricing signal, the total energy demand during on-peak hours was 82.199 GJ, and the total energy demand during off-peak hours was 191.17 GJ. Therefore, 30.0688% of the demand occurred during on-peak hours, and 69.9312% occurred during off-peak hours.

Figure 35b shows the power demand profile of the 1000 EWHs for Wednesday only. In Cases 1-3, a shift in demand from on-peak hours to off-peak hours is desirable, with the goal that less than 30.0688% of demand will occur during on-peak hours in those cases. Figures 35a and 35b will be used as a basis for comparison for Cases 1-3.

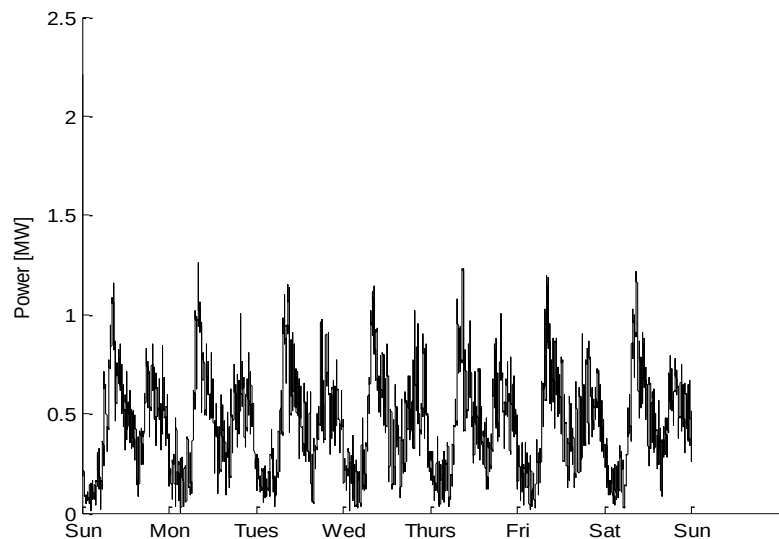


Fig. 35a: Total Power Demand of 1000 EWHs, Case 0.

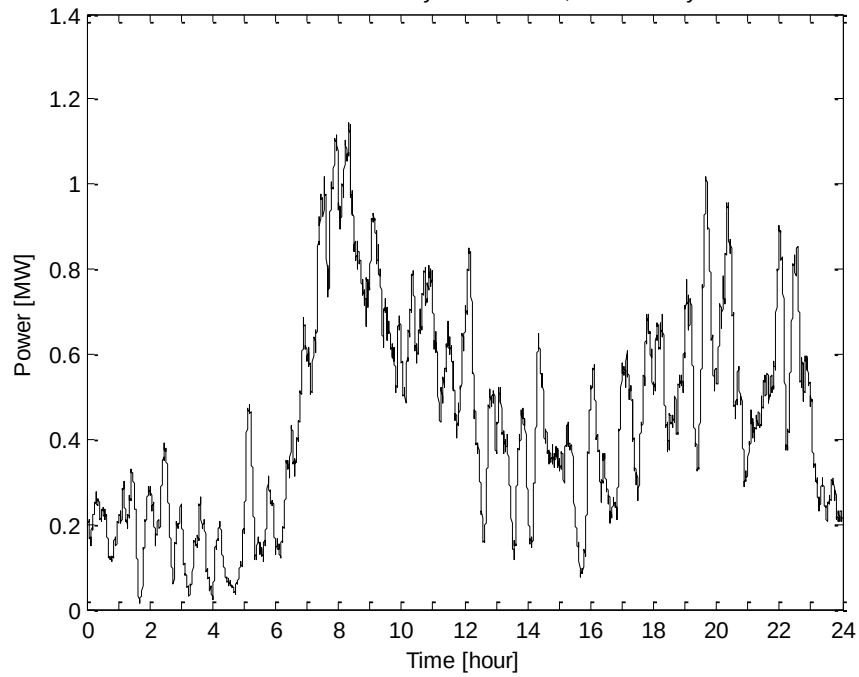


Fig. 35b: Total Power Demand of 1000 EWHs, Wednesday, Case 0.

Figures 36a and 36b show the total power demand of 1000 typical residences.

This will be used as a basis for comparison of load shifting in Cases 1-3. In Figure 36b it is especially evident that the residential demand profile is heavily influenced by the EWH demand profile, because the morning and evening peaks occur at approximately the same times.

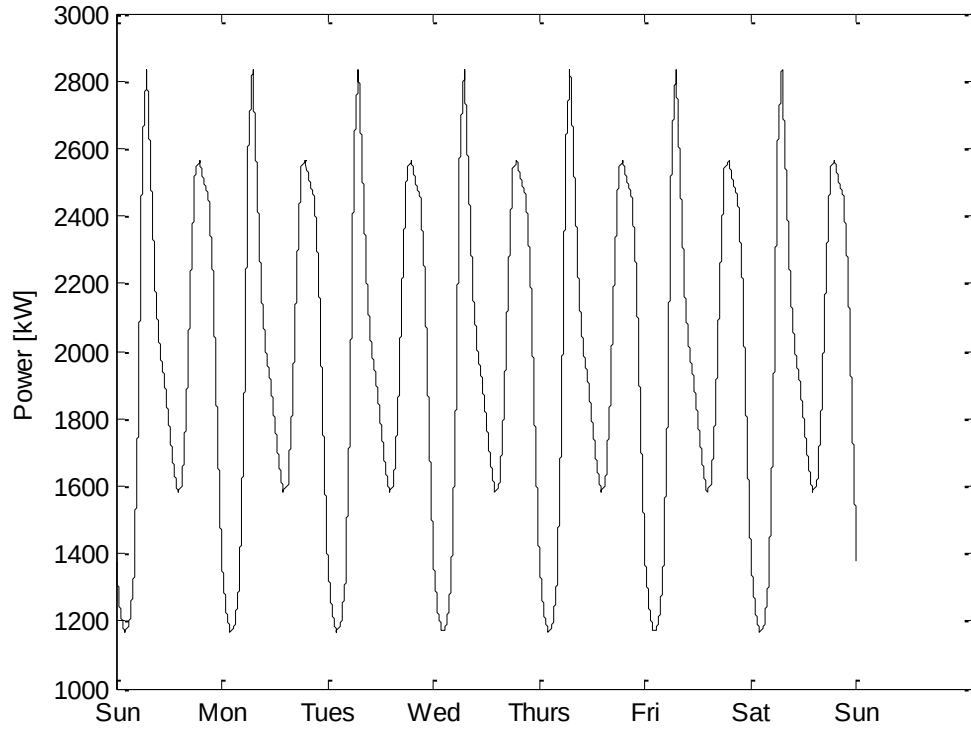


Fig. 36a: Total Power Demand of 1000 Typical Residences, Case 0.

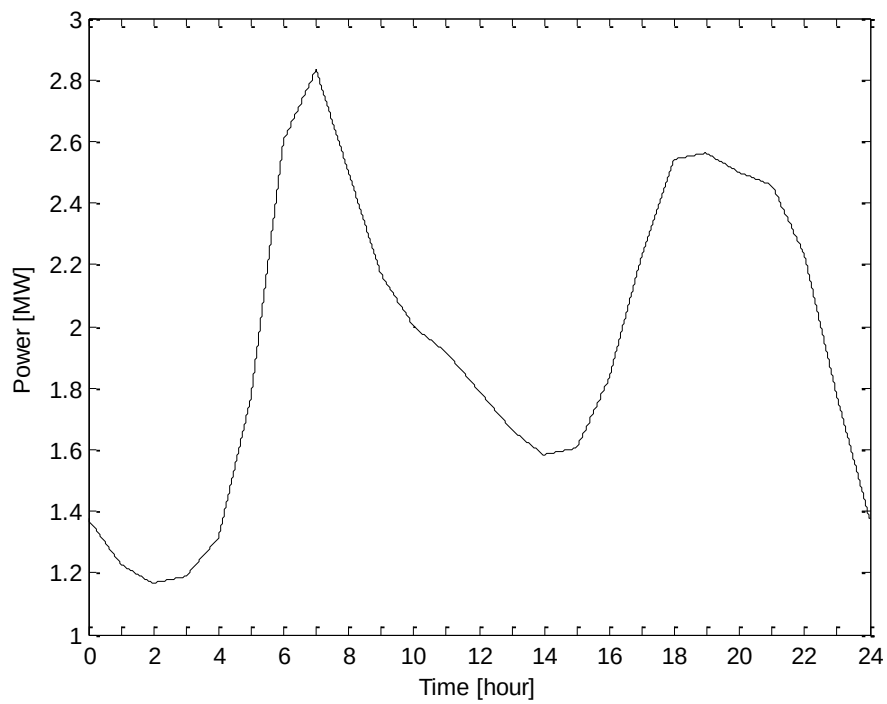


Fig. 36b: Total Power Demand of 1000 Typical Residences, Wednesday, Case 0.

Goal 3: Peak Load Equality or Reduction

The maximum power demand, excluding the initial transient in which many EWHs are in the ON state, was 1.260 MW. This will be used as a basis for comparison for Cases 1-3, to determine peak load reduction.

Goal 4: Total Energy Demand Equality or Reduction

The total energy consumed by all EWHs in the 7-day period, shown in Figure 37, was 273.36 GJ (or 75.933 MWh), and the average power demand in this no-setpoint control case was 451.9983 kW. These will be used as a basis for comparison for Cases 1-3, to determine total energy reduction.

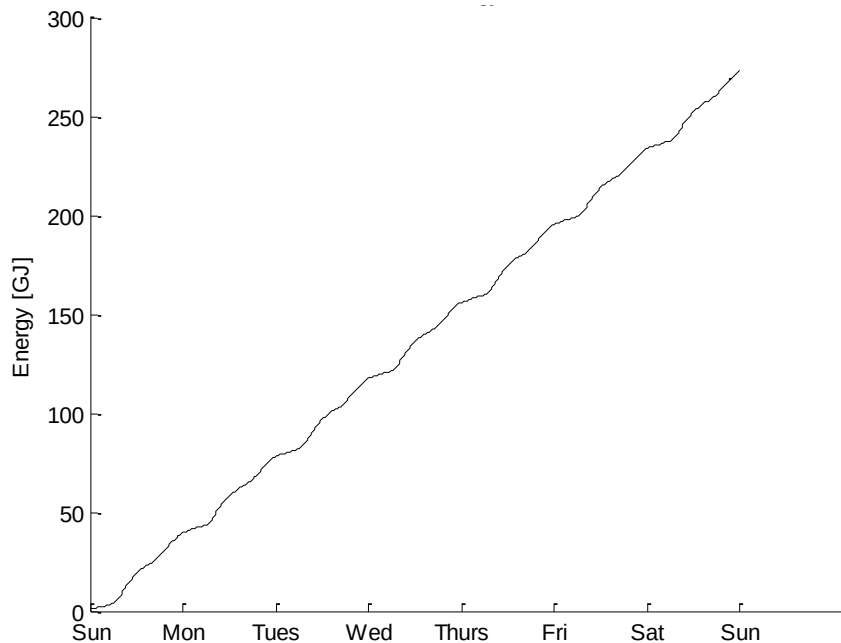


Fig. 37: Cumulative Energy Demand, Case 0.

Goal 5: Economic Benefit to Customer

Based on Figure 37, the average EWH in this case consumes 75.9357 kWh of energy in one week. Under the flat-rate pricing scheme, the total cost for the average EWH in one week is \$8.7905. (Under the time-of-use pricing scheme, the total cost for the average EWH in one week would have been \$4.8616 with no thermostat setpoint control, but this does not allow the customer to take part in response to that pricing scheme and therefore save money. That scenario will be addressed in Case 2.)

Goal 6: Provide Desired Balancing Reserves

This case cannot provide balancing reserves in response to the desired balancing reserve signal. The setpoints remain constant for the entire 7-day simulation.

Case 1: EWH Thermostat Setpoint Control Based on Balancing Reserves Desired by Utility

In Case 1, the desired balancing reserve was the only control signal. The setpoints of the EWHs were adjusted between 126°F and 160°F in order to supply the needed balancing reserve.

Goal 1: Maintain Customer Comfort Level

The hot water supply was always maintained within reasonable and safe operating limits. The thermostat setpoints ranged from 126°F to 160°F. The water temperature inside the EWH tank had a minimum of 116°F and a maximum of 160°F. Figure 38 shows the water temperature profiles of all 1000 EWHs in the model, for the entire week-long simulation period.

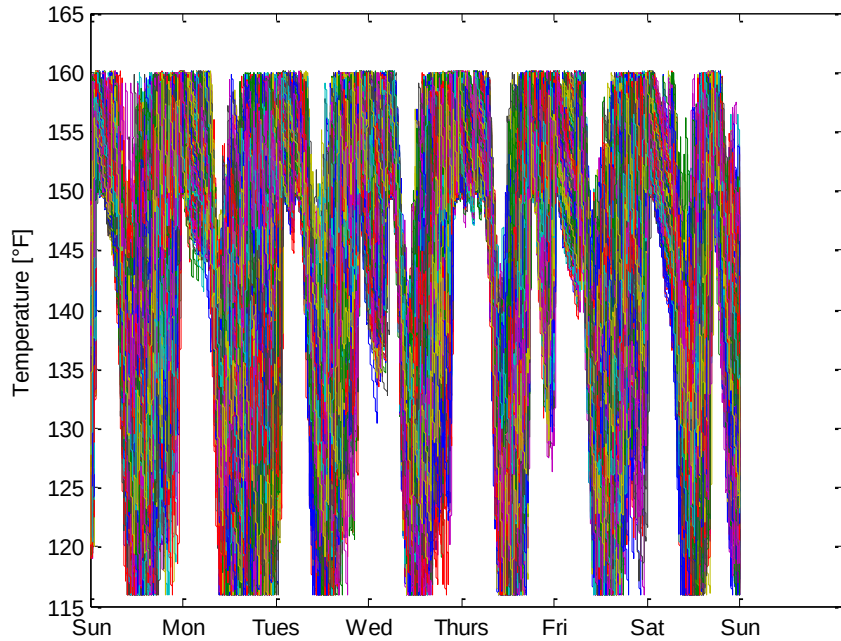


Fig. 38: Outgoing Water Temperature of Each EWH, Case 1.

The diversity of the EWH population at any given time is of great importance to balancing reserve control. The first measure of diversity is the state of the EWHs. The states can be deduced from the temperature plot, as ON when the temperatures are increasing, and OFF when the temperatures are decreasing. At most times, the EWHs are evenly distributed between increasing and decreasing. The second measure of diversity is temperature range of the EWH population at a given time. A larger distribution of temperatures is desirable, so that the setpoints of EWHs can be adjusted to provide balancing reserve without increasing above 160°F or below 126°F. This experiment generally had a distribution of temperatures of at least 10°F.

Figure 39 shows the thermostat setpoint temperatures of all EWHs. Note that the setpoints are generally higher late at night and in early morning, when wind generation is generally higher and demand is generally lower. The large diversity in the setpoints

during daytime hours indicates that EWHs are asked to provide similar amounts of inc and dec during these times.

