An Evaluation of the Water Heater Load Potential for Providing Regulation Service

Junji Kondoh, Ning Lu, *Senior Member*, *IEEE*, and Donald J. Hammerstrom, *Senior Member*, *IEEE*

Abstract—**This paper investigates the possibility of providing aggregated regulation services with small loads, such as water heaters or air conditioners. A direct-load control algorithm is presented to aggregate the water heater load for the purpose of regulation. A dual-element electric water heater model is developed, which accounts for both thermal dynamics and users' water consumption. A realistic regulation signal was used to evaluate the number of water heaters needed and the operational characteristics of a water heater when providing 2-MW regulation service. Modeling results suggest that approximately 33,000 water heaters are needed to provide a 2-MW regulation service 24 hours a day. However, if water heaters only provide regulation from 6:00 to 24:00, approximately 20,000 will be needed. Because the control algorithm has considered the thermal setting of the water heater, customer comfort is maintained. Therefore, the aggregated regulation service provided by water heater loads can become a major source of revenue for load-serving entities when the smart grid enables the direct load control.**

Index Terms—demand-side management, direct load control, electric water heaters, regulation service, wind power integration.

I. Introduction

The United States installed more than 10,000 MW of new wind power to the U.S. electrical grid in 2009, almost 40% of its newly installed capacity [1]. Many studies have been conducted to examine the technical feasibility and issues of using wind energy to generate 20% of the nation's electricity by 2030 [2,3]. A major operational issue identified is that both the ramp-rate and magnitude of the regulation requirement are expected to increase significantly. In meeting increased ramp and capacity requirements, the regulating generators may not be able to operate close to their preferred operating points, resulting in lower efficiencies. Faster regulating movements also increase mechanical stresses on these generators, shortening their lifetimes and increasing the wear-and-tear cost.

Pumped-hydro power plants, batteries, flywheels, distributed generation resources, and demand-side management (DSM) are flexible energy options that could provide the needed fast-response ancillary services [4,5]. Of these options, DSM is the least studied and exploited. Since 2006, markets for regulation service from DSM programs have opened in Pennsylvania, New Jersey, Maryland Interconnection, and LLC (PJM), but due to the strict telemetry requirement, all the participants of these programs have been large industrial customers [6].

However, the deployment of the smart grid will enable communication and control between buildings and utility control centers. Therefore, this paper aims to demonstrate that thermostatically controlled appliances (TCAs) can provide regulation when aggregated, and small residential or commercial customers may be able to participate in regulation markets in the future. The TCAs include residential heating, ventilation, and air conditioning (HVAC) systems; electric water heaters; and refrigerators.

There are two control methods in DSM: direct load control and indirect load control. In direct load control, the power consumption of loads is controlled directly by a utility or a system operator regardless of the customers' will. It is easy to adjust the demand precisely, but it is hard to maintain acceptable levels of comfort for the end users when the load-shedding period is longer than the period for which the TCAs are capable of coasting. By contrast, in indirect load control, the power consumption of loads is controlled manually by the customers or automatically by the appliances, with consideration given to information such as real-time electricity tariff and frequency deviation in power systems. For example, the set point control of TCAs according to the real-time electricity tariff affects end users less than load shedding. However, the relationship between varying amounts of the external parameter (e.g., electricity tariff) and power consumption is very complicated. Not only is the relationship nonlinear, but also the power consumption may oscillate because of the lack of load diversity after the control is initiated [7]. Thus, direct load control has been often adopted in demonstration projects and practical applications of DSM using TCAs [8–11].

The suitable TCAs for regulation application are (a) always in operation since regulation is required at all times and (b) high capacity in order to obtain an appreciable response with few appliances. Therefore, electric water heaters (EWHs) are promising in the United States. The authors have studied autonomous controls of EWHs according to power system frequency deviation [12–14] or local voltage deviation [15], and indirect controls according to real-time electricity tariffs [16–18]. This paper focuses on the direct control of EWHs to adjust their power consumption to follow regulation signals.

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Since EWHs store thermal energy, the consumption during the short (or over) supply period can be shifted rather than simply reduced (or increased). In short, the electricity will have to be consumed either earlier or later. Although energy payback from a group of controlled EWHs was considered as the reaction from customers in previous works [19,20], the thermal dynamics of the EWH must be modeled properly to simulate its electricity consumption when responding to regulation signals under the restriction to minimize end users' discomfort. This paper presents the EWH model in Section II and the control algorithm for providing regulation services in Section III. The modeling results are discussed in Section IV. The conclusions and future work are summarized in Section V.

II. The Modeling of the Electric Water Heater

To model the electricity consumption of an EWH, it is critical to model the heat transfer process of a water heater considering hot water consumption. This section introduces the thermal dynamic equations and then presents the modeling of the hot water consumption.

A. *The Thermal Dynamics Model of an EWH*

As shown in Fig. 1, conventional electric water heaters in the United States have two pairs of a heating element and a thermostat [21]. Only one heating element can be turned on at any one time. When hot water is being used, cold water enters the bottom of the tank and remains there because it is denser than hot water [22]. Thus, the water in the tank is vertically divided into three layers: hot water, cold water, and a mixing layer in between, as shown in Fig. 1.

