# Real-Time Demand Response Through Aggregate Electric Water Heaters for Load Shifting and Balancing Wind Generation

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***Abstract*—Demand response (DR) has shown to be a promising tool for balancing generation and demand in the future power grid, specifically with high penetration of variable renewable generation, such as wind. This paper evaluates thermostat setpoint control of aggregate electric water heaters (EWHs) for load shifting, and providing desired balancing reserve for the utility. It also assesses the economic benefits of DR for the customers through time-of-use pricing. Simulation results reveal the achievement of the economic benefits to the customers while maintaining their comfort level and providing a large percentage of desired balancing reserve at the presence of wind generation.**

***Index Terms*—Aggregate electric water heaters (EWHs), balancing reserve, demand response, load shifting, smart grid, time-of-use (ToU) pricing, wind generation.**

## I. INTRODUCTION

THE U.S. Department of Energy has established goals for a smart electric power grid, which facilitates customer participation and incorporation of clean, renewable generation sources, such as wind. "Enabling informed participation by customers" and "accommodating all generation and storage options" are two primary goals of smart grid identified by the U.S. DOE [1]. The first objective implies that in addition to allowing utility-based control of devices, the customers must also be given the opportunity to control their own power consumption and override any control signal from the utility to control/alter their power consumption in case needed. The second objective includes the incorporation of variable renewable energy sources (RES) on the electric power grid. However, the uncertain and variable nature of RES can create problems for power systems in providing balancing reserves when RES penetration is high, e.g., exceeding 20% [2]. As RES penetration increases, the conventional solution is to increase the amount of available reserve [3]. Since spinning reserves are mostly provided by fossil fuel-based power plants, their operation is costly and results in increased release of undesired emissions. While it is necessary to account for the variability of RES generation with balancing reserves, it is also desirable to have the ability to store any excess available power, e.g., any excess wind power, so that the excess power won't have to be curtailed [4].

One possible way to accomplish the above tasks is through demand response (DR). Specifically, residential electric water heaters (EWHs) and heat pumps are good candidates for this purpose, since electric energy can be stored as heat energy in their hot water tanks. Moreover, their control is both simple and fast. This paper is limited to control of EWHs only.

Residential EWHs account for approximately 20% of the U.S. residential daily energy demand and are the largest contributors to the morning and evening peaks in residential power demand [5]. It is therefore desired to shift a considerable percentage of EWHs power demand from hours of higher power demand to lower demand hours by heating the water during off-peak hours or when excess renewable energy is available. This procedure can also result in a large percentage of the balancing reserve necessary to integrate wind energy generation onto the grid. Therefore, it will be economically beneficial to the customers as well as utilities. However, considering that heat energy storage increases the heat losses of EWHs, the proposed DR algorithm should operate without significantly increasing the average daily energy demand and maximum power demand of the EWHs.

Thermostatically-controlled appliances (TCA) have been of interest in the last more than two decades to evaluate their benefits for load shifting and peak load shaving, e.g., [6]–[17]. Different control approaches from voltage control ([6], [7], [15]) to thermostat setpoint control, ([8], [10]–[12], [16], [17]) and ON/OFF control based on frequency deviation, ([9], [13], [14]) have been proposed for controllable residential loads to provide balancing reserve. The impacts of large-scale energy storage systems have also been investigated for balancing the variable renewable generation [18]. The following shortcomings relative to TCA control can be identified in the previous research, which have been addressed in this paper:

- Lack of economic benefit analyses to show the impact of direct load control (DLC) program on the cost of energy for the customers and utilities in [6]–[17],

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- Lack of accumulative energy analysis to show any increase/decrease in total energy consumption in [8]–[17],
- Violation of comfort level for some customers, reported in [16], [17]
- The need for additional expensive equipment (i.e., electronic switches and power electronic devices) for voltage control, proposed in [6], [7],
- Lack of investigation on load shifting together with a price signal response on a large number of controllable devices, [6]–[17],
- Short-term (i.e., few hours) simulation which doesn't reveal the pros and cons of the method proposed in the long-term (i.e., few days) considering weekdays and weekend days, [14],

In this paper, we evaluate the capability of aggregated EWHs as a DR tool to respond to control signals generated by the utility for load-shifting and balancing reserve. The thermostat setpoints of 1000 aggregated EWHs are controlled by the utility to respond to a time-of-use (ToU) pricing signal during the on-peak hours. As a result, some of the consumers electrical energy demand will be shifted from on-peak hours to off-peak periods. During the off-peak hours, the EWHs respond to a desired balancing reserve signal which also includes wind generation. However, the signal generated by the utility can be overridden by the customers if they choose to do so. We have not explored the consumers' override option in this paper.

The proposed model is compared to a no-control case, as well as to each of the above two control strategies (ToU pricing and balancing reserve). An important goal of the comparison is to assess the economic benefits of the proposed DR strategy for the customers, while maintaining safe water temperatures. It is desired to maintain this economic benefit without significantly increasing the total EWHs energy consumption and peak power demand. An actual desired balancing reserve signal is used in this study [19].

The rest of the paper is organized as follows. Section II covers the model formulation for both single and aggregated EWHs. The proposed thermostat setpoint control of aggregated EWHs is presented in Section III; simulation setup and configuration are covered in Section IV; and simulation results and discussions are given in Section V. Finally, the paper is concluded in Section VI.

## II. Problem Formulation

Thermostat setpoint control of EWHs is one method to control their power consumption, which can be used: 1) to shift and flatten the demand profile and 2) to provide the balancing reserves needed in the presence of intermittent energy resources. An EWH has a thermostat setpoint ($T^i_{set}(t)$), and a deadband ($D$), where the temperature of the water inside the tank of each EWH ($i$) must be maintained within the range of the thermostat setpoint, i.e.:

$$T^i_{set}(t) - D \le T_i(t) \le T^i_{set}(t) \tag{1}$$

where $T_i(t)$ is the temperature of hot water inside of the tank of EWH $i$ at time $t$. The tank of an EWH has a certain amount of thermal insulation (R value). This insulation is not 100% efficient, resulting in some heat loss. The heat loss through the tank increases when hot water with higher temperature is stored in the tank. A brief description of the modeling of an individual EWH and aggregated EWHs follows. More details on single residential EWH model are provided in [7], [20].