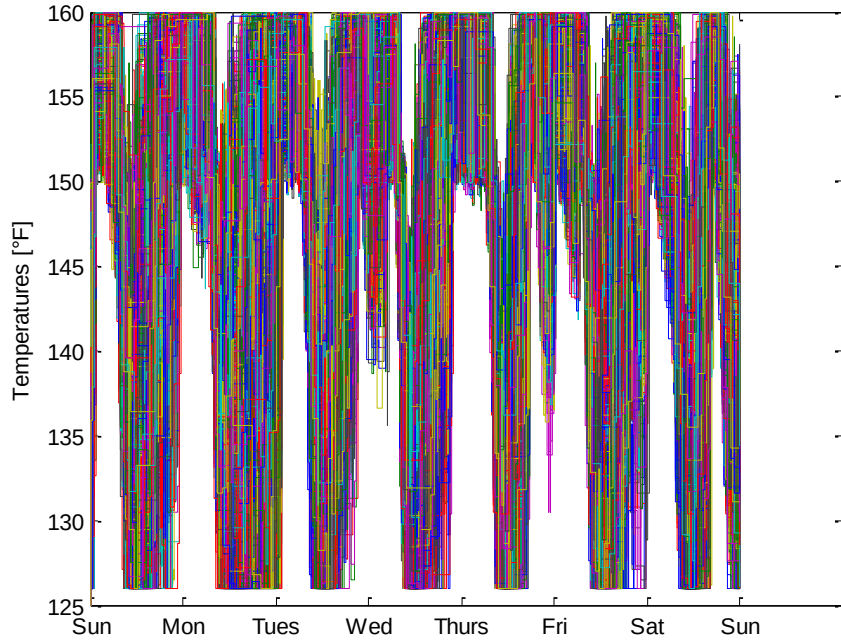


Fig. 39: Thermostat Setpoint Temperatures of Each EWH, Case 1.

Goal 2: Load Shifting from On-Peak to Off-Peak Hours

The total energy consumed by the 1000 EWHs in the 7-day simulation period was 279.66 GJ (or 77.683 MWh), as shown in Figure 42. Figure 40a shows the power demand profile of the 1000 EWHs for the 7-day period. The total energy demand during on-peak hours was 48.218 GJ (less than 82.199 GJ as in Case 0), and the total energy demand during off-peak hours was 231.44 GJ. Therefore, 17.2417% of the demand occurred during on-peak hours (less than 30.0688% as in Case 0), and 82.7583% occurred during off-peak hours. Figure 40b shows the power demand profile of the 1000

EWs for Wednesday only, in which the aforementioned shift in demand from on-peak hours to off-peak hours in Case 1, as compared to Case 0, is more apparent.

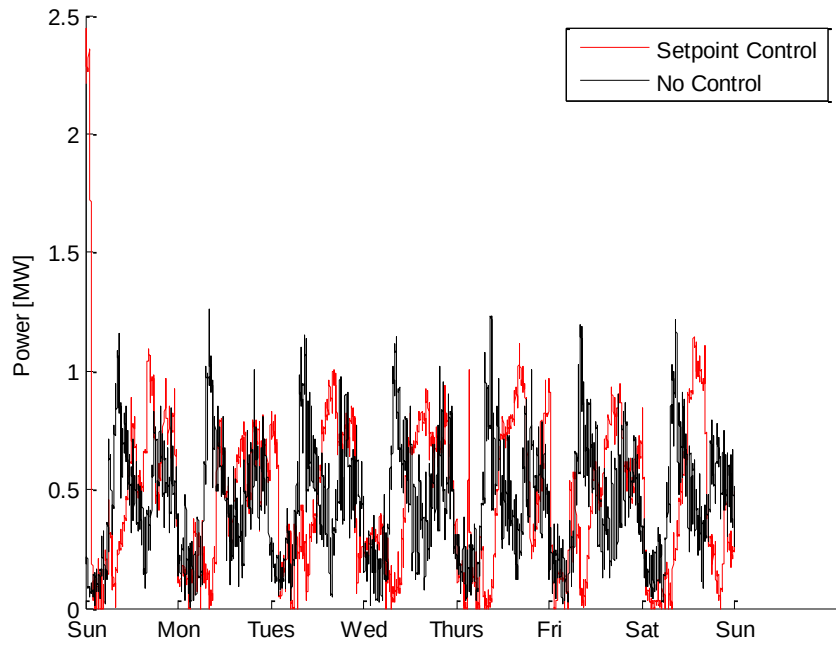


Fig. 40a: Total Power Demand of 1000 EWHs, Case 1.

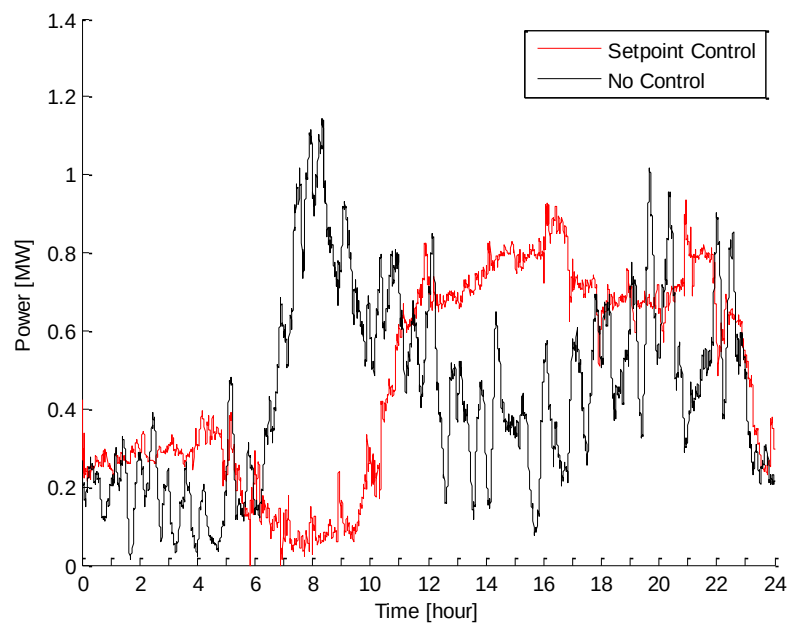


Fig. 40b: Total Power Demand of 1000 EWHs, Wednesday, Case 1.

Figures 41a and 41b show the total power demand of 1000 typical residences, in response to the winter balancing reserve signal, and the winter time-of-use pricing signal. There is some shifting of the demand of residences from on-peak to off-peak hours overall. In Figure 41b, it is especially easy to see that the residences in Case 1 have lower demand during the morning on-peak hours than Case 0, although Case 1 also has higher demand during the evening on-peak hours.

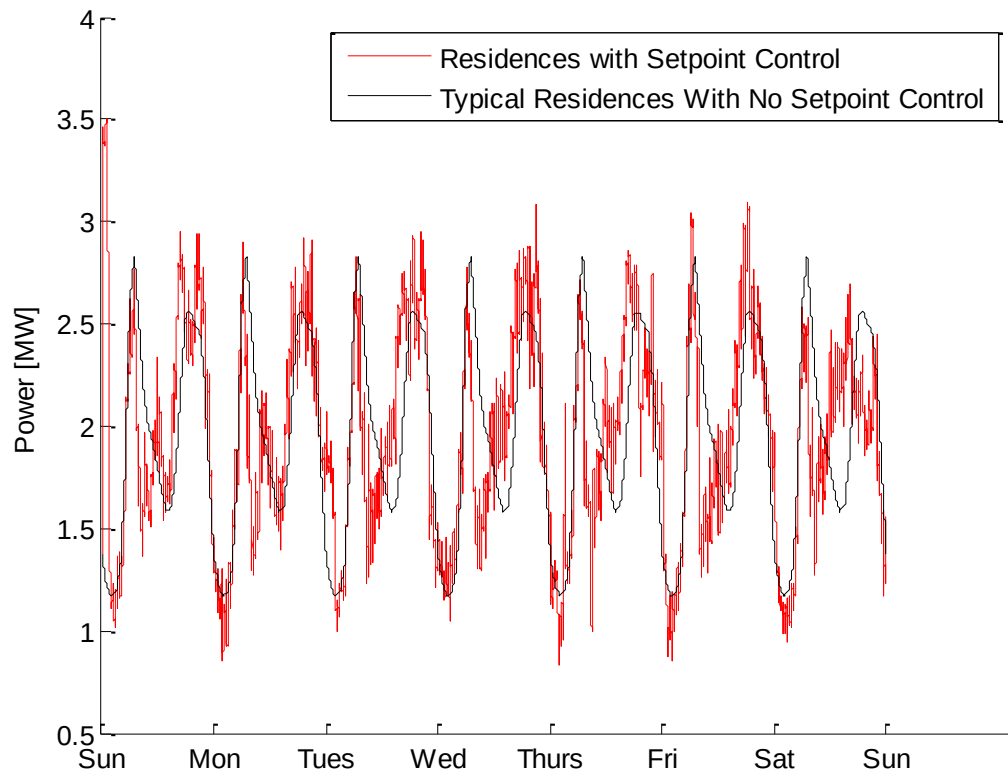


Fig. 41a: Total Power Demand of 1000 Typical Residences, Case 1.

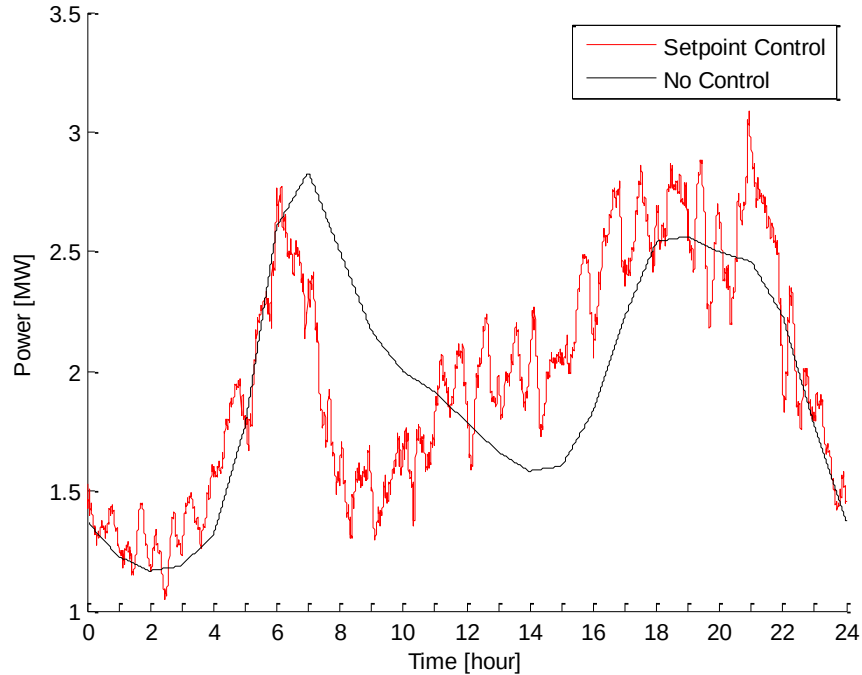


Fig. 41b: Total Power Demand of 1000 Typical Residences, Wednesday, Case 1.

Goal 3: Peak Load Equality or Reduction

The peak load in this setpoint control case was 8.9286% lower than in the no setpoint control case. The maximum power demand in the no control case was 1.260 MW, and was 1.148 MW in this setpoint control case (Figure 40).

Goal 4: Total Energy Demand Equality or Reduction

The total energy demand of the 1000 EWHs for the 7-day period for Case 1 (and Case 0) is shown in Figure 42. The total energy consumed in one week by all EWHs in the model is 279.66 GJ (or 77.683 MWh). This is 2.3011% more energy than in Case 0 with no thermostat setpoint control, and therefore a 2.3011% increase in average power

demand over the no setpoint control case, as shown in Figure 42. The average power demand in this setpoint control case was 462.3994 kW.

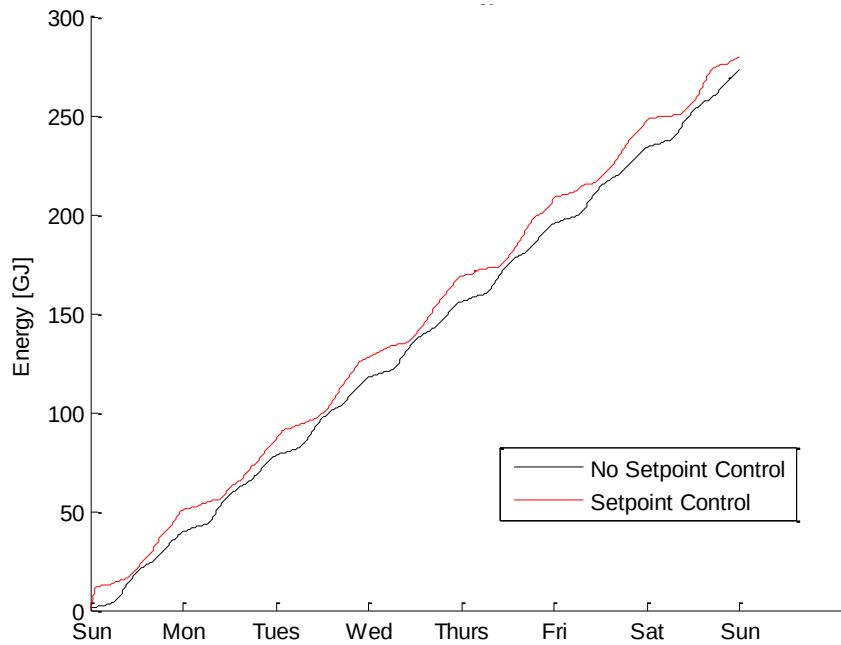


Fig. 42: Cumulative Energy Demand, Case 1.

Goal 5: Economic Benefit to Customer

The average EWH in this setpoint control model consumes 77.6831 kWh of energy in one week. Under the flat-rate pricing scheme, the total cost for the average EWH is \$8.9461, which is 1.7700% more expensive than in the \$8.7905 cost in Case 0.

Goal 6: Provide Desired Balancing Reserves

Figure 43 shows the absolute error between the balancing reserve desired by the utility and the balancing reserve created by the 1000 EWH population. The line width in the following figure makes it appear that there were lasting errors, but, in fact, this

control case provides perfect matching (no difference between desired balancing reserve and balancing reserve created) 93.17% of the time.

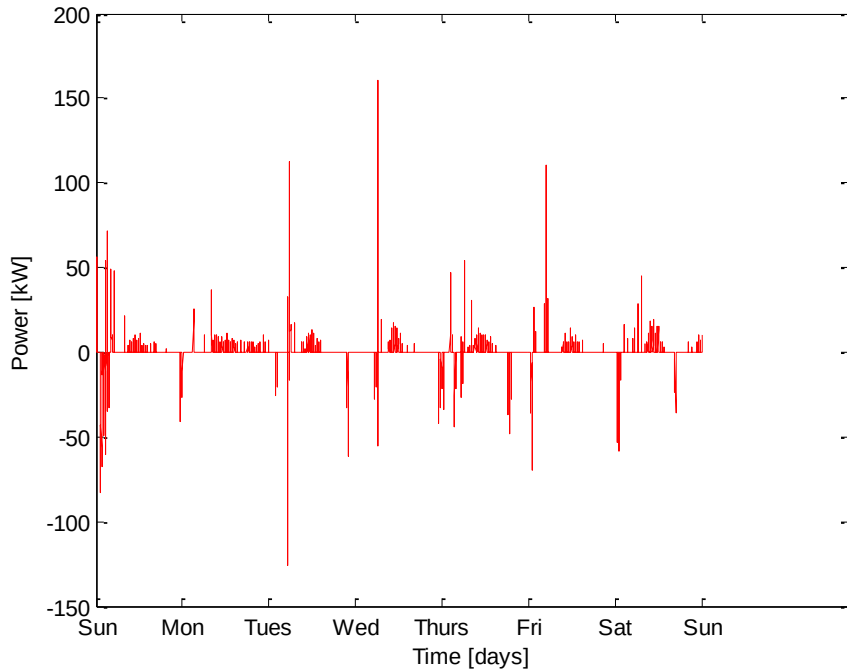


Fig. 43: Absolute Error Between Balancing Reserve Desired and Created, Case 1.