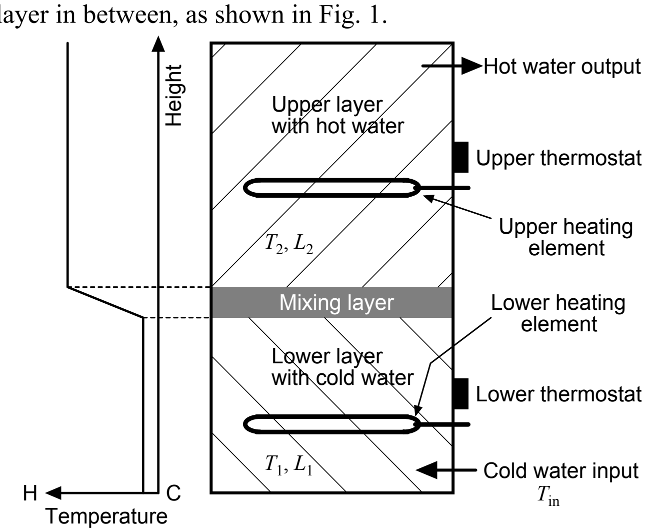

Fig. 1: Configuration and temperature profile of an EWH

The mixing layer moves from the bottom to the top of the tank when hot water is drawn out of the tank [23,24].[1] If the cold water layer rises to the level that triggers the lower thermostat, the lower heating element is turned on to heat the cold water. If hot water is continuously drawn out, the cold water layer may rise to a level that triggers the upper thermostat. Then, the upper heating element is turned on while the lower heating element is turned off to give priority to heating only the top layer. Once the top layer has been heated, the thermostat turns off the top heating element and turns on the lower heating element to heat the water from the bottom.

To simplify the modeling process with consistency in terms of energy balance, the following assumptions were made:

- The thickness of the mixing layer is zero. Then two layers were modeled with fixed volumes: the lower layer (Layer 1) with a volume of L_1 and the upper layer (Layer 2) with a volume of L_2.
- Inside a layer, the water temperature is uniform. The upper layer temperature, T_2, is always higher than or equal to the lower layer temperature, T_1.
- The upper thermostat monitors T_2, and the lower thermostat monitors T_1.
- The upper element heats only the upper water layer.
- If $T_1 < T_2$, the lower element heats only the lower layer. If $T_1 = T_2$, it heats both layers.
- The cumulative amount of water L_{used}, which is used after T_1 reaches T_2 once, is considered. The temperature of water moving from the lower layer to the upper layer is T_2 when $L_{used} < L_1$, and it is T_1 when $L_{used} \geq L_1$. When T_1 reaches T_2 by heating the lower layer, L_{used} is reset to zero. This assumption simulates the rise of the mixing layer.

Thus, the energy balance equations for the upper and lower layers are simplified as follows:

$$cmL_1 \frac{dT_1}{dt} = p_{1e} - p_{a1} - p_{21}$$
$$cmL_2 \frac{dT_2}{dt} = p_{2e} - p_{a2} + p_{21} - p_{hw} \qquad (1)$$

where c and m are the specific heat capacity and density of water, respectively; p is the thermal power and the subscripts of p indicate the movement of heat. For example, p_{1e} is thermal power transferred from the lower heating element to water in the lower layer, p_{a1} is heat radiation from water in the lower layer to the ambient air, and p_{hw} is hot water consumption.

The power input by the lower or upper heating element p_{ie} (i = 1 or 2) is calculated as $p_{rate}s_i$ where p_{rate} is the rated power of the heating element, s_i is the state of the thermostat ($s_i = 0$ at the "off" state, and $s_i = 1$ at the "on" state). The thermostat turns on when T_i decreases to less than the lower threshold T_{lth} ($= T_{set} - \Delta T_{th}/2$) and turns off when T_i increases to more than the upper threshold T_{uth} ($= T_{set} + \Delta T_{th}/2$), where T_{set} is the temperature setting and ΔT_{th} is temperature differential [25,26]. The upper and lower thermostats are modeled to have identical set points.

Heat radiation p_{ai} (i = 1 or 2) is calculated as

$$p_{ai} = cmL_i(T_i - T_a)/\tau \qquad (2)$$

where T_a is ambient temperature, and τ is the time constant and is set to 120 h in this study. When T_i = 120°F, T_a = 60°F, and L_i = 80 gal (303 l), p_{ai} is around 100 W, which is almost the same as the loss (91 to 96 W) indicated in the table on a catalog [27].

The parameters of the model are summarized in Table I.

[1] Such layers appear when the temperature difference between the hot water and cold water layers is more than 20 to 25°C.

