Aggregated Generic Load Curve for Residential Electric Water Heaters

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***Abstract*—Advanced control techniques may be used to regulate the operation of residential appliances to establish a virtual power plant. The electric water heater may be regarded as a "uni-directional battery" and a major component of a hybrid residential energy storage system. One of the main constraints of implementing demand response with EWH relates to the unpredictable customer behavior, which influences the domestic water tank temperature as well as the EWH operation cycle. This study analyzes the operation of multiple water heaters and develops an aggregated generic water heater load curve for the average residential customer based on experimental data retrieved from the A.O. Smith Corporation. An equivalent thermal model capable of capturing the typical customer behavior and estimating the per unit hot water usage was developed. The proposed aggregated generic EWH load curve was validated through an example demand response program, in which the morning peak demand is shed in order to store the surplus PV power at midday in the EWH. Based on the representative hot water draw profile and the electric power profile, the change in average tank temperature was estimated and maintained within the customer acceptable range.**

***Index Terms*—Electric Water Heater (EWH), Generic Curve, Demand Response (DR), Smart Home, Virtual Power Plant (VPP), Smart Grid.**

I. INTRODUCTION

The near-ubiquity of Electric water heaters (EWHs) make them one of the most advantageous appliances to participate in the virtual power plant (VPP) operation for residential buildings. Due to the large thermal mass of water tanks, EWHs could be regarded as a heat reservoir as well as an energy sink. The good insulation of EWH tanks lead to high equivalent resistances, resulting in less energy loss [1]. These properties allow EWHs to, for a short period of time, shed grid power while maintaining the water temperature at the reference temperature. On the other hand, EWHs can also be used to absorb surplus PV generation. There are multiple benefits of incorporating EWHs into home energy management as the PV penetration keeps rising. Recent research indicate that incorporating EWHs could lead up to 30% reduction in battery capacity for residential homes [2].

The water heating load makes up a great portion of a typical total house load [3]. The unpredictability of customer behavior makes quantifying the benefits of controlling EWHs difficult. A typical aggregated load for EWHs has a morning and evening peak [4]. User comfort needs to be ensured while implementing the demand response (DR) calls for the monitoring of the water tank temperature. The water temperature in the tank must be high enough to meet the user demand and cannot exceed the stipulated safety reference. However, technologies such as mixing valves may be integrated to allow the water tank temperature up to 145F remain within acceptable operation range [5], [6].

In previous studies, the hot water draws for 48 representative days were evaluated based on measured data from California homes [7]. The proposed schedules are used in the California Building Energy Code Compliance for Residencial buildings (CBECC-Res) [8]. Another study calculates the aggregated EWH load by relating to the hot water usage activities [9]. An EWH demonstration report shows the reduction in both power and electricity usage that is possible [10]. The Smart Water Heater Simulator in the EPRI DERMS simulation framework emulates a smart water heater with communications capabilities [11].

In this paper, the aggregated generic load for residential EWHs is proposed based on experimental data retrieved from the industrial collaborator, A.O. Smith. The dynamic relationship among EWH working status, tank temperature, and hot water usage is identified and evaluated using equivalent thermal models. An aggregated generic curve for hot water usage, which represents the average user behavior, is also proposed. The VPP control through DR was implemented by shifting the morning peak to the midday when the PV generation is relatively high. The results from this study indicate that maintaining the tank temperature within acceptable ranges is possible while participating in DR.

II. ELECTRIC WATER HEATER PROJECT OVERVIEW

In 2018, the A.O. Smith group in conjunction with Lowe's initiated a program to explore the potential benefits of smart EWHs for the grid and analyze trends in customer behaviors. Approximately 800 customers with the "EnergySmart" EWH model participated in the program, in which appliance usage data was retrieved and evaluated. The EWH heater models include an optional CTA-2045 port adaptor and utility communication module to ensure smart communication with their provider. (Fig. 1).