In Figure 44, the difference between the balancing reserve desired and the balancing reserve created can be seen, for a period of time when the balancing reserve matching was good. Note that the tiny differences between them is due to the fact that if the balancing reserve needed is less than half of one EWH power, that is, less than 2.25 kW, then no EWHs can be changed in order to more closely satisfy the desired balancing reserve.

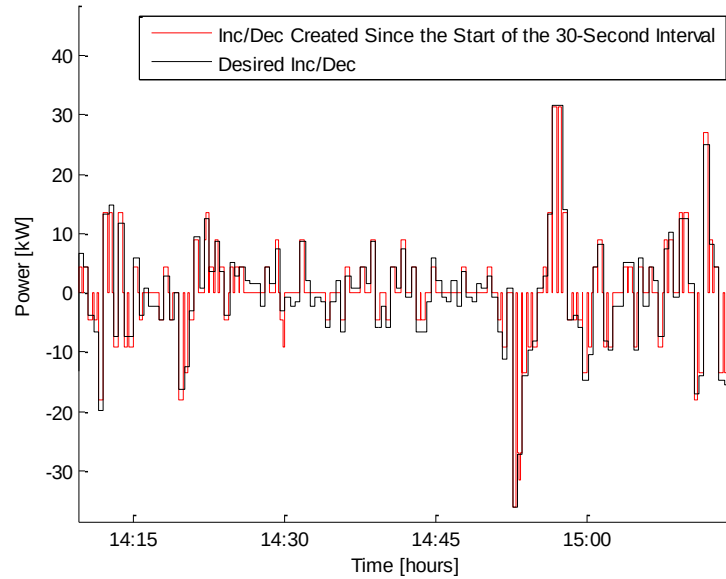


Fig. 44: Balancing Reserve Desired and Created, Sunday, Case 1.

Figure 45 shows the balancing reserve desired and the balancing reserve created when there were not enough EWHs available to satisfy the balancing reserve needed. The large error seen just after 5:45 AM corresponds to the largest error on the plot in Figure 43.

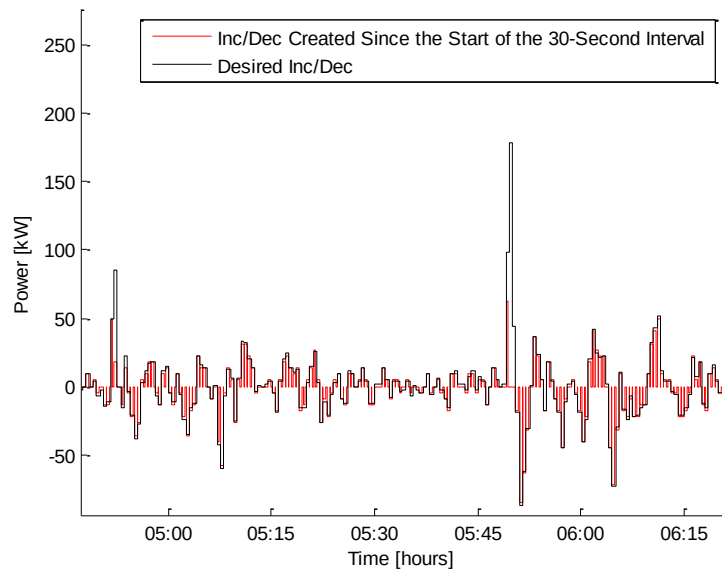


Fig. 45: Balancing Reserve Desired and Created, Wednesday, Case 1.

The very large error in the balancing reserve created occurred during the early morning hours. Nearly all of the EWHs were in the OFF state, as shown in Figure 46. When a large amount of INC was needed at this time, or an increase in reserve and therefore decrease in demand, there were not enough EWHs in the ON state to turn OFF, and thus reduce the power demand and satisfy the balancing reserve needed.

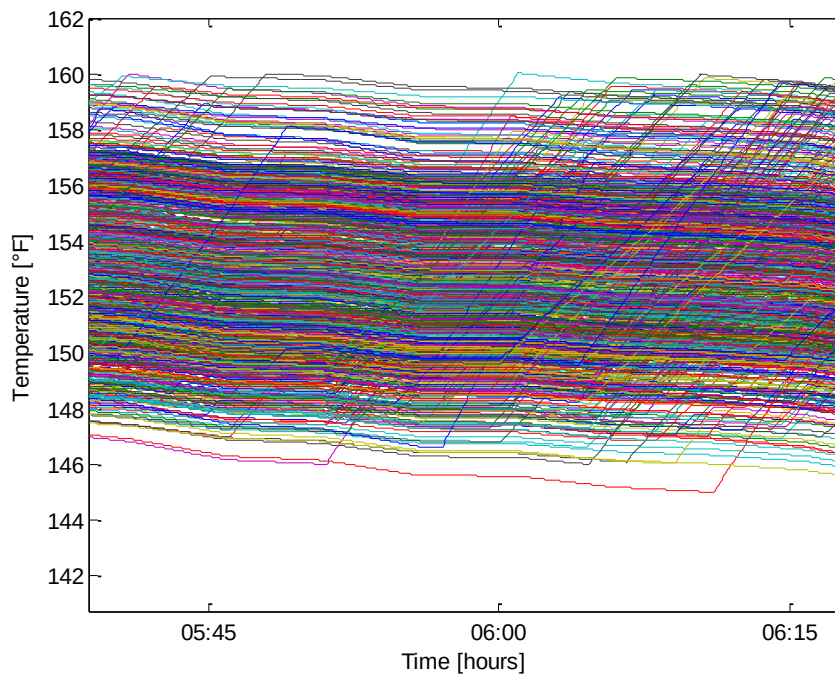


Fig. 46: Outgoing Water Temperature of Each EWH, Wednesday, Case 1.

Figure 47 shows the PDF for the absolute value of the absolute error between the balancing reserve desired by the utility and the balancing reserve created by the 1000 EWH population. There was a high probability of very small errors, and a very low probability of high errors.

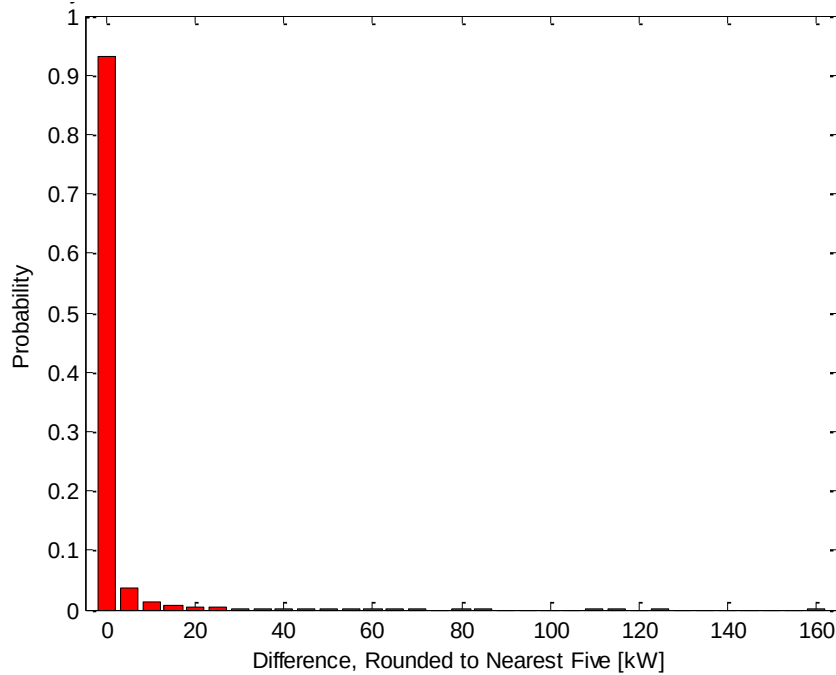


Fig. 47: Probability Distribution Function for Absolute Error Between Balancing Reserve Desired and Created, Case 1.

Case 2: EWH Thermostat Setpoint Control Based on Time-of-Use Pricing

In Case 2, the thermostat setpoints of the EWHs remained constant at 130°F during off-peak hours for Case 2A, and 160°F during off-peak hours for Case 2B. Therefore, the water temperatures remained between 120°F and 130°F during off-peak hours for Case 2A, and 150°F and 160°F during off-peak hours for Case 2B. During on-peak hours, the thermostat setpoints for both scenarios were set to 126°F, and therefore the water temperatures remained between 116°F and 126°F. No balancing reserves were supplied in Case 2.

Case 2A: Maximum Thermostat Setpoint 130°F

Goal 1: Maintain Customer Comfort Level. The hot water supply was always maintained within reasonable and safe operating limits. The thermostat setpoints ranged from 126°F to 130°F. The water temperature inside the EWH tank had a minimum of 116°F and a maximum of 130°F, as shown in Figure 48.

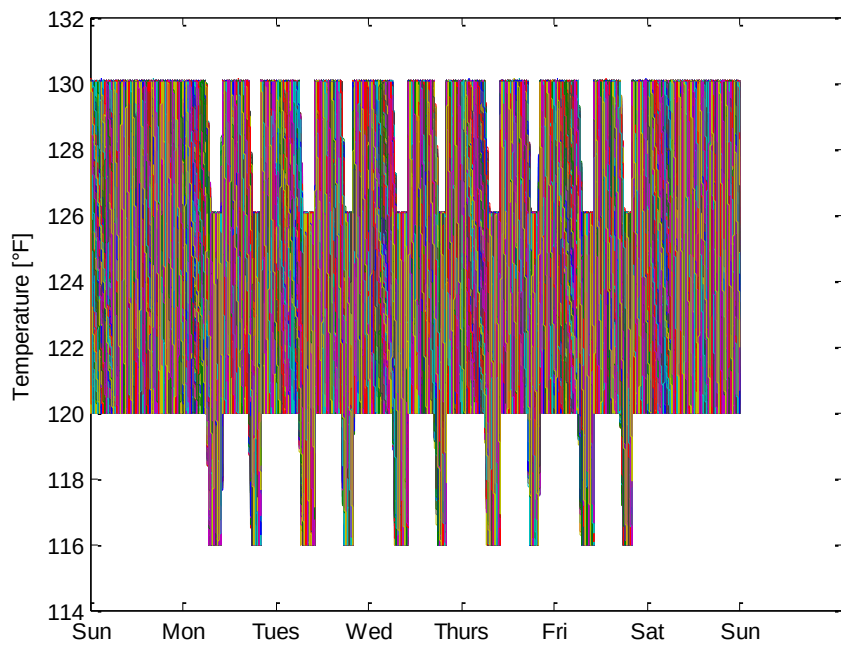


Fig. 48: Outgoing Water Temperature of Each EWH, Case 2A.

Figure 49 illustrates that the thermostat setpoints were not at all diversified in Case 2A. This will be important when load-shifting and peak power demand are analyzed below.

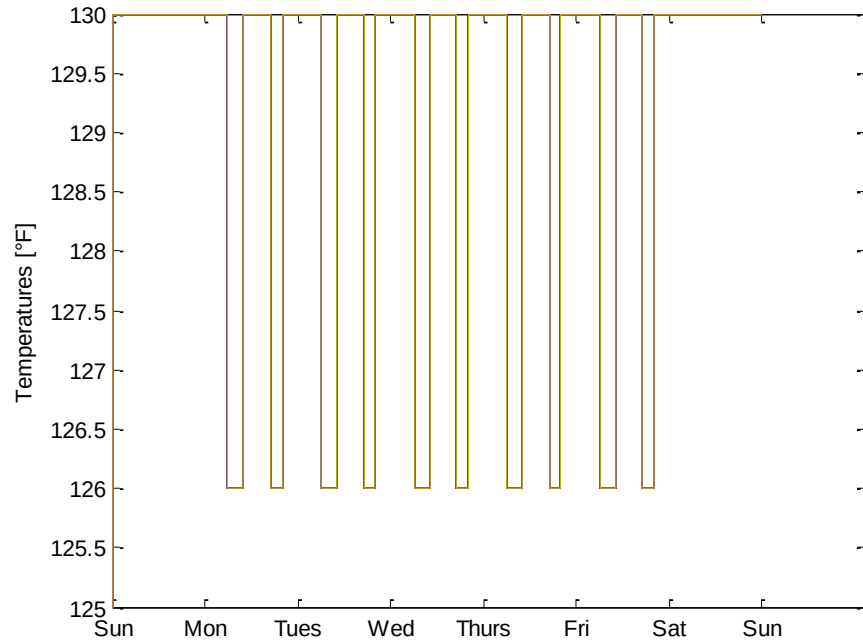


Fig. 49: Thermostat Setpoint for Each EWH, Case 2A.

Goal 2: Load Shifting from On-Peak to Off-Peak Hours. Figure 50a shows the power demand profile of the 1000 EWHs for the 7-day period, for Case 2A and Case 0. The total energy consumed was 273.11 GJ (or 75.864 MWh). The total energy demand during on-peak hours was 67.033 GJ (less than 82.199 GJ as in Case 0), and the total energy demand during off-peak hours was 206.08 GJ. Therefore, 24.5444% of the demand occurred during on-peak hours (less than 30.0688% as in Case 0), and 75.4556% occurred during off-peak hours. Figure 50b illustrates that the power demand profiles of Case 2A and Case 1 are similar, because both cases had the same setpoints during off-peak hours, although Case 2A has much higher peaks in power demand at the ends of the on-peak periods. This issue will be further addressed in the analysis of “Goal 3: Peak Load Equality or Reduction.”

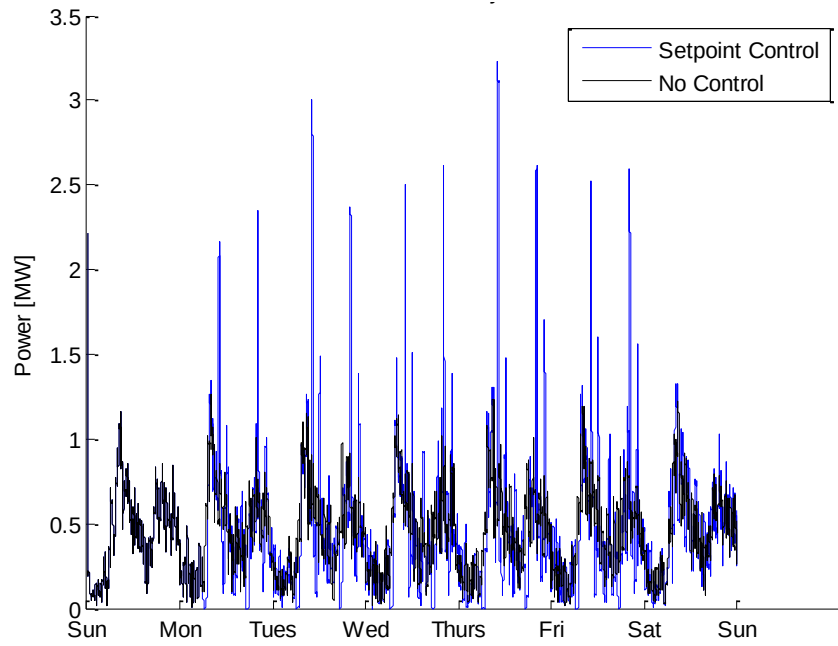


Fig. 50a: Total Power Demand of 1000 EWHs, Case 2A.