TABLE I
THE PARAMETERS OF THE EWH MODEL

Items		Values
Whole water volume	L_0	50 gal (190 l)
Lower water volume	L_1	30 gal (114 l)
Upper water volume	L_2	20 gal (76 l)
Setting temperature	T_{set}	125°F (52°C)
Temperature differential	ΔT_{th}	10°F (12°C)
Water inlet temperature	T_{in}	60°F (16°C)
Ambient temperature	T_a	60°F (16°C)
Rated power	p_{rate}	4.5 kW

B. The Modeling of the Hot Water Consumptions

Based on load surveys, such as the End-Use Load and Consumer Assessment Program (ELCAP) data collected by the Bonneville Power Administration (BPA) [28], hourly water heater load profiles (p_{ave}), which is the average of all of the residential samples, are derived and used to generate the time series of hot water consumption (p_{hw}) for an individual EWH.

The typical amount of hot water demand for activities in the United States [29] and Sweden [30] are shown in Tables II and III, respectively. Although Tables II and III show different amounts for hot water demand, both tables indicate that demand is more than 2.0 kWh per main activity. Further, Table III indicates that hot water consumption is 25.2 kW (= 2.1 kWh / 5 min) in the case of a shower at 55°C (131°F).

TABLE II
MAIN HOT WATER DEMAND PER FIXTURE FOR PRIVATE RESIDENCE IN U.S., CALCULATED AT A FINAL TEMPERATURE OF 140°F (60°C) [29]

Activity	Volume	Energy*
Shower	30 gal (114 l)	5.9 kWh
Bath	20 gal (76 l)	3.9 kWh
Laundry	20 gal (76 l)	3.9 kWh
Dishwasher	15 gal (57 l)	2.9 kWh

*: Calculated assuming an inlet water temperature of 60°F (16°C)

TABLE III
MAIN HOUSEHOLD HOT WATER DEMAND IN SWEDEN, ASSUMING A FINAL TEMPERATURE OF 55°C [30]

Activity	Volume	Energy*
Bath	100 l	5.2 kWh
Shower (5 min)	40 l	2.1 kWh
Dish wash	39 l	2.0 kWh

*: Calculated assuming an inlet water temperature of 10°C

The following assumptions are made to model the time series of hot water consumption, p_{hw}:

a) The minimum and maximum values of the hot water consumption p_{hw} are p_{hwmin} = 4.5 kW and p_{hwmax} = 24 kW, respectively. p_{hwmin} is the same as p_{rate}. This means that the hot water consumed cannot be recovered by electrical heating in real time; therefore, the heat energy is discharged from the hot water storage tank. Note that the maximum value p_{hwmax} is almost the same as that in the case of a shower in Table III.

b) A unit of energy E_{unit} = 2.0 kWh is consumed for every usage of hot water. Note that an EWH is turned on with every usage of the E_{unit} to compensate for the energy dissipation. This is because T_1 or T_2 drops below the lower threshold of the thermostat, owing to $E_{unit} > cmL_0\Delta T_{th}$ (= 1.22 kWh) with the settings given in Table I Thus, the minimum heating duration is

$$t_{least} \equiv \frac{E_{unit}}{p_{rate}} \tag{3}$$

Although the average load profile of EWHs (p_{ave}) is a continually changing curve, a load profile of an individual EWH is an irregular pulse train with the magnitude of p_{rate} due to turning on and off. Thus, the on/off state of each EWH was simulated for every t_{least} period while using p_{ave} curve and a random number x between 0 and 1; on state if $x < p_{ave} / p_{rate}$ and off state else.[2]

Then, a pulse of hot water consumption is assigned to every pulse of the heater load as shown in Fig. 2. In Fig. 2, t_{delay} is the time delay from the start of hot water consumption to the start of turning on a heating element. For an individual EWH, the value of t_{delay} depends on T_1 and T_2 at the start of hot water usage. Since T_1 and T_2 are not calculated at this stage, t_{delay} was distributed randomly. Note that $t_{delay} < cmL_1\Delta T_{th} / p_{hw}$ because T_1 decreases below the lower threshold of the thermostat T_{lth} within $cmL_1\Delta T_{th} / p_{hw}$ even if T_1 was at the maximum temperature, which is the same as the upper threshold of the thermostat T_{uth}, at the start of hot water usage. Some EWHs may be on for n time periods (n > 1) as shown in Fig. 3, which simulates continuous hot water consumption. However, t_{delay} was still in the range of $0 < t_{delay} < cmL_1\Delta T_{th} / p_{hw}$. Using parameter settings given in Table I, it is possible that a lack of hot water supply occurs after $n > 4$ because $4E_{unit} > cmL_0(T_{lth} - T_{in})$.

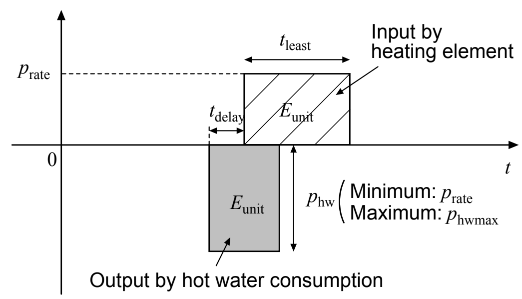

Fig. 2: Consumption profiles of a hot water usage

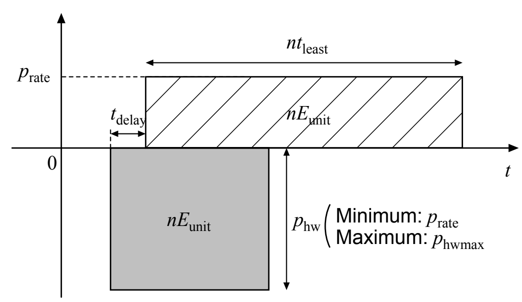

Fig. 3: Consumption profiles of multiple hot water usages

[2] Strictly speaking, p_{ave} is decreased a little on the simulation of p_{hw} profile in order to eliminate the influence of the heat radiation.