### A. Individual EWH Model

The temperature of hot water inside of the EWH tank can be obtained as a function of time by (2) [20]:

$$\begin{aligned} T_h(t) &= T_h(\tau).e^{-\left(\frac{1}{R'.C}\right)(t-\tau)} \\ &+ \{G.R'.T_{out} + B(t).R'.T_{in} + Q.R'\}.\left[1 - e^{-\left(\frac{1}{R'.C}\right)(t-\tau)}\right] \end{aligned} \tag{2}$$

where $T_h(t)$ is the water temperature inside EWH at time $t$ ($^\circ$F), $\tau$ is the previous sample ($t-1$, hours), $C$ is the equivalent thermal mass (Btu/$^\circ$F), $G$ is the ratio of the surface area to thermal resistance of the tank, $T_{out}$ is ambient environment temperature ($^\circ$F). The parameters $B$ and Q are piece-wise continuous terms whose expressions are given below ((4)) and defined in [7] and [20], and $T_{in}$ is the incoming cold water temperature ($^\circ$F). The parameters of (2) can be calculated as follows:

$$G = \frac{SA}{R}, \quad C = volume \times d_{water} \times C_p \tag{3}$$

where $SA$ is the tank surface area (ft$^2$), $R$ is the tank insulation thermal resistance (hour $\times$ ft$^2$ $\times ^\circ$ F/BTU), *volume* is the capacity of the tank (gallons), $d_{water}$ is the density of water (8.34 lbs/gallon), and $C_p$ is the specific heat of water (1.0069 BTU/(lbs $\times ^\circ$ F)). Other parameters in (2) are:

$$\begin{aligned} R' &= \frac{1}{G + B(t)} \qquad B(t) = d_{water} \times F(t) \times C_p \\ Q &= 3.4121 \times 10^{-8} \times (element\ kW\ rating) \end{aligned} \tag{4}$$

It is shown in [21] that the average EWH daily power demand profile follows that of the average total daily residential demand for both weekday and weekend, as shown in Fig. 1. We therefore use the average residential electrical demand to shape the residential hot water demand curve by multiplying the average residential power demand by $K(t)$. This parameter is the amount of hot water produced by one kilowatt of electric power from $T_{in}$ to $T_{set}(t)$ in one hour, neglecting convection losses. As shown in our previous work [7], the expression for $K(t)$ is as follows:

$$\begin{aligned} K(t) = &\frac{1000\frac{\mathrm{J}}{\mathrm{s}} \times 3600\frac{\mathrm{s}}{\mathrm{hour}}}{1.0545 \times 10^3\frac{\mathrm{J}}{BTU_{ISO}} \times 1.00\frac{BTU_{ISO}}{^\circ\mathrm{F.lbs}}} \\ &\times \frac{1}{(T_{set}(t) - T_{in}) \times 8.34\frac{\mathrm{lbs}}{\mathrm{gallon}}} \end{aligned} \tag{5}$$

Note that in this paper, $K(\mathrm{t})$ is a function of time, because it is a function of the thermostat setpoint, $T_{set}(t)$, which we are allowing to vary at each time step.

The value of hot water flow rate, $F(t)$, from each EWH tank is then equal to the consumer hot water demand rate at a given time, $F_{demand}$, as defined below:

$$F(t) = F_{demand}(t) = P_{avg}(t) \times K(t) \tag{6}$$

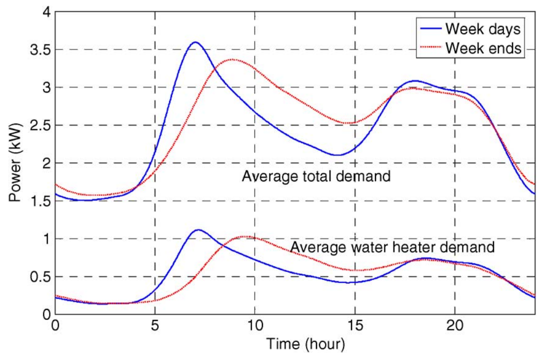


Fig. 1. Total power demand and EWH demand of an average house [7].

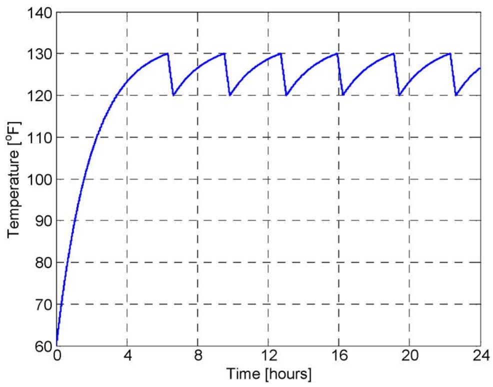


Fig. 2. Response of a single EWH with a 50-gallon hot water tank.

where $P_{avg}(t)$ is the average residential EWH power demand in kW.

Fig. 2 depicts the model response of an EWH with a 50-gallon hot water tank and consumption rate of 25 gal/hour, which is based on (2), where the EWH thermostat deadband is $D = 130 - 120 = 10°\text{F}$. The initial water temperature is assumed to be $60°\text{F}$ at the start of the simulation.

In this study, the EWHs thermostat setpoint is allowed to vary between $126°\text{F}$ and $160°\text{F}$ with a deadband of $10°\text{F}$ in some simulation cases reported in Table V (i.e., hot water temperature changes between $116°\text{F}$–$160°\text{F}$). During peak power demand hours and/or when wind power is low, the thermostat setpoint of some EWHs are brought down to as low as $126°\text{F}$ in order to reduce energy consumption. Conversely, during off-peak hours and/or when excess wind power is available, the thermostat setpoint of some EWHs are set to as high as $160°\text{F}$ to absorb the available power.