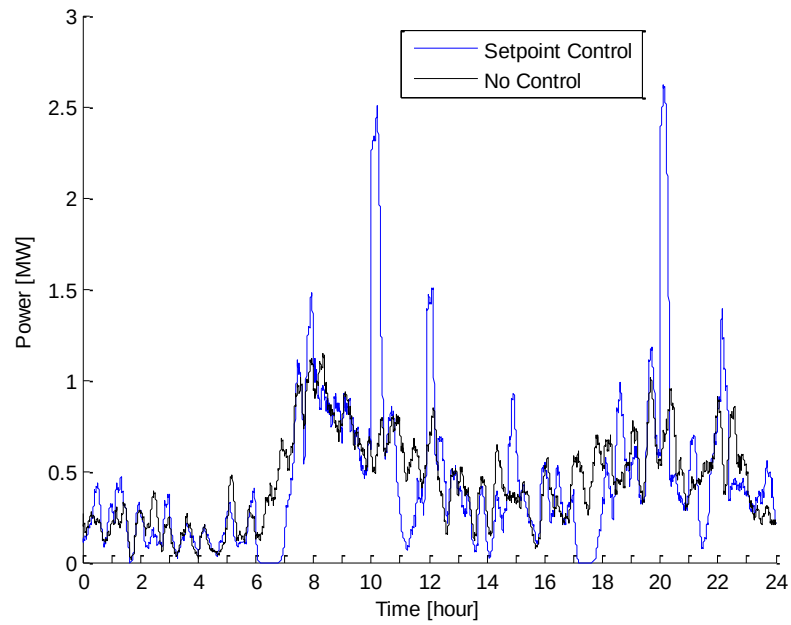


Fig. 50b: Total Power Demand of 1000 EWHs, Wednesday, Case 2A.

Figures 51a and 51b show the total power demand profile of 1000 typical residences, in response to the time-of-use pricing signal. The shift in peak demand of the EWHs results in some shifting of the peak demand of residences from on-peak to off-

peak hours, as in Figures 50a and 50b above, although it is difficult to see in the figures, because the maximum power demand during the on-peak hours is increased greatly.

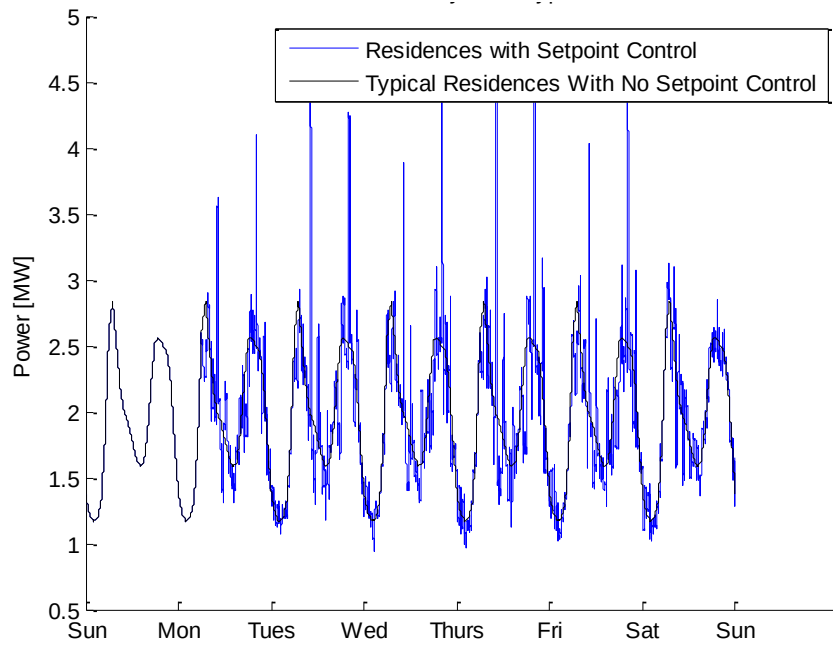


Fig. 51a: Total Power Demand of 1000 Typical Residences, Case 2A.

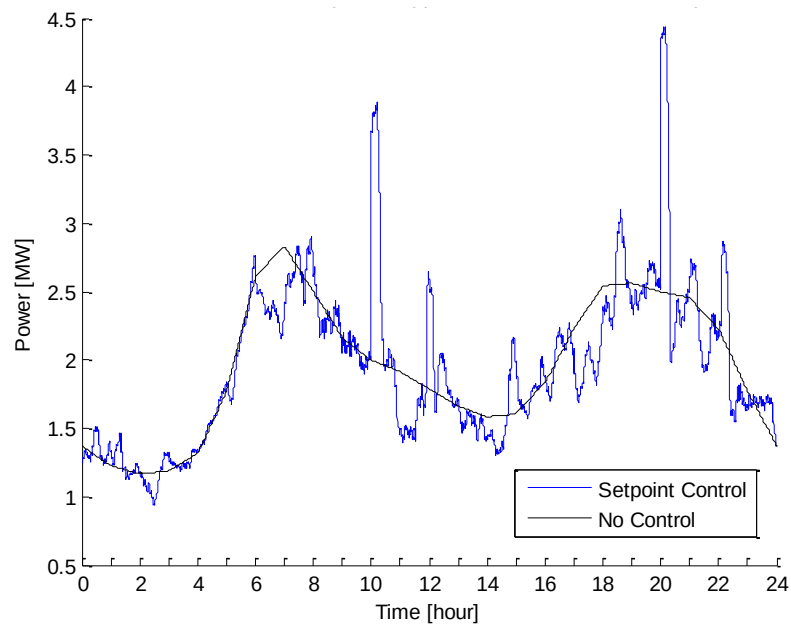


Fig. 51b: Total Power Demand of 1000 Typical Residences, Wednesday, Case 2A.

Goal 3: Peak Load Equality or Reduction. The peak load in this setpoint control case was 156.4286% higher than in the no setpoint control case. The maximum power demand in the no control case was 1.260 MW, and was 3.231 MW in the setpoint control case. This result is very undesirable. Although the customer may save money by changing the thermostat setpoint to consume less energy during on-peak hours when price is high, there is a “payback period” at the end of the on-peak hours, when the thermostat setpoints are raised again, in order to pre-heat the water for the next on-peak period. There was a 18.4503% shift in demand from on-peak to off-peak hours when compared to the no-control case, and a more than two-fold increase in maximum power. Therefore, the benefit to the utility for the load shifting would be far outweighed by the disadvantage of the increase in maximum power demand.

Goal 4: Total Energy Demand Equality or Reduction. The total energy consumed in one week by all EWHs in the model is 273.11 GJ (or 75.864 MWh). This is 0.0946% less energy than in Case 0 with no thermostat setpoint control, and therefore a 0.0946% decrease in average power demand over the no setpoint control case, as shown in Figure 52. The average power demand in this setpoint control case was 451.5709kW.

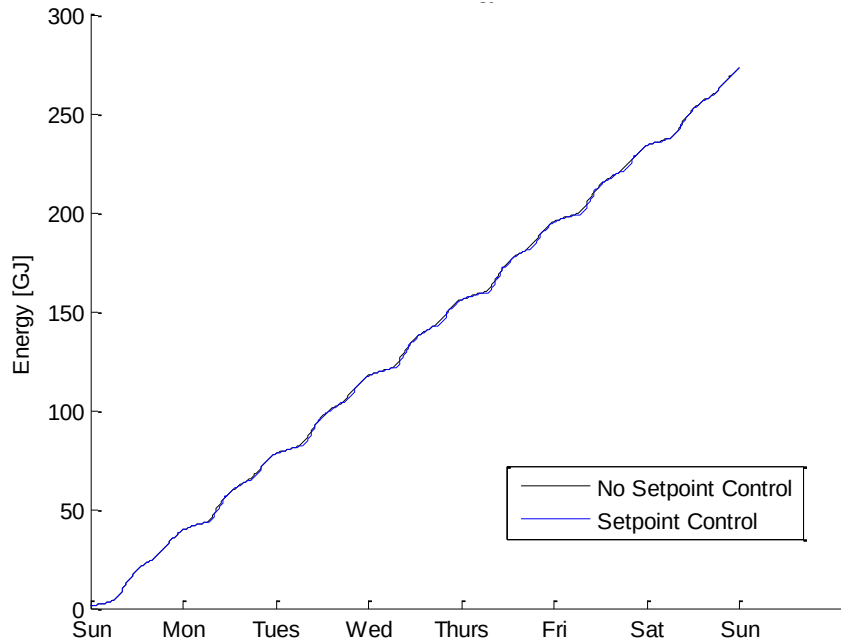


Fig. 52: Cumulative Energy Demand, Case 2A.

Goal 5: Economic Benefit to Customer. The average EWH in this setpoint control model consumes 75.8639 kWh of energy in one week. Under the time-of-use pricing scheme, total cost for the average EWH is \$4.8099, which is 45.2830% cheaper than the \$8.7905 cost in Case 0. However, due to the extremely large increase in maximum power demand, the utility would not likely use this particular method in a smart-grid environment.

Goal 6: Provide Desired Balancing Reserves. There were no balancing reserves provided in this case.

Case 2B: Maximum Thermostat Setpoint 160°F

Goal 1: Maintain Customer Comfort Level. The hot water supply was always maintained within reasonable and safe operating limits. The thermostat setpoints ranged

from 126°F to 160°F. The water temperature inside the EWH tank had a minimum of 116°F and a maximum of 160°F. Figure 53 shows the water temperature of each EWH. There is good diversity during the off-peak hours, but extremely poor diversity during the on-peak hours, and at the very beginning of the off-peak hours, when all EWHs are in the ON state at once. This will create problems in terms of maximum power demand, which will be examined later.

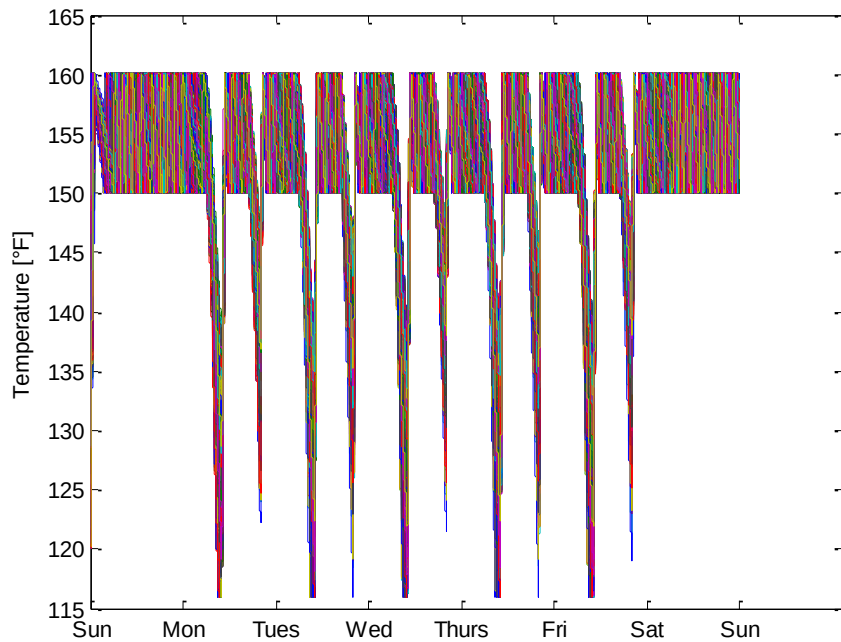


Fig. 53: Outgoing Water Temperature of Each EWH, Case 2B.

The thermostat setpoints are not diversified in this case, as evidenced in Figure 54.

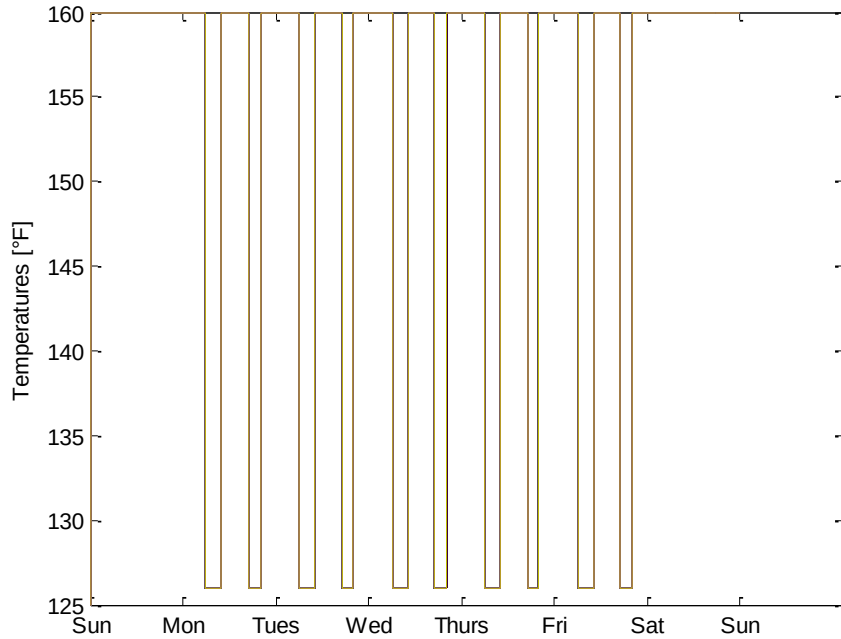


Fig. 54: Thermostat Setpoint for Each EWH, Case 2B.

Goal 2: Load Shifting from On-Peak to Off-Peak Hours. Figure 55a shows the power demand profile for the 1000 EWHs for the 7-day period. Some of the load was shifted from on-peak hours to off-peak hours, as is especially evident in Figure 55b. The total energy consumed was 289.71 GJ (or 80.475 MWh). The total energy demand during on-peak hours was 0.7537 GJ (less than 82.199 GJ as in Case 0), and the total energy demand during off-peak hours was 288.95 GJ. Therefore, 0.2601% of the demand occurred during on-peak hours (less than 30.0688% as in Case 0), and the vast majority, 99.7399%, occurred during off-peak hours. However, this case is highly undesirable, due to the extremely high maximum power demand, as will be explained later.