C. Modeling Results of the Normal EWH operation

Modeling results of an EWH at 1-minute intervals is shown in Fig. 4. In Fig. 5, four water heater load profiles are obtained when the number of water heaters, n_{EWH}, is set to 10, 100, 1,000, and 10,000, respectively. When n_{EWH} is 10, 100, or 1000, the simulated curves are rather different from the measured hourly load profile (p_{ave}). When n_{EWH} = 10,000, the simulated curve follows the p_{ave} very well. Therefore, the case of n_{EWH} = 10,000 is used hereafter for the numerical simulations.

According to the simulation result of the normal operation of 10,000 EWHs, average numbers of turn-on or turn-off of the lower and upper thermostats in EWHs, $\overline{n}_{\text{turn1}}$ and $\overline{n}_{\text{turn2}}$, were 10.91 and 0.18 per day, respectively. A lack of hot water supply occurred in 44 EWHs (0.44%), the longest being 11 minutes/day in EWH #9746. The operation power patterns and temperature variation of EWH #9746 are shown in Fig. 4. In the electric water heater #9746, n_{turn1} and n_{turn2} are 10 and 2 per day, respectively, and the lack of hot water supply occurred at 13:10 because of a large demand for hot water starting at 13:05. The slight temperature decrease without the hot water consumption is due to heat radiation to the outer air.

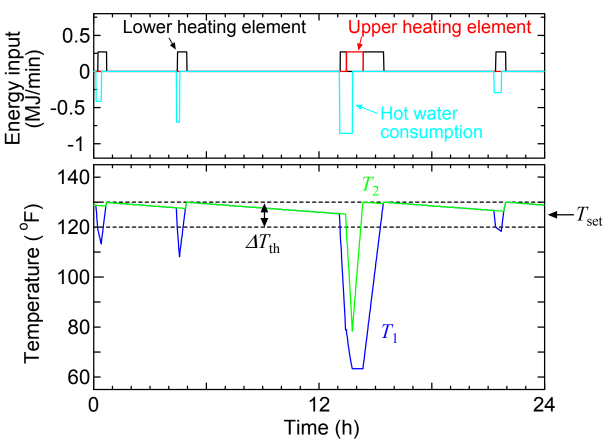

Fig. 4: Power patterns and temperature variation of the EWH #9746 in normal operation

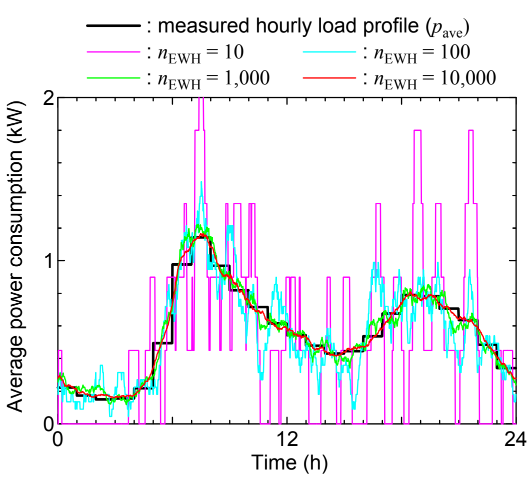

Fig. 5: Water heater load profiles in normal operation

III. THE CONTROL ALGORITHM FOR PROVIDING REGULATION SERVICES

When providing regulation service, EWHs need to work collectively and coordinate their operation. The traditional control circuit of an EWH needs to be modified to meet the requirement, and a control algorithm is needed to let the aggregated EWH response meet regulation requirements.

A. Circuit Modification

To guarantee end users' comfort, only the control circuit of the lower thermostat that controls the lower heating element is modified to let EWHs provide regulation service. The control circuit of the upper thermostat remains the same to let the upper heating element heat the cold water when significant amounts of hot water are consumed.

In Fig. 6, the modifications made to the original control circuit are shown in red. The EWH controller controls switches SW1 and SW2 and communicates with a central controller operated by the power system operator. The central controller also monitors the on/off state conditions of all thermostats and switches in its system and turns them on/off to follow the regulation signal. If central controller sends the signal to decrease the electricity consumption of the EWH, the EWH controller opens the normally closed switch, SW1. If it is required to increase the EWH electricity consumption, the EWH controller closes the normally open switch, SW2. The additional lower thermostat should have the minimum temperature differential, and its upper turning off threshold temperature should be close to that of the conventional lower thermostat.