Severe scalding can occur at water temperatures above $130°\text{F}$, and as water temperature increases, the time for scalding to occur decreases logarithmically, to 5 seconds for water at $140°\text{F}$ and to just 0.5 seconds for water at $160°\text{F}$ [23]. To avoid scalding, the outflowing hot water will be mixed with the appropriate amount of cool water ($T_{in} = 60°\text{F}$) by a thermostatic mixing valve (TMV) prior to use. In such cases, not all of the water used by the customer is supplied by the EWH tank. It can be shown that the amount of hot water demand from the tank as a function of hot and cool water temperature and hot water consumed is [22]:

$$F(t) = F_{demand}(t).\frac{T_{mixed} - T_{in}}{T_h(t) - T_{in}} \tag{7}$$

TABLE I
PARAMETERS OF 1000 EWHS IN THE AGGREGATED MODEL [7], [22]

| Parameter | Value |
|---|---|
| Parameters have 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 |
| Parameters have a Random Uniform Distribution for the 1000 EWH population. | |
| **Parameter** | **Value** |
| Thermal resistance of tank insulation, R | 10 to 20 hour*ft$^2$*°F/BTU |
| Initial ON/OFF state | Approximately half ON, half OFF |
| Initial water temperature inside of the tank | 120°F to 130°F |

TABLE II
PARAMETERS THAT ARE THE SAME FOR ALL EWHS THROUGHOUT THE DURATION OF THE SIMULATION [22]

| Parameter | Value |
|---|---|
| Temperature of cold water entering the tank, $T_{in}$ | 60 °F |
| Temperature of the ambient environment, $T_{out}$ | 70 °F |
| Deadband, $D$ | 10 °F |
| Heating element power in ON (OFF) state, $P_{avg}$ | 4.5 (0) kW |

where $T_{mixed}$ is the temperature of water after hot and cool water are mixed together. In this study $T_{mixed} = 116°\text{F}$.

### B. Aggregated EWH Model

The aggregated EWH model comprises 1000 EWHs, whose parameters, given in (2), are set randomly within specific ranges [7]. Therefore, each EWH will respond slightly differently to thermostat setpoint control. This is due to the fact that each EWH has a different demand flow rate, tank insulation thermal resistance, tank surface area, and temperature during each time step. Table I shows the different parameter values used in the simulation, which are based on the actual EWHs data.

The parameters that are the same for all EWHs for the aggregated EWH model are given in Table II.

## III. EWHS THERMOSTAT SETPOINT CONTROL

### A. Control Based on Desired Balancing (INC/DEC) Reserve Signal

A desired balancing reserve signal, called INC/DEC (increase/decrease reserve), which is different from the ACE signal, is generated by the utilities every thirty seconds. Traditionally, when generation exceeds demand, utilities start decreasing the amount of reserve generation to balance total generation and load demand, i.e., a DEC signal is generated. However, in a grid with considerable penetration of RES, it is desirable to utilize all the excess renewable power when available.

Conventional power plants are not fast enough to match their output power with RES generation. Since the effect of increase in demand is the same as decrease in generation, an increase in demand can respond fast to the DEC signal. Likewise, when demand exceeds generation, an increase in reserve (or decrease in demand) is required, and an INC signal is generated by the utility. The real set of INC/DEC signal used in our work is from a specific region served by the Bonneville Power Administration (BPA) and includes wind power generation [19]. There are approximately 1.36 million EWHs in this region for which the desired balancing reserve signal is obtained [22]. This data has been scaled for use with the 1000 EWHs in our study as given below.

$$\mathrm{INC/DEC}_{scaled} = \frac{\mathrm{INC/DEC}_{original}}{1.36 \times 10^6} \times 1000 \tag{8}$$

The scaling approach used in (8) assumes that the power demand profile of the 1000 EWHs is as smooth as that of 1.36 million EWHs. In real cases, this may not be true because there is not as much diversity in the profile of 1000 EWHs as there is in the profile of 1.36 million EWHs. However, we were not able to get information about each individual EWH because of proprietary issues.

In this section, an algorithm is presented to adjust the thermostat setpoints of the 1000 EWHs in real-time according to the INC/DEC signal. In order to start the simulation, the following assumptions are made:

- Each EWH is assigned a random state at the beginning of the simulation—either ON or OFF—with even distribution.
- Each EWH is assigned a random initial thermostat setpoint, between the pre-defined range for the different cases studied. These cases will be discussed in Section IV. This setpoint determines the maximum and minimum temperatures that the EWH may reach. In the no control case (base case), the hot water temperature inside the EWHs' tanks varies between 120°F–130°F.
- Each EWH must maintain a temperature within the 10°F deadband below its setpoint. The size of this deadband is large enough so that the EWHs will not constantly switching ON and OFF.
- Smart grid environment is assumed where each EWH's thermostat setpoint may be adjusted by the utility at any time through two-way communication.

### *B. Calculation of Required Number of EWHs for DR Based on the INC/DEC Signal*

In this study, the desired balancing reserve, INC/DEC, is the number of kilowatts of reserve or demand that needs to be created in order to balance generation with demand every 30 seconds. The proposed control algorithm runs every 5 seconds, by taking the difference between the actual balancing reserve desired and the balancing reserve that has been created since the beginning of the 30-second interval. Therefore, the needed balancing reserve is known every 5 seconds. Such communication is achievable through the current Internet as discussed in [24]. The major requirements for demand dispatch (from the communication point of view) are low-latency (about 500 ms, claimed to be available with the current Internet infrastructure) and quite small bandwidth. In [24], 3.2 million plug-in hybrid vehicles were considered in a simulation experiment with two-way communication, based on Internet protocols, to provide regulation service every 4 seconds through a central controller and load aggregators in the PJM market. Therefore, the communication requirement for our proposed control strategy could easily be achieved in the smart grid era.