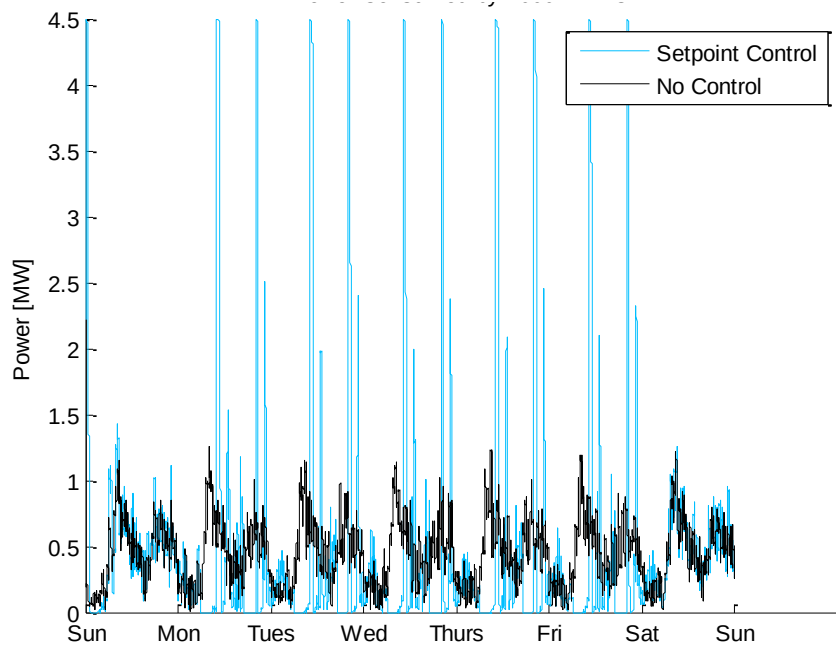


Fig. 55a: Total Power Demand of 1000 EWHs, Case 2B.

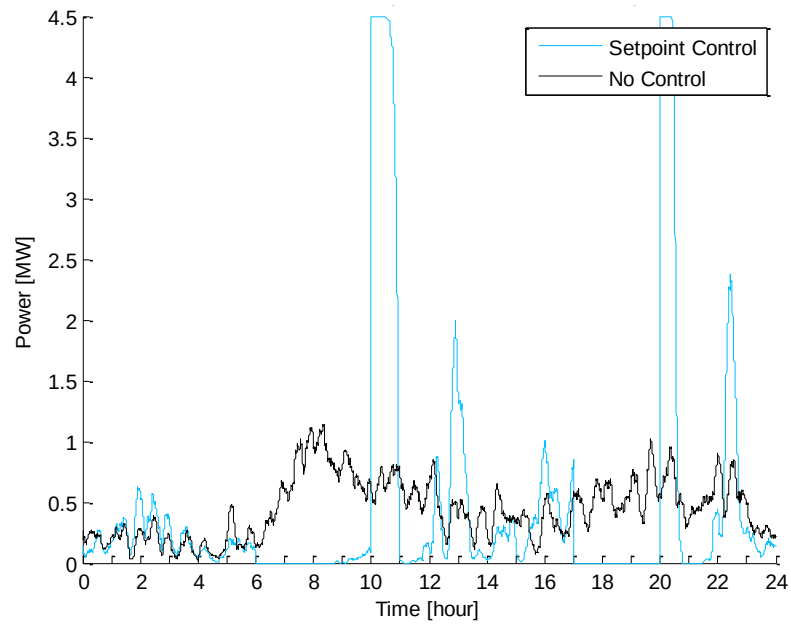


Fig. 55b: Total Power Demand of 1000 EWHs, Wednesday, Case 2B.

Figures 56a and 56b show the total power demand of 1000 typical residences, in response to the winter balancing reserve signal, and the winter time-of-use pricing signal.

The shift in peak demand of the EWHs results in successful shifting of the peak demand of residences from on-peak to off-peak hours, because the EWHs make up a large percentage of the residential demand. The disadvantage is that the spikes in the EWH power demand profile directly cause spikes in the residential power demand profile, as is especially evident when comparing Figures 55b and 56b.

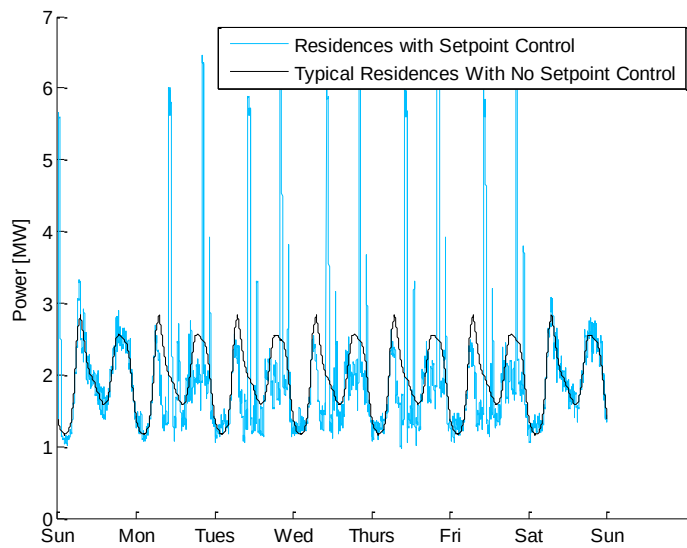


Fig. 56a: Total Power Demand of 1000 Typical Residences, Case 2B.

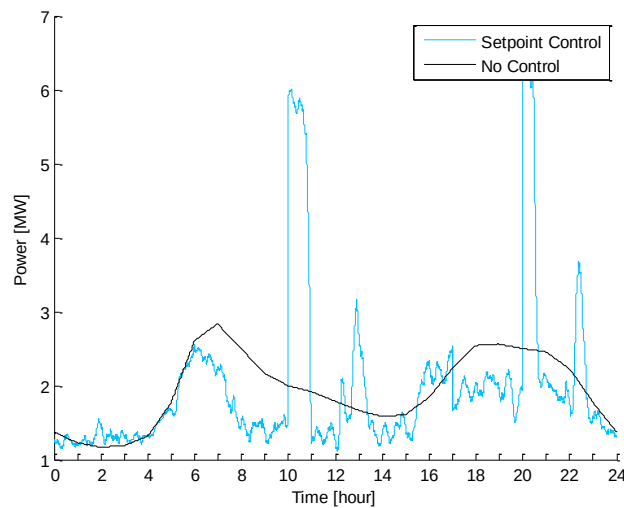


Fig. 56b: Total Power Demand of 1000 Typical Residences, Wednesday, Case 2B.

Goal 3: Peak Load Equality or Reduction. The peak load in this setpoint control case was 257.1429% higher than in the no setpoint control case. The maximum power demand in the no control case was 1.260 MW, and was 4.500 MW in the setpoint control case. This result is extremely undesirable, and would be unacceptable for the utility. Although there was a 99.0831% shift in demand from on-peak to off-peak hours when compared to the no-control case, there was nearly a three-fold increase in maximum power. Therefore, the benefit to the utility for the load shifting would be far outweighed by the disadvantage of the increase in maximum power demand.

Goal 4: Total Energy Demand Equality or Reduction. The total energy consumed in one week by all EWHs in the model is 289.71 GJ (or 80.475 MWh). This is 5.9789% more energy than in Case 0 with no thermostat setpoint control, and therefore a 5.9789% increase in average power demand over the no setpoint control case, as shown in Figure 57. The average power demand in this setpoint control case was 479.0228 kW.

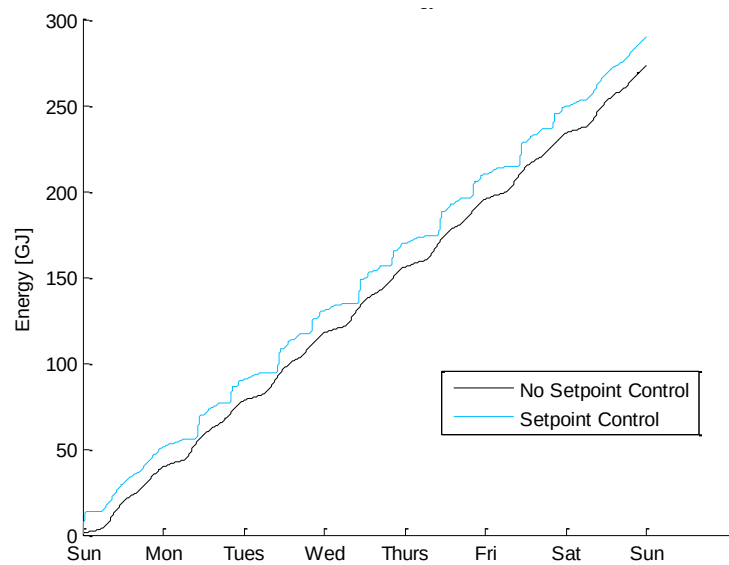


Fig. 57: Cumulative Energy Demand of the 1000 EWHs, Case 2B.

Goal 5: Economic Benefit to Customer. The average EWH in this setpoint control model consumes 80.4758 kWh of energy in one week. Under the time-of-use pricing scheme, the total cost for the average EWH is \$4.8824, which is 44.4582% cheaper than the \$8.7905 cost in Case 0. However, due to the extremely large increase in maximum power demand, the utility would not use this particular method on its own in a smart-grid environment.

Goal 6: Provide Desired Balancing Reserves. There were no balancing reserves provided in this case.

Case 3: EWH Thermostat Setpoint Control
Based on Time-of-Use Pricing, and Balancing
Reserves Desired During Off-Peak Hours

In Case 3, the thermostat setpoints of all EWHs were set to 126°F during on-peak hours, in response to the time-of-use pricing scheme, and therefore the water temperatures remained between 116°F and 126°F. No balancing reserves were supplied during on-peak hours. During off-peak hours, the EWHs provided balancing reserves, allowing the thermostat setpoints to be adjusted between 126°F and 160°F, and thus the temperatures could range between 116°F and 160°F during off-peak hours.

Goal 1: Maintain Customer Comfort Level

The hot water supply was always maintained within reasonable and safe operating limits. The thermostat setpoints ranged from 126°F to 160°F. The water temperature inside the EWH tank had a minimum of 116°F and a maximum of 160°F, as shown in Figure 58.

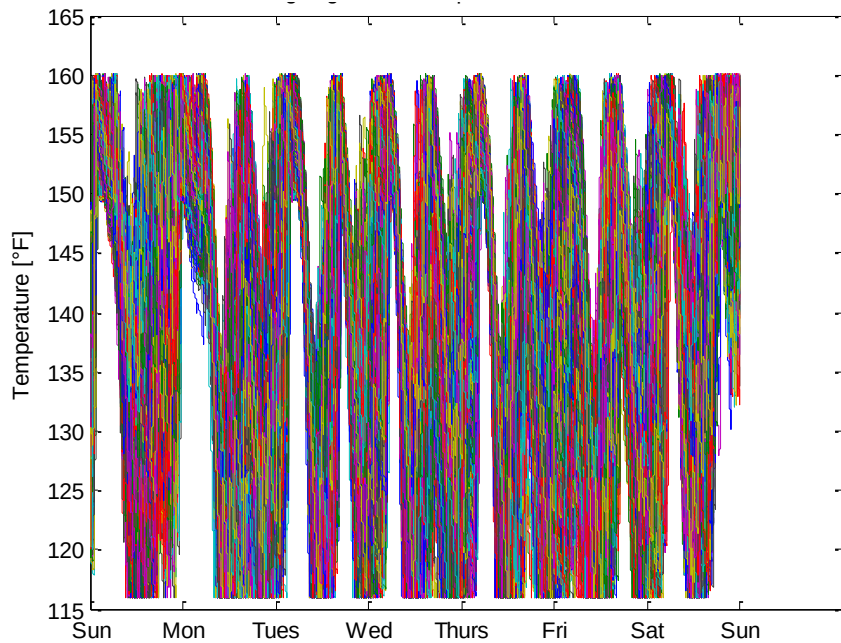


Fig. 58: Outgoing Water Temperature of Each EWH, Case 3.

As stated in Case 1, the diversity of the EWH population at any given time is of great importance to balancing reserve control – having EWHs in both the ON and OFF states, as well as a large temperature range of the EWH population. At most times, the EWHs in Case 3 are evenly distributed between increasing and decreasing, meaning that they are not all in the ON or OFF state. The exception to this is during the on-peak hours, because all EWH setpoints are minimized to 126°F, and therefore all EWH temperatures are decreasing simultaneously. However, during this time, no balancing reserve based thermostat setpoint control was implemented.

Figure 59 shows the EWH thermostat setpoints. During the on-peak hours, when all EWH setpoints were set to the minimum of 126°F, there was little diversity in the thermostat setpoints. During the off-peak hours, there was a large diversity in the thermostat setpoints.

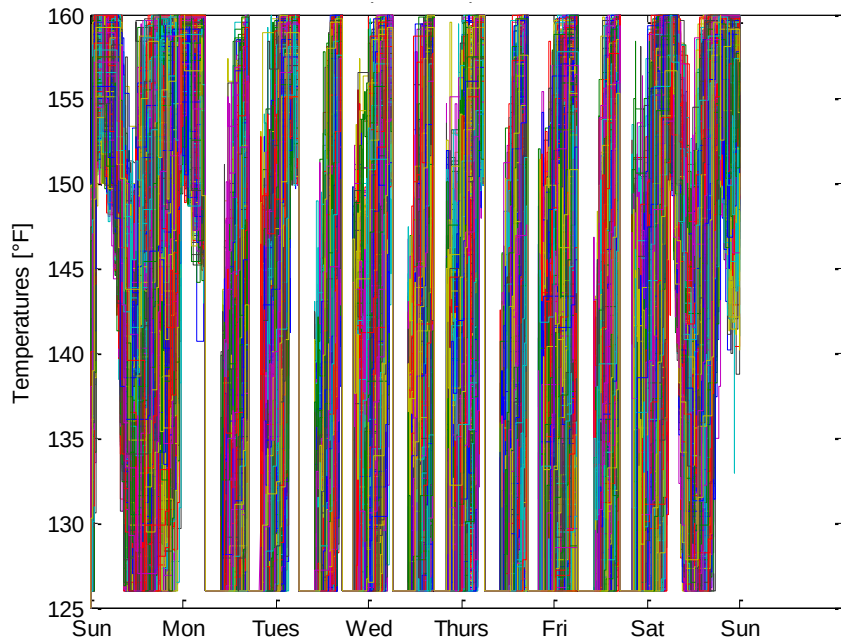


Fig. 59: Thermostat Setpoint of Each EWH, Case 3.

Goal 2: Load Shifting from On-Peak to Off-Peak Hours

Figure 60a shows the power demand profile of the 1000 EWHs for the 7-day period. The load was successfully shifted from on-peak hours to off-peak hours, as is especially evident in Figure 60b. The total energy consumed was 286.22 GJ (or 79.505 MWh). The total energy demand during on-peak hours was 4.0913 GJ (less than 82.199 GJ as in Case 0), and the total energy demand during off-peak hours was 282.1308 GJ. Therefore, 1.4294% of the demand occurred during on-peak hours (less than 30.0688% as in Case 0), and the vast majority, 98.5706%, occurred during off-peak hours.