B. The Control Algorithm

The following four control steps were implemented every 1 minute to provide minute-by-minute regulation service:

1. Each controller in an electric water heater sends c_1, c_2, and t_{after} to the central controller, where c_i is a parameter indicating previous and next on/off conditions of the thermostat (s_i) shown in Table IV, and t_{after} is the time after the last turnings on/off according to the instructions from the power system operator. In Table IV, c_1=3 means $T_1 \geq T_{\text{set}} + \Delta T_{\text{th}}/2$, and c_1=4 or 5 means s_2 will be 1 (on state) at the next control timing (c_2=1 or 2).
2. The power system operator calculates the total power consumption, P_{woc}, in the case of no active control, an upward reserve P_{ur} (Regulation up), and a downward reserve P_{dr} (Regulation down) at the next control timing, t+Δt, by all controllable EWHs.

$$P_{\text{woc}}(t+\Delta t) = P_{\text{tot}}(t) + p_{\text{rate}}\{N(c_2=2) - N(c_2=3) + N(c_1=2) - N(c_1=3) - N(c_1=5)\} \tag{4}$$

$$P_{\text{ur}}(t+\Delta t) = p_{\text{rate}} N(c_1=0, t_{\text{after}} > 5\text{ min.}) \tag{5}$$

$$P_{\text{dr}}(t+\Delta t) = -p_{\text{rate}}\{N(c_1=1, t_{\text{after}} > 5\text{ min.}) + N(c_1=2, t_{\text{after}} > 5\text{ min.})\} \tag{6}$$

where $P_{\text{tot}}(t)$ is the total power consumption by all EWHs at t, and $N(A)$ is the number of electric water heaters that satisfy condition A. Condition t_{after} > 5 minutes was considered to avoid frequent turning on/off. Here, P_{sup} is defined as the total power consumption forecasted a day ahead as the base case of no regulation. $P_{woc}(t+\Delta t)$ is almost the same as $P_{sup}(t+\Delta t)$ if the P_{sup} forecast is correct and no regulation has been implemented by t. However, once any regulation has been implemented by t, $P_{woc}(t+\Delta t)$ is no longer the same as $P_{sup}(t+\Delta t)$ since the regulation affects the thermal energy stored in EWHs.

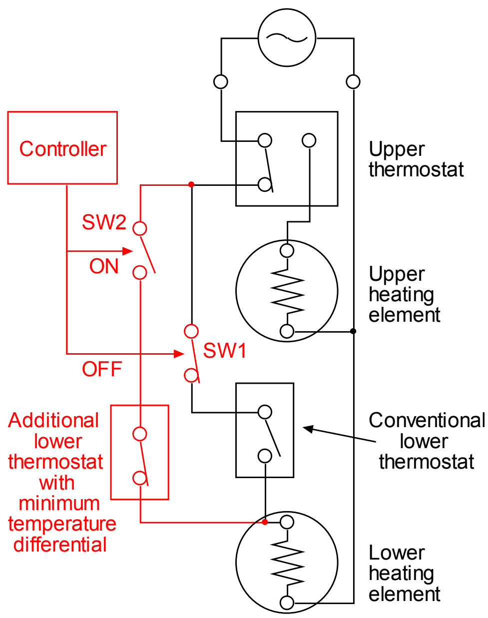

Fig. 6: The modified circuit of an electric water heater

3. If any control is required to vary the total power consumption from P_{woc} to the target value P_{tar} at $t+\Delta t$, the total power variation $\Delta P_{tar} \equiv P_{tar}(t+\Delta t) - P_{woc}(t+\Delta t)$ is attempted by changing the on/off states of the EWHs. The practical variation ΔP_{prac} can be the same as ΔP_{tar} if $P_{dr} \leq \Delta P_{tar} \leq P_{ur}$. However, ΔP_{prac} is limited to P_{dr} when $\Delta P_{tar} < P_{dr}$ or to P_{ur} when $\Delta P_{tar} > P_{ur}$, which means a lack of reserve. The practical total power consumption $P_{tot}(t+\Delta t)$ is $P_{woc}(t+\Delta t)+\Delta P_{prac}$.
4. The power system operator sends instruction to turn the switches SWi on/off toward the proper number of EWHs to implement the power variation of ΔP_{prac}.

TABLE IV
PARAMETERS REGARDING PREVIOUS AND NEXT ON/OFF CONDITIONS OF THERMOSTATS

(a) Lower heating element circuit

c_1	previous s_1	next s_1
0	0	want to be 0
1	1	want to be 1
2	0	want to be 1
3	1	must be 0
4	0	must be 0
5	1	must be 0

(b) Upper heating element circuit

c_2	previous s_2	next s_2
0	0	0
1	1	1
2	0	1
3	1	0

IV. Modeling Results

The modeling results are presented in this section. Two scenarios are presented: constant power reduction/increase and regulation service.

A. Provide the One-directional Constant Regulation Service

Let P_{reg} represent the regulation signal. First, let the water heaters respond to the constant regulation up signal. In this case, the EWHs are required to reduce their power consumption by P_{dec}. To restrict excess power payback after the regulation, it was considered that the power payback is limited within $P_{dec}/4$. In the simulation, P_{sup} was calculated as a 60-minute simple moving average of the total power consumption curve of the normal operation in Section II.C.