In order to calculate the number of EWHs that need to be turned ON or OFF, it is important to calculate how many EWHs are about to turn OFF (i.e., $N_{turningOFF}(t)$) or ON (i.e., $N_{turningON}(t)$) in the next 30-second period by reaching their upper thermostat setpoint or falling to their lower water temperature. This is done to exclude these EWHs in the proposed algorithm because they are going to change state in the next 5 seconds. It is done by comparing the water temperature of each EWH in the ON state to its thermostat setpoint $(T^i_{set}(t))$, and that of each EWH in the OFF state to its lower temperature limit $(T^i_{set}(t) - D)$. The temperature change for each EWH depends on the demanded hot water flow rate, current EWH water temperature, surface area of tank, and insulation thermal resistance of the EWH, as per (2). If the balancing reserve needed is less than half the power capacity of one EWH (less than 2.25 kW), then no EWHs will need to change state. This deadband prevents oscillations in the number of EWHs turning ON or OFF.

The balancing reserve created is calculated as follows:

$$P^{created}_{INC/DEC}(t) = -\left(P^{total}_{EWH}(t) - P^{total}_{EWH}\left(floor\left(\frac{t}{6}\right)\times 6\right)\right) \tag{9}$$

where $P^{created}_{INC/DEC}(t)$ is the balancing reserve that has been created since the beginning of the 30-second period, $P^{total}_{EWH}(t)$ is the total power consumed by all EWHs at the present 5-second period which is calculated knowing the EWHs in the ON state and their nominal power consumption (Table II), $P^{total}_{EWH}(floor(t/6) \times 6)$ is the total power consumed by all EWHs at the beginning of the 30-second period, when the desired balancing reserve signal was first deployed, and $floor()$ is the MATLAB built-in function to round numbers to the lower whole number. The needed balancing reserve is calculated as follows:

$$P^{needed}_{INC/DEC}(t) = P^{desired}_{INC/DEC}(t) - P^{created}_{INC/DEC}(t) \tag{10}$$

where $P^{needed}_{INC/DEC}(t)$ is the amount of balancing reserve that is still needed to be created in order to meet the desired balancing reserve, and $P^{desired}_{INC/DEC}(t)$ is the desired balancing reserve for the 30-second period. Finally, the number of EWHs to change at time $t$ is calculated as follows:

$$N_{change}(t) = \left| round\left(\frac{P^{needed}_{INC/DEC}(t)}{P_{EWH}}\right)\right| \tag{11}$$

where $P_{EWH}$ is the power consumed by one EWH in the ON state (given in Table II), and $round()$ is the MATLAB built-in function to round numbers to the nearest whole number.

*1) Desired Balancing Reserve Smaller (Greater) Than Zero:* If the balancing reserve needed is smaller (greater) than zero, then more DEC (INC) is required, which means a decrease (increase) in reserve or an increase (decrease) in demand is needed. Therefore, the utility control must ensure that the required number of EWHs, $N_{needed}(t)$, are turned ON (OFF) in each 5-second interval. This value is calculated as follows:

$$N_{needed}(t) = N_{change}(t) + [N_{turningON}(t) - N_{turningOFF}(t)] \times sign\left(P^{needed}_{INC/DEC}(t)\right) \quad (12)$$

where $N_{change}(t)$ is the calculated number of EWHs to be changed based on the balancing reserve signal for the next 5 seconds, $N_{turningON}(t)$ is the number of EWHs turning ON by the end of the present 5-second interval by falling to their lower temperature setpoint, $N_{turningOFF}(t)$ is the number of EWHs turning OFF by the end of the present 5-second interval by reaching their thermostat setpoint, $P^{needed}_{INC/DEC}(t)$ is the amount of balancing reserve that still needs to be created in order to meet the desired balancing reserve, and $sign()$ is the signum function in MATLAB to determine the sign of a number.

*2) 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 the net EWHs are turning ON (OFF), then an equal number of EWHs must be turned OFF (ON), so that no new balancing reserve is created, as defined by (13):

$$N_{needed}(t) = N_{turningON}(t) - N_{turningOFF}(t) \quad (13)$$

Using the $N_{needed}(t)$ calculated by the (13), there is a need for a mechanism to select the appropriate EWHs to be turned ON or OFF. If $N_{needed}(t)$ is smaller (greater) than zero, then some EWHs need to be turned OFF (ON) through thermostat setpoint control. The new setpoints are then chosen such that the thermostat setpoint of each chosen EWHs is lower (higher) than the present temperature. Once the water temperature of these EWHs is higher (lower) than their new thermostat setpoint, the EWHs will turn OFF (ON).

The proposed algorithm first makes an array, containing all of the temperatures of the EWHs in the ON (OFF) state, which are not going to turn OFF (ON) automatically in the next 5 seconds. Then, if the number of available EWHs in the ON (OFF) state is greater than or equal to $N_{needed}(t)$, then $N_{needed}(t)$ of these EWHs are chosen at random. If the number of available EWHs in the ON (OFF) state is less than $N_{needed}(t)$, then all of these EWHs are assigned new thermostat setpoints, which will cause them to turn OFF (ON). Equation (14) determines the new thermostat setpoint of each EWH to be turned OFF while (15) is used when EWHs are required to turn ON:

$$T_{new,set}(t) = T_{EWHtemp}(t) - \Delta T \quad (EWHs\ turning\ OFF) \quad (14)$$

$$T_{new,set}(t) = T_{EWHtemp}(t) + \Delta T + D \quad (EWHs\ turning\ ON) \quad (15)$$

where $\Delta T$ is a temperature deviation used to ensure that the new thermostat setpoint is lower (higher) than the present EWH temperature at the end of the 5-second period. In this study, $\Delta T$ 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. This value can be increased in real-world applications without affecting the proposed procedure.

TABLE III
BASE RATE FOR ELECTRIC ENERGY CONSUMED IN ToU PRICING SCHEME FOR PACIFIC POWER† [25]

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

† Pacific Power is a utility in Portland, OR.

TABLE IV
ToU ELECTRICITY RATE ADJUSTMENTS IN RESIDENTIAL SECTOR (RATE SCHEDULE 4) FOR PACIFIC POWER [26]

| | On-peak charge (06-10, 17-20 hours) | Off-peak credit (Rest of the day) |
|---|---|---|
| Winter | +\$0.03316 | -\$0.01125 |

## IV. SIMULATION SETUP AND CONFIGURATIONS

Five experimental models are designed to evaluate the effectiveness of the proposed thermostat control strategy. These cases (CASEs 0, 1, 2A, 2B, 3) are described below.