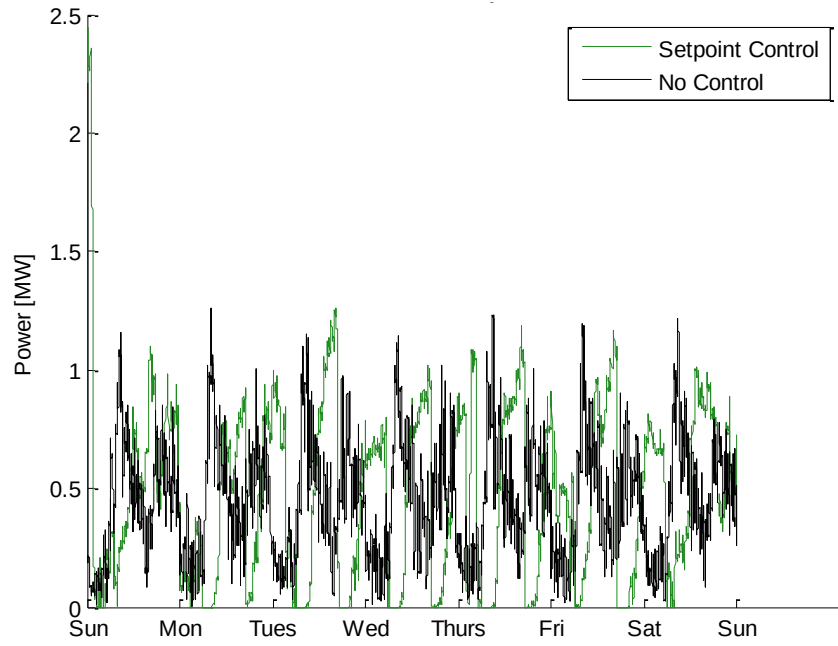


Fig. 60a: Power Demand of 1000 EWHs, Case 3.

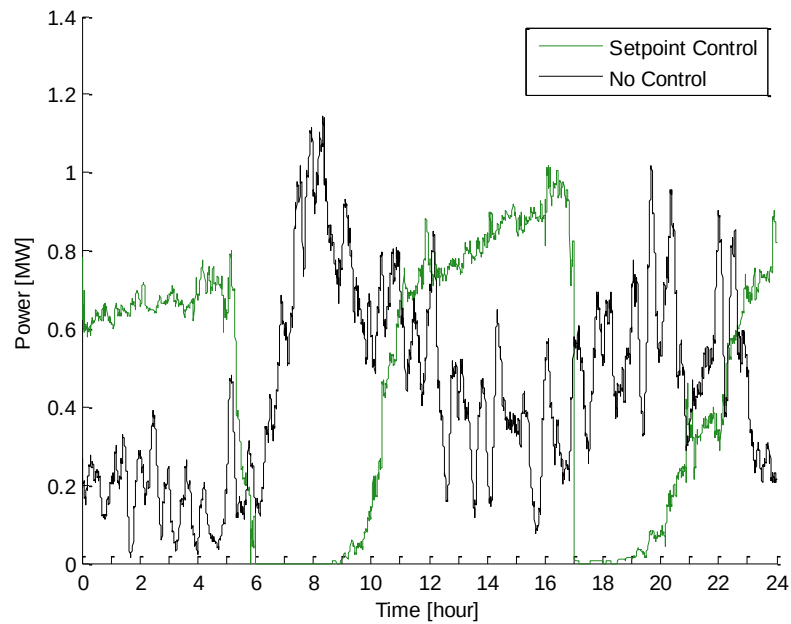


Fig. 60b: Power Demand of 1000 EWHs, Wednesday, Case 3.

Figures 61a and 61b show the total power demand of 1000 typical residences, in response to the winter balancing reserve signal, and the winter time-of-use pricing signal.

The shift in peak demand of the EWHs results in successful shifting of the peak demand of residences from on-peak to off-peak hours. This is especially evident when comparing Figures 60b and 61b, in which the peaks in the power demand for Case 3 occur at approximately the same times during the day, during off-peak hours for demand.

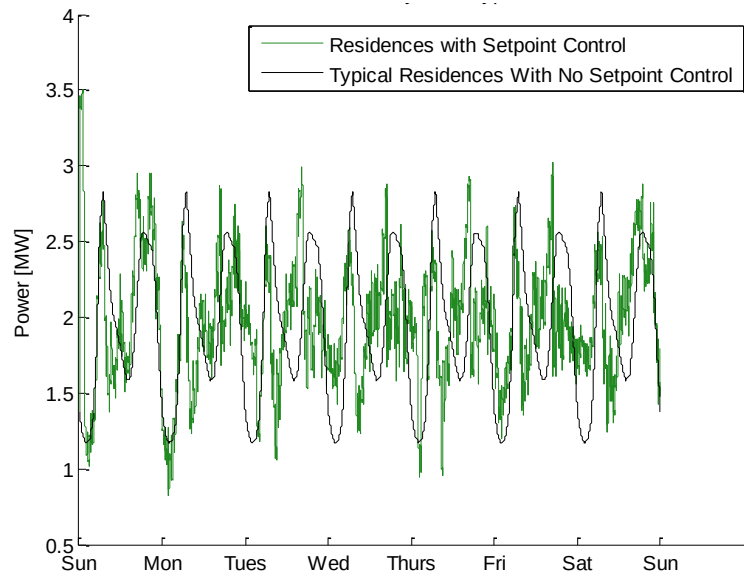


Fig. 61a: Total Power Demand of 1000 Typical Residences, Case 3.

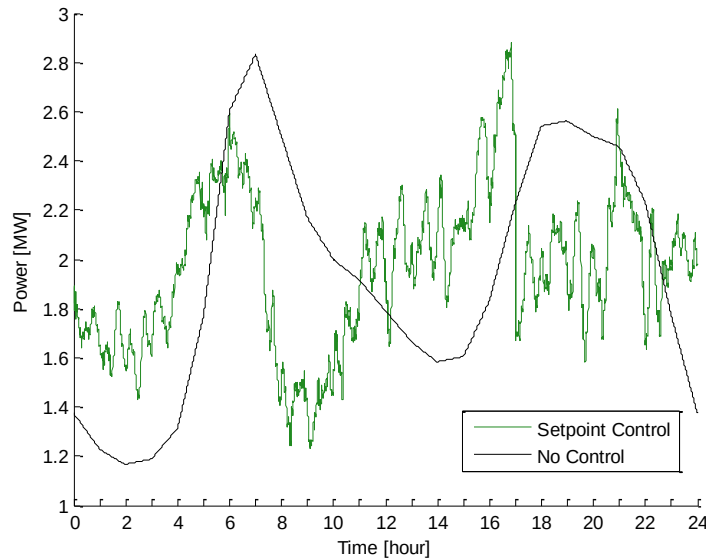


Fig. 61b: Total Power Demand of 1000 Typical Residences, Wednesday, Case 3.

Goal 3: Peak Load Equality or Reduction

The peak load remained approximately the same in this setpoint control case, as in the no setpoint control case. The maximum power demand in both cases was 1.260 MW.

Goal 4: Total Energy Demand Equality or Reduction

Figure 62 shows the cumulative energy demand of the 1000 EWHs, in response to the winter balancing reserve signal, and the winter time-of-use pricing signal. Note that it is very similar to the no setpoint control case (Case 0). There is a 4.7019% energy increase over the no setpoint control case, and therefore a 4.7019% increase in average power demand over the no setpoint control case. The average power demand in Case 3 was 473.2508 kW.

There is a noticeable difference in the rate of energy use, or the power, of the setpoint control case, as compared to the no setpoint control case. The greatest rates of energy use occurs during the middle of each day, between the morning and evening on-peak hours, and during the middle of the night, between evening and morning on-peak hours. This is because the thermostat setpoints are at the absolute minimum during on-peak hours, but are adjusted to provide balancing reserves during off-peak hours.

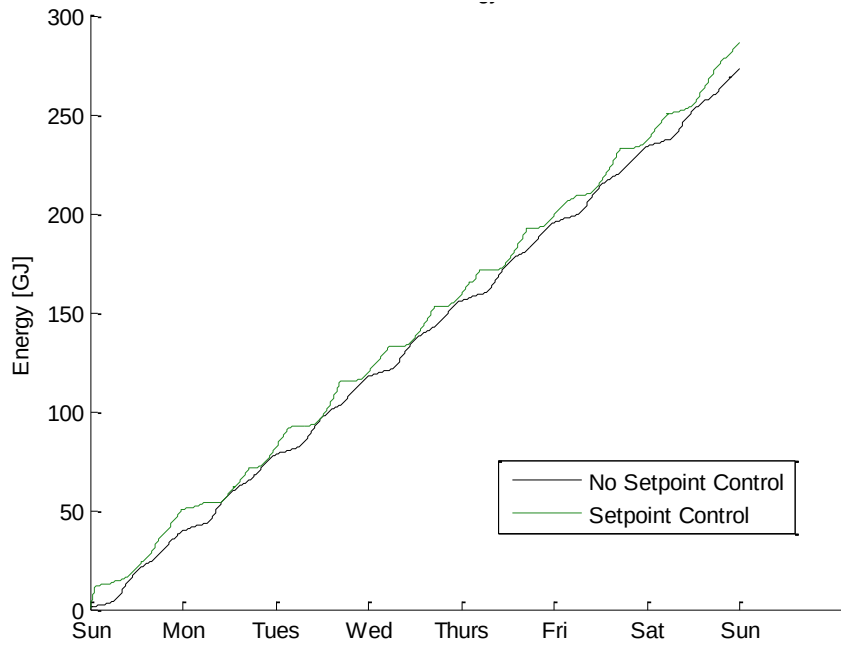


Fig. 62: Cumulative Energy Demand of the 1000 EWHs, Case 3.

Goal 5: Economic Benefit to Customer

The average EWH in this setpoint control model consumes 79.5061 kWh of energy in one week. Under the time-of-use pricing scheme, the total cost for the average EWH is \$4.8340, which is 45.0088% less expensive than the \$8.7905 cost in Case 0.

Goal 6: Provide Desired Balancing Reserves

Figure 63 shows the absolute error between the balancing reserve desired by the utility and the balancing reserve created by the 1000 EWH population. This control case provides perfect matching (0 kW difference between desired balancing reserve and balancing reserve created) 75.92% of the time. The error is partly a result of the unavailability of EWHs for demand response during on-peak hours. Additionally, loss of diversity of temperatures or ON/OFF states of the EWH population contributes to balancing reserve error, as will be addressed below.

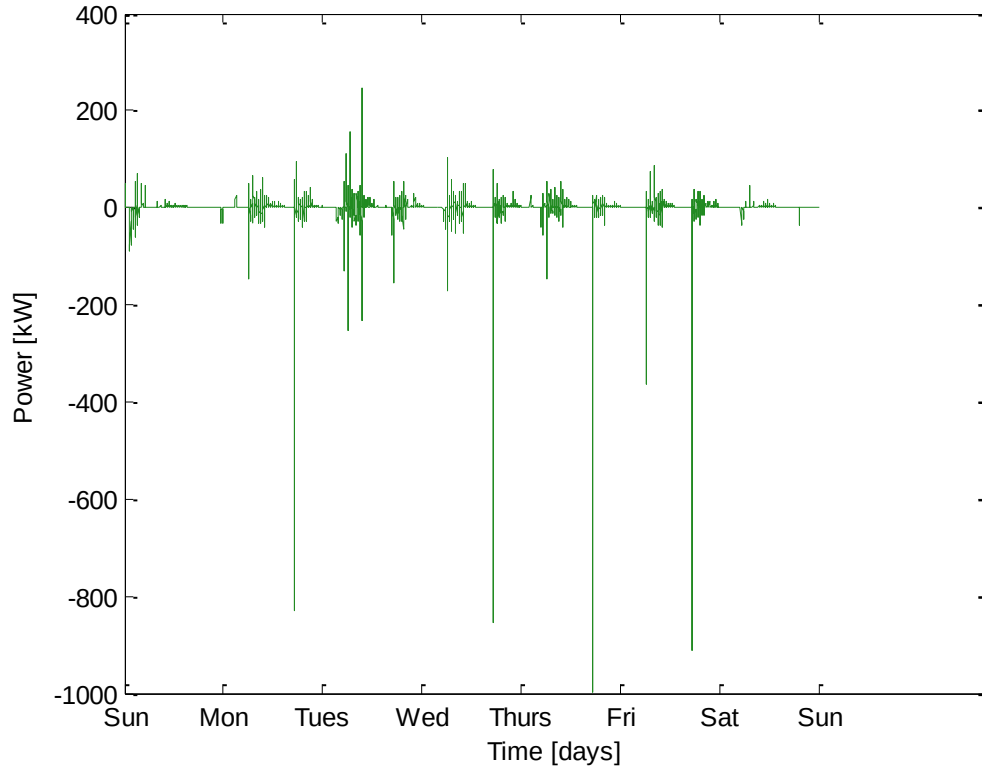


Fig. 63: Absolute Error Between Balancing Reserve Desired and Created, Case 3.

In figure 64, the difference between the balancing reserve desired and the balancing reserve created can be seen, for a period of time when the balancing reserve matching was good. Note that the tiny differences between the two waveforms is due to the fact that if the balancing reserve needed is less than half of one EWH power, that is less than 2.25 kW, then no EWHs can be changed in order to more closely satisfy the desired balancing reserve.

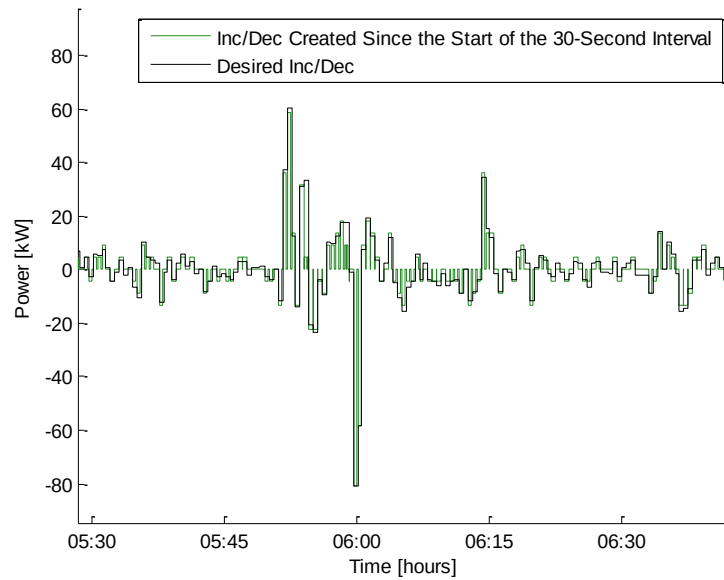


Fig. 64: Balancing Reserve Desired and Created, Saturday, Case 3.

Figure 65 shows the balancing reserve desired and the balancing reserve created when there were not enough EWHs available to satisfy the balancing reserve needed. The large error seen just after 5:00 PM corresponds to the largest error on the plot in Figure 63.