Fig. 7 shows an example of a numerical simulation under the condition P_{dec} = 1.45 MW with a regulated duration of $t_{duration}$ = 3 h from t_{start} = 6:00. In Fig. 7, the downward reserve P_{dr} was close to zero at the end of the regulation (9:00) because in many EWHs, which had been kept off-state according to instruction, the upper thermostats started to turn on. If the regulated duration was longer, the downward reserve P_{dr} would reach zero, which means the total power consumption of the EWHs could not be decreased any more. The upward reserve P_{ur} was enough since many EWHs could be turned on (c_1= 0).

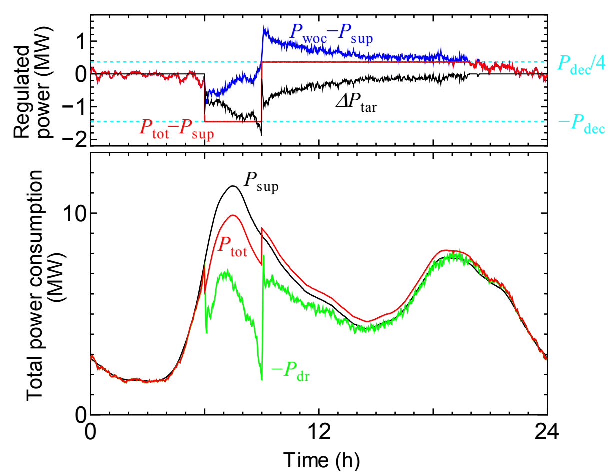

Fig. 7: Simulated power variation in constant regulation operation (P_{dec} = 1.45 MW, $t_{duration}$ = 3 h from t_{start} = 6:00)

In this simulation condition, average numbers of turnings on or off of the lower and upper thermostats in EWHs, $\overline{n}_{turn1}$ and $\overline{n}_{turn2}$, were 23.43 and 0.61 per day, respectively. A lack of hot water supply occurred in 77 EWHs (0.77%), the longest being 19 minutes/day in EWH #884. Therefore, compared with the no regulation case in Section II.C, the number of turnings on/off were doubled and the number of end users who felt uncomfortable increased by 75%.

Numerical simulations were implemented with other conditions. The results under a resolution of 0.05 MW is in Table V. Table V indicates that the available range of P_{dec} is high when power consumption by EWHs is high and the regulated duration $t_{duration}$ is short.

Compared with the total rated power, 45 MW of 10,000 EWHs, the available range of P_{dec} seems small. The reasons are as follows:

1) The rate of the "on" EWHs is low in the no regulation case (the minimum rate is only 1.5 MW/45 MW = 3% at 2:30, and the maximum rate is also only 12 MW/45 MW = 27% at 7:30). This low "on" rate results in a low downward reserve because the downward reserve is lower than the magnitude of the total power consumption.
2) A lower setting temperature and a smaller volume of EWHs in the United States (compared with those in Japan) restrict their use as energy buffers.

However, if EWHs are used for bi-directional applications such as frequency regulation, the requirement on energy buffers is relieved due to not only reduction but also an increase of power consumption. Thus, the available range of P_{reg} will increase. This application is analyzed in the next section.

Next, let the water heaters respond to the regulation down signal. In this case, the EWHs are required to increase their power consumption by P_{inc}. The results under a resolution of 0.05 MW are in Table VI. Table VI indicates that

1) The available range of P_{inc} is higher than that of P_{dec} (comparison between Case 1 in Table V and Case 6 in Table VI), since the magnitude of the upward reserve P_{ur} is higher than that of the downward reserve P_{dr}.
2) The lack of hot water supply decreased a little.

The results in this section indicate that the constant power increase is much easier to achieve than the constant power reduction.

B. Bi-directional Regulation Signals

In this section, an area control error (ACE) signal was used. The excess signal, whose absolute value is beyond the nominal value P^*_{reg}, was capped to P^*_{reg}. Two cases were modeled: Case 8 (a whole day) and Case 9 (6:00 to 24:00). The results with a resolution of 0.05 MW are presented in Figs. 8, 9 and Table VII.

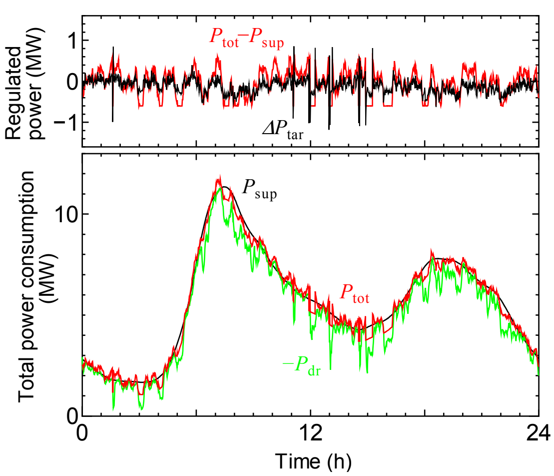

Fig. 8: Simulated power variation according to bi-directional regulation signals (P^*_{reg} = 0.60 MW, 24-h regulation)