*CASE0: No EWH Thermostat Setpoint Control:* This case represents the operation of EWHs under no thermostat setpoint control. It is used as the base case for comparison with the other four cases studied, as given below. In this case, the hot water temperature varies between 120°F to 130°F.

*CASE1: EWH Thermostat Setpoint Control Based Only on Balancing Reserve Desired by the Utility:* In this case, the balancing reserve signal from the utility is used for EWH thermostat setpoint control for the whole day. In our study, the utility has full control over the thermostat setpoints of all EWHs. The hot water temperature varies between 116°F to 160°F in this case.

*CASE2: EWH Thermostat Setpoint Control Based Only on ToU Pricing:* ToU 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 power during off-peak hours and less during peak hours. In this study, it is assumed that all the customers participate in this DR program because of the economic benefit they gain. Oregon-based Pacific Power's electricity pricing rate structure for residential application is used in this study. It includes a constant charge depending on the amount of monthly electric energy consumption, as tabulated in Table III, and on-peak hours extra charge and off-peak hours credits, as given in Table IV.

In this study, the prices reported in Tables III and IV are used in all CASEs for the sake of comparison.

In this case, the thermostat setpoints of all EWHs are set to the minimum allowable temperature, 126°F (i.e., $T_{water} \geq 116°F$) during on-peak hours. During off-peak hours, two different cases are defined. In CASE2A, the EWHs thermostat setpoints are set to 130°F during off-peak hours. However, this may not allow the EWHs to store enough thermal energy to make it through the on-peak hours without reaching the minimum temperature and thus turning ON. Therefore, another scenario, CASE2B, is introduced where the thermostat setpoints

TABLE V
BRIEF DESCRIPTION OF ALL FOUR DIFFERENT CASES

| Case NO. | Description |
|---|---|
| CASE0 | No control (hot water temperature: 120°F-130°F) |
| CASE1 | Thermostat setpoint control - balancing reserves only (hot water temperature: 116°F-160°F) |
| CASE2A | Thermostat setpoint control –ToU pricing only (hot water temperature: 116°F-130°F) |
| CASE2B | Thermostat setpoint control – ToU pricing only (hot water temperature: 116°F-160°F) |
| CASE3 | Thermostat setpoint control - balancing reserve and ToU pricing (hot water temperature: 116°F-160°F) |

are set to 160°F during off-peak hours. In this case, when the on-peak period begins, the majority of EWHs have a temperature between 150°F and 160°F. The goal is for the EWHs to remain in the OFF state during the on-peak periods, i.e. not reaching the lower limit of water temperature (116°F) to cause the EWHs to turn back ON.

*CASE3: EWH Thermostat Setpoint Control Based on ToU Pricing, and Balancing Reserve Desired:* In CASE3, both the ToU pricing signal and balancing reserve signal are used. The ToU pricing signal has the highest priority of the two control signals due to the customer's desire for economic benefit. In this case, the EWHs operate based on ToU pricing signal during on-peak hours, and their setpoints are set to 126°F, the minimum allowable setpoint which ensures that the temperature of the water in the EWH tank never fall below 116°F. Thus, the EWHs consume less energy when the price for electricity is high. During off-peak hours, when the electricity price is low, all the EWHs opt into balancing reserve based setpoint control, and all setpoints are maintained between 126°F and 160°F. Table V summarizes the five cases discussed above.

The above experimental simulation cases are carried out focusing on six GOALs (areas of performance) discussed below.

*GOAL1: Maintain Customer Comfort Level:* The water within the EWH tank must always remain within safe temperature limits, as defined in Table V for each case. This is the highest priority goal, and is never allowed to be compromised.

*GOAL2: 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.

*GOAL3: Peak Load Equality or Reduction:* The maximum aggregated EWH power demand in the control cases should be less than or equal to their maximum power demand in the no-control case. Significant increase in peak power demand is undesirable because this would necessitate the availability of large spinning reserves capacity which is not cost effective to the utility and customers and not environmentally friendly.

*GOAL4: 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 is undesirable to the customers. A small increase in energy demand can be compensated by the utility through direct payment or other methods as an incentive offered to the customers to participate in the program. In a better scenario, the economic benefits for the participating customers should compensate for the cost of the excess energy used.

TABLE VI
BRIEF DESCRIPTION OF ALL SIX DIFFERENT GOALS

| GOAL NO. | Description |
|---|---|
| GOAL1 | Maintain customer comfort level |
| GOAL2 | Load shifting from on-peak to off-peak hours |
| GOAL3 | Peak load equality or reduction |
| GOAL4 | Total energy demand equality or reduction |
| GOAL5 | Economic benefit to the customer |
| GOAL6 | Provide desired balancing reserves |

*GOAL5: Economic Benefit to the Customer:* The total cost to the customer in the control cases should be less than or equal to the total cost in the no-control case. It occurs when the customers shift their energy consumption from on-peak hours to off-peak periods, which will also result in flattening utility's power demand profile. Therefore, this strategy will benefit both the utility and customers.

*GOAL6: Provide Desired Balancing Reserves:* This is 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. In this study, minimal error is half of the power capacity of one 4.5 kW EWH (i.e., 2.25 kW). With this goal, some of the balancing reserves currently provided by fossil fuel based spinning reserve would be provided through EWHs DR. It can also allow high penetration of wind generation into the power grid. Table VI summarizes all six goals.

## V. SIMULATION RESULTS AND DISCUSSION

In this section, two sets of simulation results showing the operation of the 1000 EWHs will be discussed. As it will be shown in Section V-A, among the different CASEs studied (Table V), CASE3 proves to be the best choice for the utility while it also has economic benefit for the customers. Therefore, simulation results for this case are given and discussed first in the below Section V-A. A comprehensive comparison between the results obtained for the different cases, based on the six goals discussed above, is presented in Section V-B.