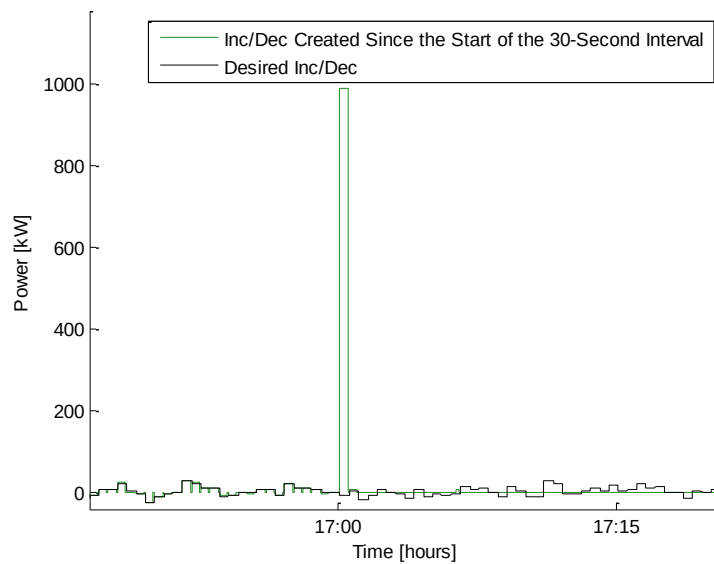


Fig. 65: Balancing Reserve Desired and Created, Thursday, Case 3.

The very large error in the balancing reserve created occurred at the beginning of the on-peak hours. At this point, all EWH setpoints were decreased to 126°F. Coincidentally, nearly one quarter of all EWHs were in the ON state, and this change in setpoint caused them to turn OFF at the same time. This change in power consumption corresponds to the state change viewable in Figure 66. Before 17:00 (5:00 PM) on Thursday, the temperatures of nearly one quarter of all EWHs are increasing, meaning that they are in the ON state and thus consuming power. After 17:00, the temperatures of all EWHs are decreasing, meaning that they are now in the OFF state and thus not consuming power. This instantaneous change in power demand for nearly one quarter of the EWHs caused a spike in the balancing reserve created. This problem could be avoided by the utility, because the thermostat setpoint decrease at the beginning of each on-peak period is predictable behavior. As the peak period nears, the utility operator could take steps to ensure that the number of EWHs in the ON state is small, by requesting more INC. This could spread the balancing reserve errors over time, instead of having one very large mismatch at the beginning of an on-peak period.

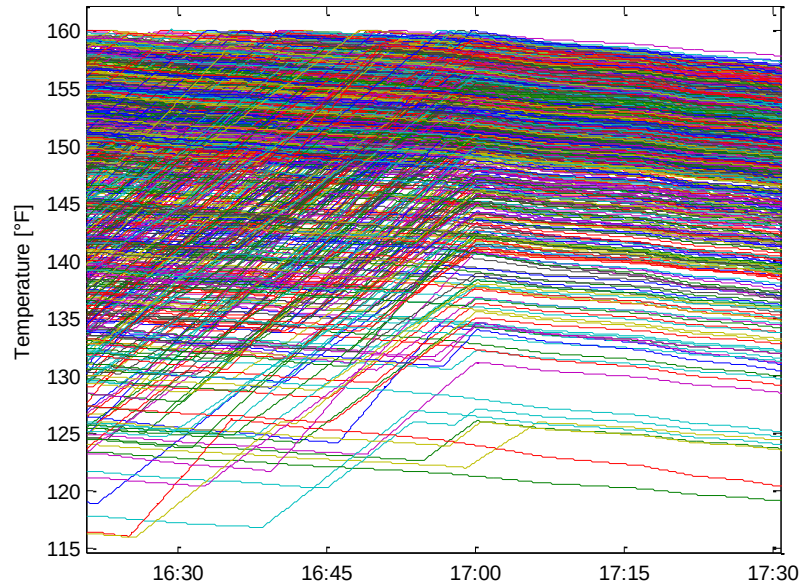


Fig. 66: Outgoing Water Temperature of Each EWH, Thursday, Case 3.

Figure 67 shows the PDF for the absolute value of the absolute error between the balancing reserve desired by the utility and the balancing reserve created by the 1000 EWH population. There was a high probability of very small errors, and a very low probability of high errors.

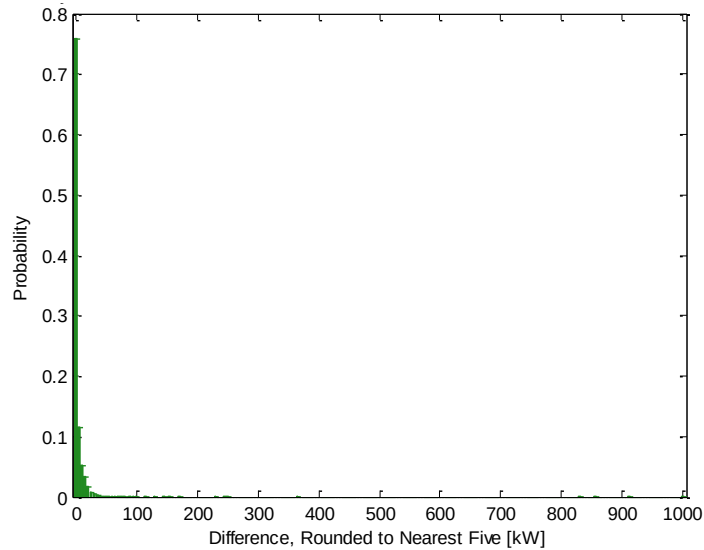


Fig. 67: Probability Distribution Function for Absolute Error Between Balancing Reserve Desired and Created, Case 3.

ANALYSIS OF SIMULATION RESULTS

Six Areas of Analysis of Experimental Results

For reference, the four experimental cases are summarized below:

Case 0: No EWH Thermostat Setpoint Control

Case 1: EWH Thermostat Setpoint Control Based on Balancing Reserves Desired by Utility

Case 2A: EWH Thermostat Setpoint Control Based on Time-of-Use Pricing; Maximum Thermostat Setpoint 130°F

Case 2B: EWH Thermostat Setpoint Control Based on Time-of-Use Pricing; Maximum Thermostat Setpoint 160°F

Case 3: EWH Thermostat Setpoint Control Based on Time-of-Use Pricing, and Balancing Reserves Desired During Off-Peak Hours

This section provides examination of the performance of each of the four experimental cases, for each of the six areas of analysis, summarized below:

1. Maintain Customer Comfort Level

Maintain hot water supply available, within safe temperature limits

2. Load Shifting from On-Peak to Off-Peak Hours

Ratio of total energy demand during on-peak hours to total energy demand during off-peak hours should be minimal

3. Peak Load Equality or Reduction

Maximum power demand in control cases lower than in no-control case

4. Total Energy Demand Equality or Reduction

Total energy consumed in control cases lower than in no-control case; directly proportional to average power demand reduction

5. Economic Benefit to Customer

Total cost to customer in control cases lower than in no-control case

6. Provide Desired Balancing Reserves

Balancing reserve created in control cases matches balancing reserve desired by utility

Goal 1: Maintain Customer Comfort Level

In all experimental cases, customer comfort level was maintained for the entire 7-day period. The hot water supply was always maintained within reasonable and safe operating limits. The thermostat setpoints ranged from 126°F to 160°F. The water temperature inside the EWH tank never decreased below 116°F, and therefore stayed above the ideal growth range for harmful Legionella bacteria strains. The temperature never increased above of 160°F, therefore prolonging tank life and allowing maximum efficiency by decreasing mineral buildup that results from higher water temperatures. However, only Cases 1, 2B, and 3 allowed the water temperature to reach 160°F, the minimum required to kill sulfate-reducing bacteria.

Goal 2: Load Shifting from On-Peak to Off-Peak Hours

Figure 68 compares the total energy demand during on-peak hours for all EWHs for the 7-day period for all cases.

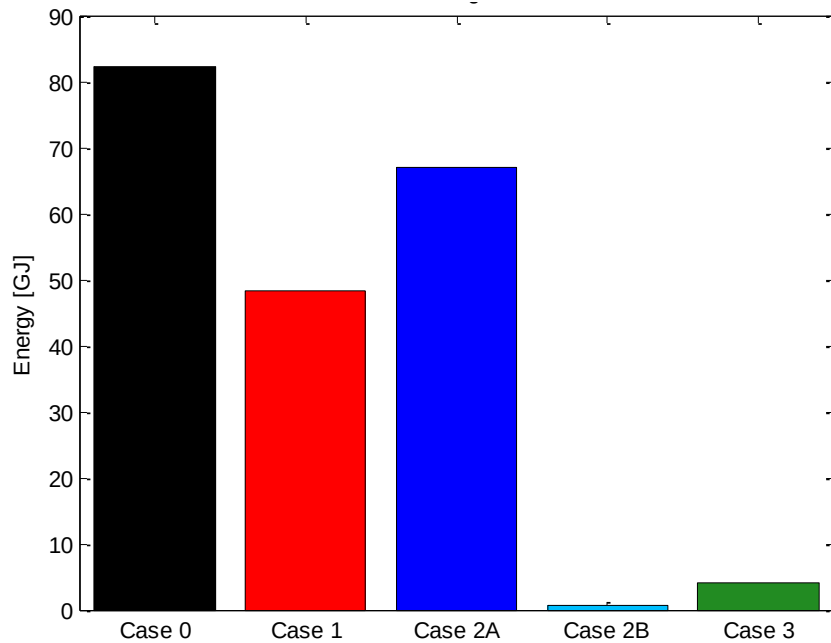


Fig. 68: Total Demand During On-Peak Hours (Case 0: No EWH Thermostat Setpoint Control; Case 1: EWH Thermostat Setpoint Control Based on Balancing Reserves Desired by Utility; Case 2A: EWH Thermostat Setpoint Control Based on Time-of-Use Pricing; Maximum Thermostat Setpoint 130°F; Case 2B: EWH Thermostat Setpoint Control Based on Time-of-Use Pricing; Maximum Thermostat Setpoint 160°F; Case 3: EWH Thermostat Setpoint Control Based on Time-of-Use Pricing, and Balancing Reserves Desired During Off-Peak Hours).

In Case 2, when the goal is to reduce the demand during on-peak hours, the nominal thermostat setpoint of 130 °F during off-peak hours does not allow the EWHs to store enough energy to last through the peak periods. The result is that the minimum allowable temperature is reached before the end of the peak period, and the EWHs must turn back on, and thus consume some energy during peak hours.

Case 1 is more successful than Case 2A, because the thermostat setpoints required for balancing reserve control allow the EWH temperatures to be greater during off-peak hours. During on-peak hours, when a reduction in demand is generally desired, the EWHs have more thermal energy stored, and so are more available to have their setpoints

lowered. In Case 2A, the thermostat setpoints are all 130°F during off-peak hours. However, this does not allow the EWHs to store enough thermal energy to make it through the on-peak periods without reaching the minimum temperature of 116°F and turning ON, thus consuming energy during on-peak hours.

Case 2B and 3 are by far the most successful in shifting the load from on-peak to off-peak times. The balancing reserve control allows the temperatures to increase as high as 160 °F during off-peak hours. Then, when the setpoints are forced to the minimum allowable setpoint during on-peak hours, the EWHs have more thermal energy stored (in comparison to Case 2A). EWHs store enough thermal energy during the off-peak hours so that the temperature does not reach the minimum of 116°F during the on-peak hours. Case 2B allows EWHs to have a higher average temperature during off-peak hours, and thus slightly less EWHs consume energy during on-peak hours in Case 2B than Case 3. In Case 3, 1.4294% of the demand occurred during on-peak hours, as compared to 30.0688% in Case 0 and 17.2417% in Case 1. The 4.0913 GJ on-peak demand of Case 3 was 95.0227% less than the 82.199 GJ on-peak demand of Case 0. This would greatly benefit the utility and help to flatten the demand profile.

Goal 3: Peak Load Equality or Reduction

Figure 69 compares the maximum power demand in each case. The maximum possible load, if all EWHs were to be in the ON state at once, is 4.5 MW.

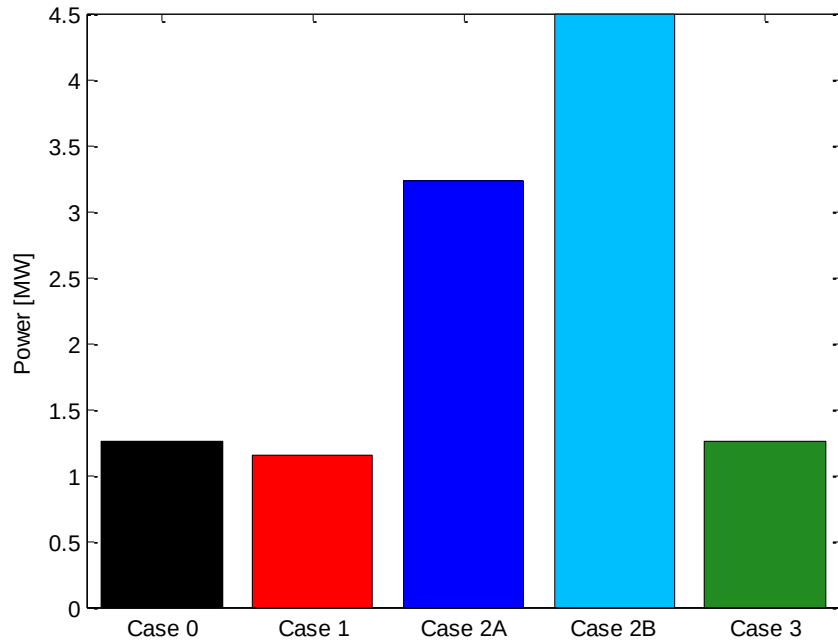


Fig. 69: Maximum Total Power Demand (Case 0: No EWH Thermostat Setpoint Control; Case 1: EWH Thermostat Setpoint Control Based on Balancing Reserves Desired by Utility; Case 2A: EWH Thermostat Setpoint Control Based on Time-of-Use Pricing; Maximum Thermostat Setpoint 130°F; Case 2B: EWH Thermostat Setpoint Control Based on Time-of-Use Pricing; Maximum Thermostat Setpoint 160°F; Case 3: EWH Thermostat Setpoint Control Based on Time-of-Use Pricing, and Balancing Reserves Desired During Off-Peak Hours).

Case 0 had a higher peak power demand than Cases 1 and 3. This is because in Case 0, the ON/OFF cycling of the EWHs is only controlled by the water demand, and all EWHs' water demand curves peak at the same times. In Cases 1 and 3, the desired balancing reserve signal also influences when the EWHs turn ON and OFF, and so fewer EWHs are in the ON state at the same time. Case 3 has a higher peak demand than Case 1, however, because at the end of the on-peak period in Case 3, the setpoints are all at the minimum value, and so the EWHs can only respond to DEC, or increases in power demand. The EWHs cannot always provide the needed balancing reserves, because the

temperature limits must be maintained, but the balancing reserve control does help to decrease the maximum load on the system.

In Case 2, the customer has full control over the EWH temperature setpoints. The customer's goal is to take full advantage of the time-of-use pricing scheme, and reap the greatest financial benefit possible. Therefore, the thermostat setpoints are set to 126°F during on-peak hours, when price is most expensive.

In Case 2A, customers leave their thermostat setpoints at 130°F, the same as in the base model, during off-peak hours, in order to allow the water to be pre-heated during the off-peak hours. However, this pre-heating does not allow the EWHs to store enough thermal energy to make it through the on-peak periods without reaching the minimum temperature of 116°F and turning ON, thus consuming power at a higher price, and causing the customer to pay for electricity when the price is highest.

In Case 2B, customers set their thermostat setpoints to 160°F, the maximum allowable temperature, during off-peak hours, in hopes of storing more thermal energy during off-peak hours. The result is that most EWHs store enough thermal energy during the off-peak hours so that the temperature does not reach the minimum of 116°F during the on-peak hours. Very few EWHs turn on during the on-peak hours, and 0.7537 GJ of energy is consumed during on-peak hours in Case 2B, whereas Case 2A consumed 67.033 GJ during on-peak hours. The cost to the customer is lower in Case 2B than in each of the other cases.