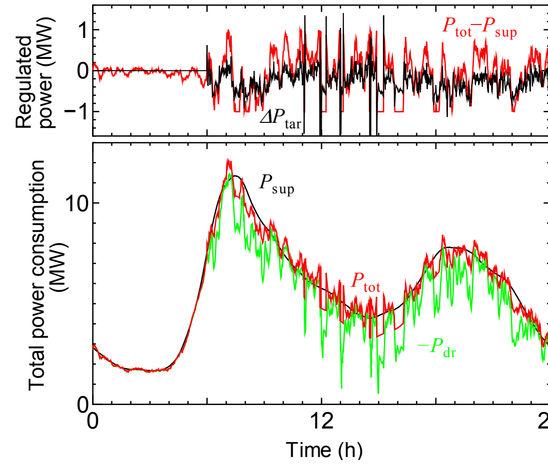

Fig. 9: Simulated power variation according to bi-directional regulation signals (P^*_{reg} = 1.00 MW, 18-h regulation from 6:00)

The results indicate:

- As shown in Fig. 8, the bottleneck occurred between 1:00 and 4:00 for the whole-day case, during which period the demand of hot water is the lowest. If P^*_{reg} = 0.65 MW, a lack of downward reserve, P_{dr}, occurred at 3:10. Compared with the result of constant power reduction during 3 h from 1:00 in Table V (Case 1), the applicable range of regulation increased 1.5 times (from 0.40 MW to 0.60 MW) since continuous downward regulation during the minimum demand period was around 20 minutes only.
- As shown in Fig. 9, the bottleneck occurred between 13:00 and 16:00 for the 18-h case. If P^*_{reg} = 1.05 MW, a lack of downward reserve, P_{dr}, occurred at 13:03. Compared with the result of constant power reduction during 3 h from 13:00 in Table V (Case 3), the applicable range of regulation increased a little from 0.90 MW to 1.00 MW. However, compared with the result of constant power reduction during 1 h from 14:00 in Table V (Case 4), the applicable range of regulation decreased from 1.15 MW to 1.00 MW, in spite of shorter continuous downward regulation (less than 10 minutes). The reason is that power consumption had to be reduced twice, once at 12:58 and again at 13:01 after a requirement to increase power consumption at 13:00 in the case to follow regulation signals (Case 9). That is to say, the downward reserve, P_{dr}, was drastically decreased by the first power reduction at 12:58, and then the second request of power reduction from 13:01 was sent before there was sufficient recovery of the downward reserve, P_{dr}, from the previous reduction. This occurred because there was the limit of $t_{\mathrm{after}} > 5$ minutes to avoid frequent turnings on/off as shown in Eq. (6).

TABLE V
SIMULATION RESULTS WITH DIFFERENT REGULATION CONDITIONS (CONSTANT POWER REDUCTION CASES)

Case			Maximum	Number of turning on/off				Lack of hot water		
No.	t_{start}	t_{duration}	P_{dec}	$\overline{n}_{\text{turn1}}$	$\overline{n}_{\text{turn2}}$	$n^{\max}_{\text{turn1}}$	$n^{\max}_{\text{turn2}}$	Number	Ave. duration	Max. duration
No regulation case				10.91	0.18	26	6	44	2.9 min	11 min
1	1:00	3 h	0.40 MW	17.96	0.33	48	6	60	3.1 min	15 min
2	6:00	3 h	1.45 MW	23.43	0.61	64	8	77	3.4 min	19 min
3	13:00	3 h	0.90 MW	17.42	0.32	48	6	64	3.0 min	11 min
4	14:00	1 h	1.15 MW	12.20	0.20	36	6	47	2.9 min	11 min
5	14:00	0.5 h	1.35 MW	11.56	0.19	30	6	46	2.9 min	11 min

TABLE VI
SIMULATION RESULTS WITH DIFFERENT REGULATION CONDITIONS (CONSTANT POWER INCREASE CASES)

Case			Maximum	Number of turning on/off				Lack of hot water		
No.	t_{start}	t_{duration}	P_{inc}	$\overline{n}_{\text{turn1}}$	$\overline{n}_{\text{turn2}}$	$n^{\max}_{\text{turn1}}$	$n^{\max}_{\text{turn2}}$	Number	Ave. duration	Max. duration
No regulation case				10.91	0.18	26	6	44	2.9 min	11 min
6	1:00	3 h	1.10 MW	19.95	0.11	34	4	39	2.4 min	10 min
7	2:00	1 h	3.15 MW	12.77	0.13	28	6	42	2.6 min	11 min

TABLE VII
SIMULATION RESULTS WITH DIFFERENT REGULATION CONDITIONS (BI-DIRECTIONAL REGULATION SIGNALS CASES)