### A. Simulation Results for CASE3

In CASE3, the thermostat setpoints of all EWHs are set to 126°F during on-peak hours, in response to the ToU pricing scheme. During off-peak hours, the EWHs provide balancing reserves, allowing the thermostat setpoints to be adjusted between 126°F and 160°F. The performance of the EWHs is evaluated below, relative to the six GOALs given in Table VI.

*GOAL1: Maintain Customer Comfort Level:* Fig. 3 shows the outgoing water temperature of the 1000 EWHs during one week of simulation for CASE3. It is clear that the hot water supply is always maintained within reasonable and safe operating limits, (116°F–160°F).

The diversity of the parameters of the EWH population (Table I) as well as a large temperature range of the EWHs at any given time is of great importance for a successful DR program. In this regard, during off-peak hours the EWHs in CASE3 are evenly distributed between increasing and decreasing water temperature. However, during the on-peak hours all the EWHs respond to the ToU pricing signal, i.e. their thermostat setpoints

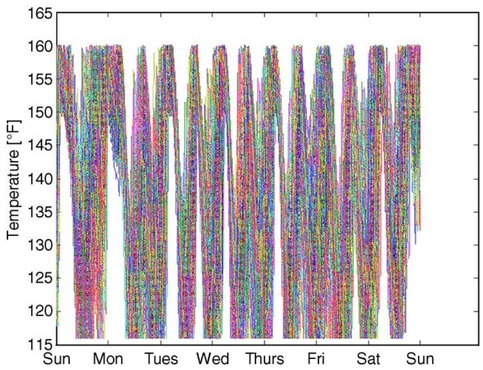


Fig. 3. Outgoing water temperature of 1000 EWHs, CASE3.

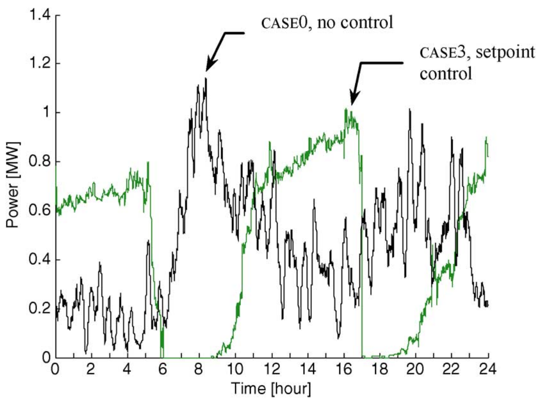


Fig. 4. Total power demand of 1000 EWHs, Wednesday, CASE3.

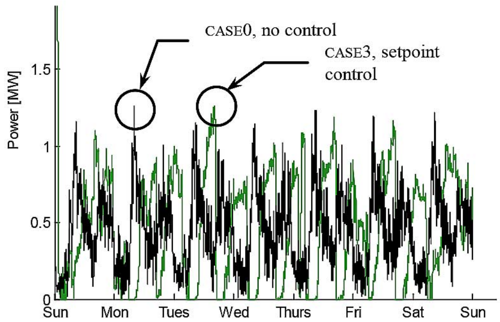


Fig. 5. Total EWHs demand for the one-week of simulation.

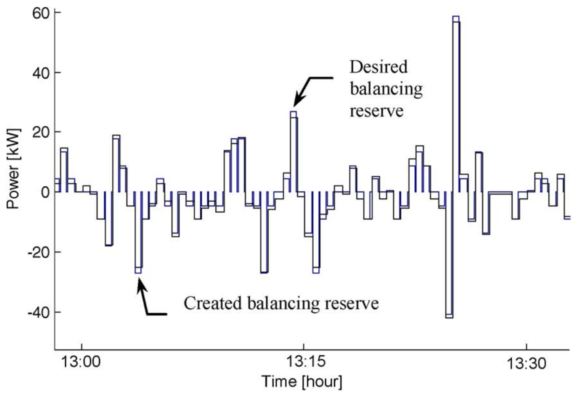


Fig. 6. Balancing reserve (INC/DEC signals) desired and created, Saturday, CASE3.

are lowered to 126°F so that they mostly stay off, and as a result, their water temperature decreases.

*GOAL2: Load Shifting From On-Peak to Off-Peak Hours:* Fig. 4 shows the total EWHs' power demand in response to CASE3 for a winter day. It is clear that, compared to the no-control case, the total EWHs power demand during on-peak hours has been reduced and shifted to off-peak hours. These are important steps toward flattening the distribution system load profile.

As shown in Fig. 4, it is clear that the EWHs' energy use in CASE3 (compared to CASE0) has been shifted from the on-peak hours to the off-peak periods due to ToU pricing. Considering that the EWH demand is only a portion of the total residential demand, the EWH load shifting helps in flattening the total residential demand profile.

*GOAL3: Peak Load Equality or Reduction:* The total EWHs' peak demand for the one-week simulation study remained approximately the same in CASE3 as in the no setpoint control, CASE0 as shown in Fig. 5. The peak demand is circled in the figure for both CASEs. The maximum EWHs power demand in both cases is 1.26 MW during a week.

*GOAL4: Total Energy Demand Equality or Reduction:* In CASE3, the total energy consumption of the 1000 EWHs increased by 4.7% compared to the no-control case (CASE0). In spite of this increase in energy use, there is still economic benefit for both the participating customers and the utility because of the benefit gained from ToU pricing, as discussed below (GOAL5), and the fact that the energy consumption of most of the EWHs is shifted to the off-peak hours (GOAL2). The cost of increase in the EWHs energy consumption due to heat loss can also be considered as a portion of the cost of the DR ancillary services.

*GOAL5: Economic Benefit to the Customer:* Under the ToU pricing scheme, the total weekly cost for the average EWH is \$4.92 (as shown in Fig. 11), which is 45.01% less expensive than the \$8.89 cost in CASE0. This is a great economic benefit for the customers even if they are not compensated by the utility for the small increase in the EWH energy consumption due to heat loss.