The customer benefits financially in Case 2B, but causes a very large problem for the utility. In Case 0, the peak power demand was 1.260 MW. This peak was lower in

Case 1– 1.148 MW – and equal in Case 3. However, Case 2 had much higher peak power demand – 3.231 MW in Case 2A, and 4.500 MW in Case 2B, wherein the customer had the greatest financial benefit.

If the customer is allowed full control over the thermostat setpoint on smart programmable EWHs in a time-of-use pricing environment, there will be a financial benefit to the customer, but a huge disadvantage to the utility, because of the 195.9% increase in peak power demand. A possible way to reduce the magnitude of the peak power demand at the end of the on-peak hours could be to slightly randomize the times at which the thermostat setpoints increase. The viability of this method was successfully simulated in experiments by Pacific Northwest National Laboratory, in which appliances turned ON or OFF in order to stabilize grid frequency [27].

If the utility were to supplement this time-of-use pricing with an additional stipend for participation in the aforementioned randomization scheme, or even impose a penalty for non-participation in this randomization, in order to alleviate the increase in peak power demand, it may be a viable option for the utility. However, the utility would have to perform a detailed cost analysis of the cost of this stipend and time-of-use pricing scheme, and compare with the cost of not using time-of-use pricing at all. Based upon the results of this research, a time-of-use pricing scheme alone, in an environment in which the customer has full control over the EWH setpoint, is recommended against.

Goal 4: Total Energy
Demand Equality or Reduction

The primary goals of these experiments were providing balancing reserves and load shifting from on-peak to off-peak periods. Total energy is less important, but would be a concern if the total energy were to increase greatly for any of the control methods. In that case, it may be ruled out, as was Case 2 due to the extremely large increase in maximum power demand. In the case of total energy demand for these experiments, all cases were within 10% of each other. Figure 70 compares the total energy consumed by all EWHs in the 7-day simulation period. Note that total energy demand is directly proportional to average power demand. Therefore, the average power demand was also within acceptable limits for all cases.

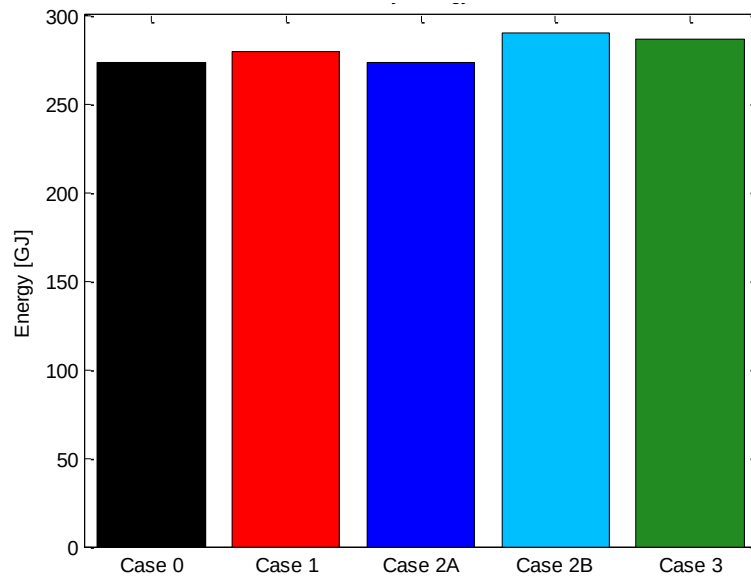


Fig. 70: Total Weekly Energy Demand (Case 0: No EWH Thermostat Setpoint Control; Case 1: EWH Thermostat Setpoint Control Based on Balancing Reserves Desired by Utility; Case 2A: EWH Thermostat Setpoint Control Based on Time-of-Use Pricing; Maximum Thermostat Setpoint 130°F; Case 2B: EWH Thermostat Setpoint Control Based on Time-of-Use Pricing; Maximum Thermostat Setpoint 160°F; Case 3: EWH Thermostat Setpoint Control Based on Time-of-Use Pricing, and Balancing Reserves Desired During Off-Peak Hours).

Recall the temperature ranges that were allowed in each case. Case 2A, which had the lowest average water temperature, also had the lowest energy demand. The next lowest average water temperature was Case 0, which had the next lowest energy demand. The trend is similar for all other cases – as average water temperature increases, energy demand also increases. At a given water demand rate, a higher temperature decreases the percentage of this water that flows from the EWH tank. However, the conduction losses – energy lost by heating incoming cool water – are higher at higher water temperatures, due to the higher density of thermal energy carried in the outflowing hot water. The losses depend not only upon the average temperature and average water demand rate, but exactly which water demand rate corresponds to which temperature for each EWH at each sampling period. At higher water demand rates, which occur during on-peak hours, the decrease in water temperature will have a larger effect upon the losses, than will the increase in temperature during off-peak hours when water demand rate is much lower. Case 3 consumed 4.7019% more energy than Case 0. When the amount of load shifting from on-peak to off-peak hours and balancing reserves provided are taken into account, this small energy increase is justified by the ancillary services provided.

Goal 5: Economic Benefit to Customer

In Case 0 and Case 1, the flat-rate pricing scheme was employed. In Case 2 and Case 3, the time-of-use pricing signal was used to allow the consumer to control the thermostat setpoints of the EWHs during on-peak hours in which higher prices were implemented. Figure 71 compares the average cost of electricity for a single EWH in the 7-day period.

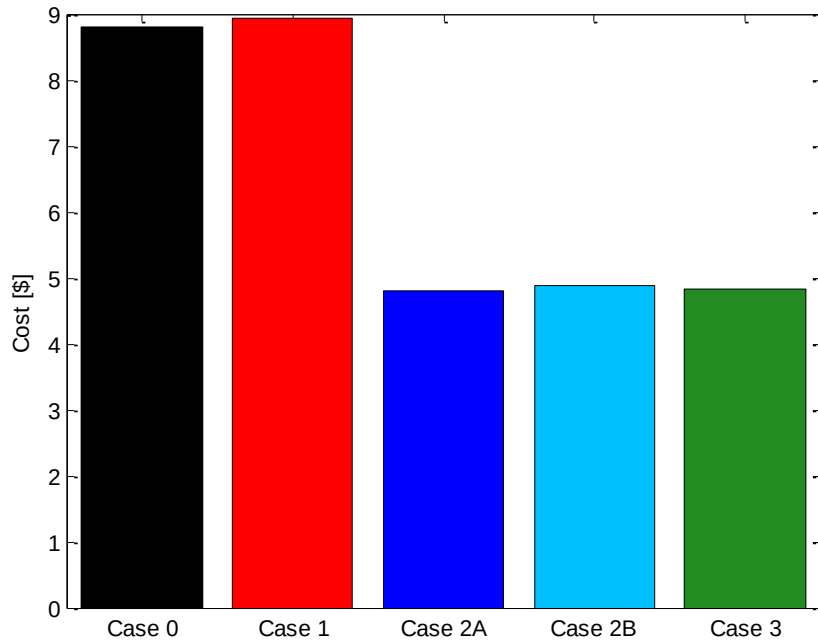


Fig. 71: Average Weekly Cost per EWH (Case 0: No EWH Thermostat Setpoint Control; Case 1: EWH Thermostat Setpoint Control Based on Balancing Reserves Desired by Utility; Case 2A: EWH Thermostat Setpoint Control Based on Time-of-Use Pricing; Maximum Thermostat Setpoint 130°F; Case 2B: EWH Thermostat Setpoint Control Based on Time-of-Use Pricing; Maximum Thermostat Setpoint 160°F; Case 3: EWH Thermostat Setpoint Control Based on Time-of-Use Pricing, and Balancing Reserves Desired During Off-Peak Hours).

Case 0 and Case 1 are most expensive, because these two cases do not allow the EWH's thermostat setpoint to adjust in response to the time-of-use pricing signal, and thus are analyzed for the flat-rate pricing scheme. In Case 2A, where time-of-use pricing is the only signal used for thermostat setpoint control, there is a definite economic advantage to consumers over Case 0 and Case 1. However, the extremely large increase in maximum power in Case 2A has caused it to be ruled out as a possible method of control.

In both Cases 2B and 3, the customer responded to the pricing signal by lowering the thermostat setpoint to 126°F during on-peak hours and opting out of the demand

response balancing reserve control program, thus using identical on-peak thermostat setpoints. However, the cost was 1.0012% lower in Case 3 than in Case 2B. This is due to the fact that in Case 2B, the EWH thermostat setpoints were always 160°F during off-peak hours, thus causing the EWHs to consume more energy overall, and more energy during off-peak hours, as compared to Case 3.

When compared to Case 0, Case 3 was 45.0088% less expensive to the customer, and therefore very economically advantageous. In Case 1, or if there were not an economic advantage to the customer in Case 3, the utility would have to provide an economic incentive in order to encourage customer participation in the demand response program.

Goal 6: Provide Desired Balancing Reserves

Figure 72 compares the accuracy with which the balancing reserve created by each case matched the balancing reserve desired by the utility. In Case 0 and Case 2, there were no balancing reserve control signals, and so the balancing reserve matching could not be evaluated.

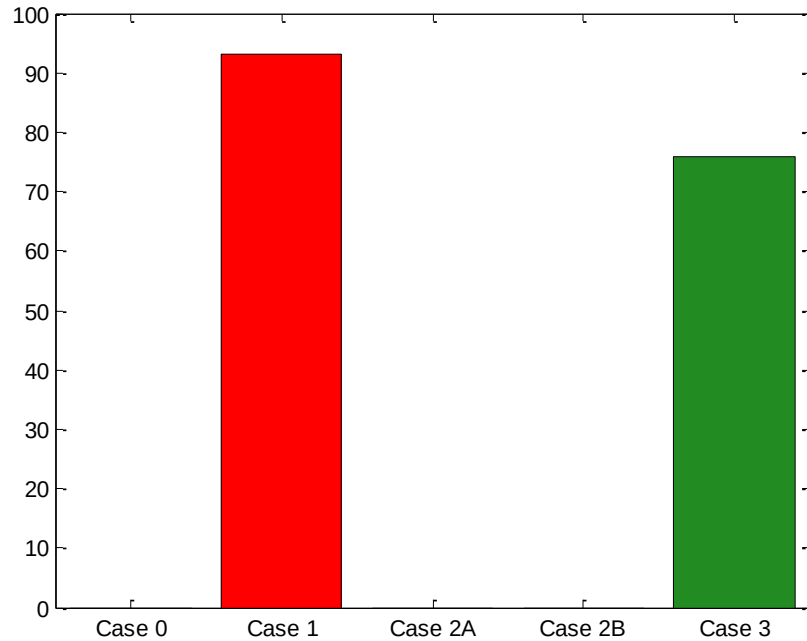


Fig. 72: Percent of Time with Zero Error in Providing Desired Balancing Reserve (Case 0: No EWH Thermostat Setpoint Control; Case 1: EWH Thermostat Setpoint Control Based on Balancing Reserves Desired by Utility; Case 2A: EWH Thermostat Setpoint Control Based on Time-of-Use Pricing; Maximum Thermostat Setpoint 130°F; Case 2B: EWH Thermostat Setpoint Control Based on Time-of-Use Pricing; Maximum Thermostat Setpoint 160°F; Case 3: EWH Thermostat Setpoint Control Based on Time-of-Use Pricing, and Balancing Reserves Desired During Off-Peak Hours).

Case 1, in which the only control signal was balancing reserve desired, was able to provide the needed balancing reserves a higher percentage, 93.17%, of the time. This is because in Case 3, the pricing signal takes priority, and so balancing reserves are not provided during peak demand hours, in order to reduce the cost to the consumer.

Case 3 still provides a very large percentage of balancing reserves. There was zero error between the balancing reserve desired and balancing reserve created 75.92% of the time. The percentage is lower than in Case 1, because the EWHs opt out of setpoint control during peak demand hours, therefore leaving 35 less hours (20.83% less hours) per week that providing needed balancing reserves is a priority. Therefore, it is logical

that Case 3 provides the needed balancing reserves 17.25% less of the time than in Case 1. Additionally, at the end of on-peak hours, the setpoints of all EWHs are set to the minimum. Therefore, at the start of off-peak hours, EWHs are generally only able to provide DEC, or increases in demand, until the water temperatures increase beyond 126°F, thus making them available for INCs.

CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

Four control methods of aggregate EWH control were explored. The highest priority goal was to uphold customer comfort and safety by maintaining the water temperatures within safe limits. This goal was met with total success. The second highest priority goal was to provide load shifting from on-peak demand hours to off-peak demand hours, as defined specified by Pacific Power's time-of-use electricity pricing signal. The no-control case failed in this area, consuming the highest proportion of the demand occurred during on-peak hours of any of the experimental cases.

The EWH population cannot always supply the desired balancing reserve. If the EWH supply is running out, the system operator (or aggregator acting for the operator) knows exactly how much of the desired balancing reserve can be supplied by the EWHs, and therefore how much of the desired balancing reserve must be supplied by other resources available for load-generation balancing. In a smart grid environment, when EWH thermostat setpoints are able to be controlled by the utility, the EWHs can provide a majority of the desired balancing reserves necessary to accommodate the incorporation of wind generation, and thus increase the reliability of the system and economically benefit the utility, which would normally provide these balancing reserves with fossil fuel-powered generation, all while maintaining customer comfort and safety. (Recall that EWHs opt out of desired balancing reserve-based thermostat setpoint control to minimize demand during on-peak hours.)

When time-of-use pricing is implemented in conjunction with the aforementioned desired balancing reserve-based thermostat setpoint control, the energy

consumed during on-peak hours is reduced significantly. Shifting demand from on-peak to off-peak hours will allow energy generated from wind to be used in place of other non-renewable, costly, or polluting sources, such as coal, natural gas, and nuclear. It will also help to flatten the demand profile at the distribution level, so that less generation is required from fossil fuel-powered peaking power plants. Added benefits of combined control via time-of-use pricing signal and desired balancing reserves, are a reduction in peak load and a large decrease in cost to the consumer over the base case. Both the consumer and utility can benefit from this method of combined control.

Other thermostatically controlled residential devices, such as HVAC systems and refrigerators, could also participate in demand response programs, using the same method of combined time-of-use pricing signal and desired balancing reserve signal from the utility. With more available dispatchable loads, the desired balancing reserves could be provided by demand-responsive loads a higher percent of the time.

In addition to wind, intermittent solar energy generation on the power grid could be partially or fully accommodated using this method. Future research could also include modeling of a distribution system which includes the responsive EWHs and wind generation from the experiments in this thesis, in order to analyze the stability of frequency and voltage of the grid.

The control scheme presented in this thesis will help reduce the load at the bus level. If this control scheme were to be implemented on the power grid, it would also be useful to take into consideration the locations of the EWHs in different parts of the distribution system. This could allow the utility to not only alter the overall consumer

demand, but change consumer demand in specific areas, and thus reduce congestion on specific transmission lines.

There are numerous benefits possible for the utility, consumer, and environment, when demand response is implemented on the smart grid, by means of thermostat setpoint control of residential EWHs.

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