Case			Maximum	Number of turning on/off				Lack of hot water		
No.	t_{start}	t_{duration}	P^{*}_{reg}	$\overline{n}_{\text{turn1}}$	$\overline{n}_{\text{turn2}}$	$n^{\max}_{\text{turn1}}$	$n^{\max}_{\text{turn2}}$	Number	Ave. duration	Max. duration
No regulation case				10.91	0.18	26	6	44	2.9 min	11 min
8	0:00	24 h	0.60 MW	18.61	0.27	48	6	60	3.0 min	11 min
9	6:00	18 h	1.00 MW	21.58	0.35	53	8	60	3.2 min	18 min

- Table VII indicates that in order to apply to 2-MW bi-directional regulation signals, 2/0.60×10,000 = 33,333 EWHs are required for the whole-day (24 h) regulation, and 2/1.00×10,000 = 20,000 EWHs are required for the 18-h regulation from 6:00. However, the available ranges of the nominal value, P^{*}_{reg}, for power regulation shown in Table VII are for the cases with the specific regulation signals used in this simulation. The values depend on the signals and may vary when different signals are applied.
- Regarding the numbers of turning on/off, since the nominal life cycles of thermostats are 30,000 [26] and the conventional lifetime of an electric water heater is around 15 years, around 11 times of turning on/off are acceptable per day. Table VII indicates that $\overline{n}_{\text{turn1}}$ is just around 11 in the no-regulation case, but it increases twice in the cases to follow the regulation signals. However, in the regulation applications, the number of devices to turn on/off the lower heating element increases from one to four, as shown in Fig. 6. Since $\overline{n}_{\text{turn1}}$ is the number of turnings on/off by all four devices, this increased $\overline{n}_{\text{turn1}}$ must be acceptable. There is no concern over the thermostat for the upper heating element, since $\overline{n}_{turn2}$ is much lower than 11 in all cases.
- Table VII indicates that the number of EWHs in which the lack of hot water supply occurred was increased by 36%, from 44 to 60, by following the regulation signals. However, it is not significant since the probability of lack of hot water (0.6%) is still low.

V. CONCLUSIONS

This paper focuses on the direct control of EWHs to adjust their power consumption to follow regulation signals. First, a simulation model of a dual element EWH was developed while considering the energy balance. Then, hot water demand on each EWH was estimated from the measured average load profile. Next, the control method of EWHs for regulation was proposed. Finally, operations of EWHs were numerically simulated, and their regulable power consumption was evaluated. The results indicated that 33,000 EWHs are required for the whole-day (24 h) regulation to apply to 2-MW bi-directional regulation signals by the proposed control scheme. The bottleneck of the regulation is for the period with less power consumption, from 0:00 to 6:00. If the regulation during the period is not necessary, 20,000 EWHs are required for the other 18-h regulation.

The modeling results suggest that with a smart grid in place, the load-serving entities can extend the control to appliances and collect additional revenue from the regulation market to recover the cost invested in the two-way communication and control network. The consumers can also benefit economically by offering their appliances to provide the service to help integrate more renewable resources into the power grid.

Our future work will extend the research to other appliances and study the economics of the implementation.

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Junji Kondoh received the D.Eng. degree from the Tokyo Inst. of Tech. in 1998. He then joined the Electrotechnical Laboratory (ETL). He is now a senior research scientist at the Energy Technology Research Institute (ETRI) in the National Institute of Advanced Industrial Science and Technology (AIST) in Japan. Recently he has been engaged in research on electric power systems with large amounts of renewable energy.

Ning Lu (M'98-SM'05) received her B.S.E.E. from Harbin Institute of Technology, Harbin, China, in 1993, and her M.S. and Ph.D. degrees in electric power engineering from Rensselaer Polytechnic Institute, Troy, New York, in 1999 and 2002, respectively. Dr. Lu joined the Laboratory in 2003. She is a senior research engineer with the Energy and Environment Directorate, Pacific Northwest National Laboratory, Richland, WA. Her research interests are in the modeling and analyzing power system load behaviors with a focus on the smart grid technology implementation on power system distribution grids. Dr. Lu has managed research projects in smart house technology development, modeling climate impacts on residential and commercial building energy consumption, wind integration studies, and wide-area energy storage management systems. Dr. Lu is a senior member of the IEEE.

Donald J. Hammerstrom (M'94-SM'07) is a senior research engineer in the Energy and Efficiency Division at Pacific Northwest National Laboratory, Richland, Washington. He led the U.S. Department of Energy's GridWise(R) Testbed Projects, including the Olympic Peninsula and Grid Friendly Appliance projects in Washington and Oregon from 2004 through 2007. He is presently Principal Investigator of the Pacific Northwest Smart Grid Demonstration and leads technology development of grid-responsive electric loads, including the autonomous Grid Friendly(TM) controller. Prior to rejoining Battelle, he designed power converters, biological sample collectors, and surface decontamination systems for startup companies in Washington State. He has authored United States patents in the diverse areas of energy management systems, power electronic converters, microtechnology, microbe decontamination, and aerosol sample collection. Dr. Hammerstrom earned a B.A. in chemistry from St. Olaf College, Northfield, Minnesota, a B.S. in education from Eastern Montana College, Billings, Montana and M.S. and Ph.D. degrees in electrical engineering from Montana State University, Bozeman, Montana in 1991 and 1994, respectively.