*GOAL6: Provide Desired Balancing Reserves:* Fig. 6 shows the desired and created balancing reserve (INC/DEC) signals for CASE3 for one half hour period during the off-peak hours, 13:00–13:30. These two curves are on top of each other most of the time. For the one-week simulation, the desired and created balancing reserve (INC/DEC) signals matched perfectly 75.92% of the time (i.e., the difference was less than 2.25 kW). This is a reasonable achievement given the fast variation of the actual balancing reserve signal.

Fig. 7 shows the Probability Distribution Function (PDF) for the absolute value of the absolute error between the balancing reserve desired by the utility and that created by the 1000 EWH population. There was a high probability of very small errors, and a very low probability of large errors.

## *B. Comparison of the Different Control Strategies*

In this subsection, the performance of the control strategies (CASEs) are compared relative to the six GOALs discussed above.

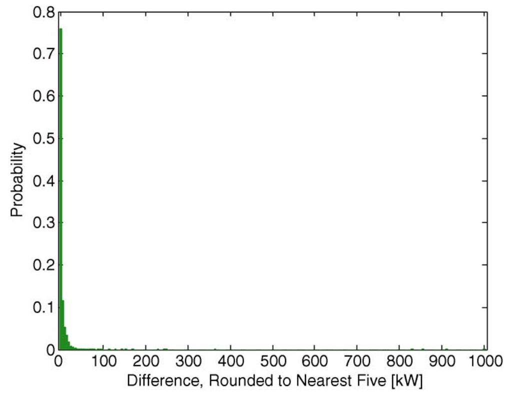


Fig. 7. PDF for absolute error between balancing reserve desired and created, CASE3.

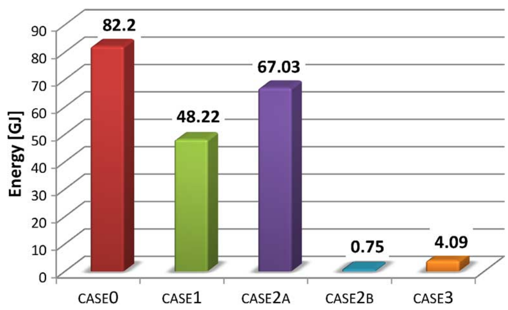


Fig. 8. Total demand during on-peak hours for different cases.

*GOAL1: Maintain Customer Comfort Level:* In all experimental cases, customer comfort level is maintained for the entire one-week simulation. The hot water supply is always maintained within the reasonable and safe operating limits, as defined (for each case) in Table V [22]. Only CASEs 1, 2B, and 3 allowed the water temperature to reach 160°F.

*GOAL2: Load Shifting From On-Peak to Off-Peak Hours:* Fig. 8 compares the total energy demand during on-peak hours (06–10, 17–20 hours) for all EWHs for the one-week of simulation for all cases.

In CASE2A, the maximum thermostat setpoint of 130°F during off-peak hours does not allow the EWHs to store enough energy to last through the peak periods. As a result, many of the EWHs reach their lower setpoints during the on-peak hours and turn ON. Therefore, in CASE2A, the EWHs use more energy during on-peak hours. However, in CASE1, the balancing reserve signal is used throughout the day which turns ON and OFF the EWHs during the on-peak hours. This is why the cost of energy is less in CASE2B compared to CASE1, which will be discussed in GOAL5. CASE2B is very successful compared to CASE2A because of the higher thermostat setpoint (160°F) during the off-peak hours, as opposed to 130°F in CASE2A. Therefore, in CASE2B, the EWHs have more thermal energy stored for use during the on-peak hours and their energy consumption during this period is very small.

CASEs 2B and 3 are by far the most successful in shifting the load from the on-peak periods to the off-peak hours. In both CASEs, the balancing reserve control allows the water temperature to increase to as high as 160°F during the off-peak hours. However, the average water temperature during the on-peak hours is higher in CASE2B than in CASE3, because in CASE3,

TABLE VII
THE ONE-WEEK ENERGY CONSUMPTION OF THE EWHS DURING OFF-PEAK AND ON-PEAK PERIODS FOR DIFFERENT CASES

| CASE NO. | Off-peak hours energy [GJ] | On-peak hours energy [GJ] | % of the one-week on-peak power to total EWHs demand |
|---|---|---|---|
| CASE0 | 191.17 | 82.20 | 30.07% |
| CASE1 | 231.44 | 48.22 | 17.24% |
| CASE2A | 206.08 | 67.03 | 24.54% |
| CASE2B | 288.95 | 0.75 | 0.26% |
| CASE3 | 282.13 | 4.09 | 1.43% |

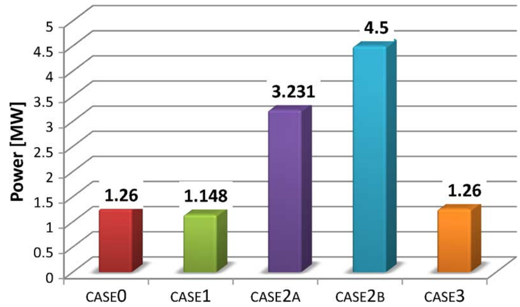


Fig. 9. Maximum total EWHs' power demand for different cases.

the EWHs are controlled during the off-peak hours with the balancing reserve signal which causes some EWHs not to reach to the maximum 160°F setpoint. Therefore, more energy is used during the on-peak hours in CASE3 than in CASE2B. Table VII shows the total EWHs' energy consumption during the off-peak and on-peak hours, and the percentage of EWHs' on-peak energy consumption to their total energy consumption for the one-week simulation study.

It is clear from Table VII that in CASE3 the EWHs use significantly less energy during the on-peak hours compared to the other cases without undesirable peak power demand increase, which will be discussed in GOAL3. This would greatly benefit the utilities and help to flatten their daily electric demand profile considering that the EWHs consume roughly 30% of the total electrical energy consumption in the residential sector during the peak-demand periods [7].

*GOAL3: Peak Load Equality or Reduction:* Fig. 9 compares the maximum power demand of the 1000 EWHs in each case. The maximum possible demand, if all EWHs were to be in the ON state at once, is 4.5 MW. CASE0 had a slightly higher peak power demand than CASE 1. This is because in CASE0, the ON/OFF cycling of the EWHs is only controlled by the hot water demand, while in CASE1 the desired balancing reserve signal also influences the operation of EWHs. As a result, fewer EWHs are turned ON at the same time in CASE1.

In CASEs 2A and 2B, the thermostat setpoints of all EWHs are set to their ceilings during off-peak hours (130°F in CASE2A and 160°F in CASE2B). This will cause all EWHs to act in the same way at the same time and decreases diversity. As a result, more EWHs stay in the ON mode at the same time during the off-peak hours, compared to CASEs 0, 1 and 3 and result in a higher peak power (Fig. 9). Moreover, the higher thermostat setpoint in CASE2B further increases the chance of having all EWHs in the ON mode at the same time. Therefore,

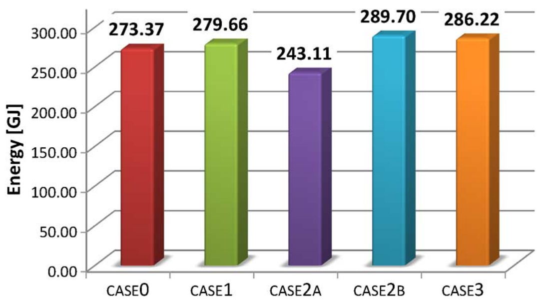


Fig. 10. Total weekly energy demand for different cases.

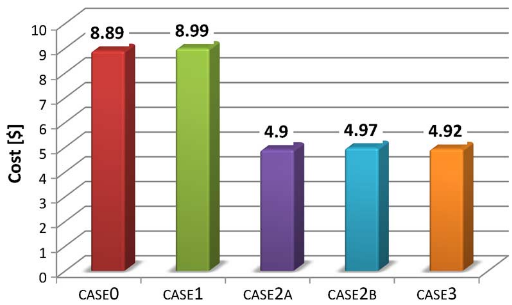


Fig. 11. Average weekly cost per EWH for different cases.

it can be concluded that CASEs 2A and 2B cannot be the options for the utility.

CASE3 has a slightly higher peak demand than CASE1. It is because the hot water temperature in most EWH tanks has reached close to the minimum value allowed (116°F) at the end of the on-peak period. Therefore these EWHs can only respond to DECs (i.e., increases in power demand.)

*GOAL4: Total Energy Demand Equality or Reduction:* Fig. 10 compares the total energy consumed by all EWHs in the one-week simulation period. The total one-week energy consumption of all EWHs is within 10% of each other in the different cases studied. Since the primary goals of these experiments are to provide balancing reserves and shift some of the demand from the on-peak hours to the off-peak periods, total energy consumption is less important as long as it is not increased greatly. CASE3, which was the most effective case of all for load shifting and providing balancing reserve (without increasing peak power demand) had about 4.7% increase in total energy consumption than the no-control case (CASE0). This small increase in energy consumption can be justified as the cost of ancillary services provided for the utility.

*GOAL5: Economic Benefit to the Customer:* In all CASEs, the price of the electricity is kept the same, as reported in Tables III and IV. But, the ToU pricing signal is only used as control signal in the CASEs 2A, 2B and 3. Fig. 11 compares the average cost of electricity for a single EWH in the one-week simulation period.

CASEs 0 and 1 are the most expensive ones, because electricity price doesn't affect power consumption through the ToU pricing signal. In CASEs 2A and 2B, the ToU pricing signal is the only signal used for thermostat setpoint control. These cases have a definite economic benefit for the consumers over CASEs 0 and 1. However, the large increases in the peak power in CASEs 2A and 2B (Fig. 9) have caused these cases to be ruled out as a possible method of control.

Although in both CASEs 2B and 3, the customers responded to the pricing signal by lowering the EWH thermostat setpoint to 126°F during the on-peak hours, the cost was 1.01% lower in CASE3 than in CASE2B. This is due to the fact that in CASE2B, the EWHs thermostat setpoints are always 160°F during the off-peak hours, thus causing the EWHs to consume more energy overall, as compared to CASE3, where the balancing reserve signal is used during off-peak hours.

*GOAL6: Provide Desired Balancing Reserves:* In CASEs 0 and 2 (2A and 2B), there were no balancing reserve control signals, and the balancing reserve matching could not be evaluated. CASE1, in which the only control signal was the desired balancing reserve, was able to provide the needed balancing reserves a higher percentage (93.17%) of the time compared to 75.92% for CASE3. This is because in CASE3, the pricing signal takes priority during on-peak hours, and balancing reserves are not provided during those periods.

Overall, CASE3 is considered the most effective amongst all the CASEs studied, as it provides economic benefit to the participating customers, as well as some load shifting and balancing reserve for the utility without considerable increase in energy consumption.

## VI. Discussion and Conclusion

This study shows that thermostat setpoint control of aggregated EWHs can be beneficial to the utility as well as the participating customers. The proposed method considers load shifting and price signal response simultaneously, investigates the impacts of the method for a week as opposed to few hours, and includes economic benefit analysis for the customers to participate in the DR program.

Five control methods were explored considering six goals with the highest priority goals being customer comfort level and safety (i.e., maintaining the water temperature within safe limits) and load shifting from on-peak demand hours to off-peak hours. Simulation results show that among the five control methods studied, the method that combines utility control of EWHs thermostat setpoint control along with customers responding to the ToU price signal provided by the utility (CASE3) yields the best results. It provided hot water (between 116°F–160°F) all the time, resulted in a significant reduction of EWHs' demand during the on-peak hours and provided load shifting. It also provided balancing reserves for the utility in the presence of wind generation (75.92% of the time during off-peak hours). Moreover, this control method resulted in a large reduction (45.01%) in the cost of electricity for the customers compared to the no-control case (CASE0). Therefore, both the utility and customers can benefit from this control method.

In addition to wind power, solar power could also be partially or fully accommodated using the proposed method. Beyond the benefits to the utility and customers, such DR strategies will also have invaluable environmental benefits, i.e. reduction in undesired emissions, as a result of avoiding the use of fossil fuel-based spinning and non-spinning reserves.

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