The first year of this two-year project witnessed a growing number of participants, peaking at nearly 500 electric water

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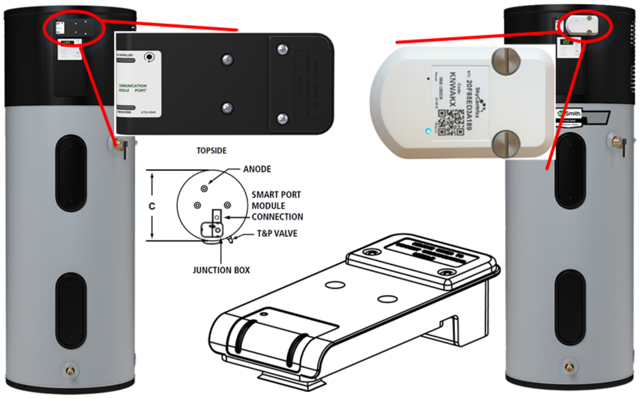

Fig. 1. The illustrative parts of A.O.Smith "EnergySmart" model and CTA-2045 standard port. The "EnergySmart" model is smart grid ready and implements standardized communications for demand response.

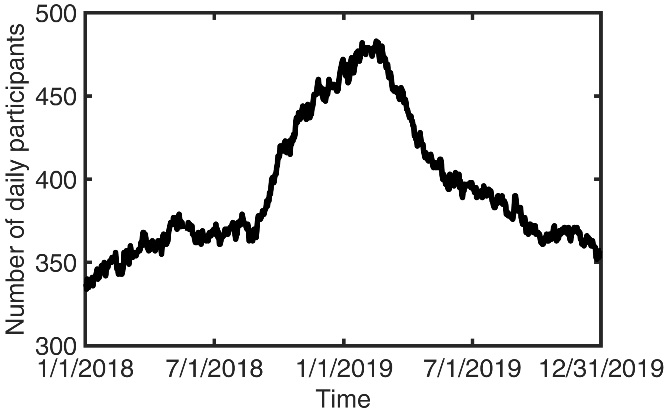

Fig. 2. Daily number of EWH in service. Approximately 800 participants were involved in the program and an increase from inception till early 2019 can be observed before the gradual decline.

heaters recorded per day in early 2019 (Fig. 2). Based on the reported data, up to 100 participants opted out of the program at inception and only 140 EWHs participated through the entire length of the project (Fig. 3).

III. MATHEMATICAL MODEL

This study presents an approach for developing an aggregated generic power curve for aggregated EWHs based on the experimental data retrieved from the Lowe's project. The operation status (ON or OFF) of each EWH participating in the programs was collected and analyzed at 1-minute resolution. For this program, it is assumed that all the EWH are rated for 5kW.

The daily power curve for EWHs is influenced by multiple factors including the hot water usage, outlet and inlet water temperature, duct insulation, heating element efficiency and other user-influenced parameters. Hence, there is variation in the power curve from one EWH unit to the other. A typical residential EWH would normally have two or three short heating cycles daily. Only when the number of EWHs being analyzed is fairly large is the aggregated EWH power relatively smooth with trends.

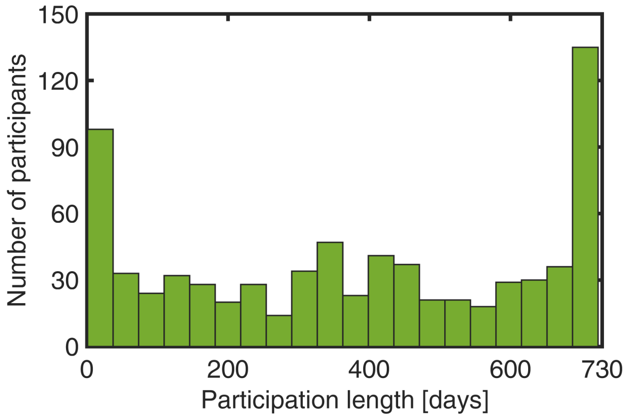

Fig. 3. Participant engagement over the duration of the research. Reduction in the number of participants in some cases were attributed to changes in internet settings and monitoring hardware devices being disconnected.

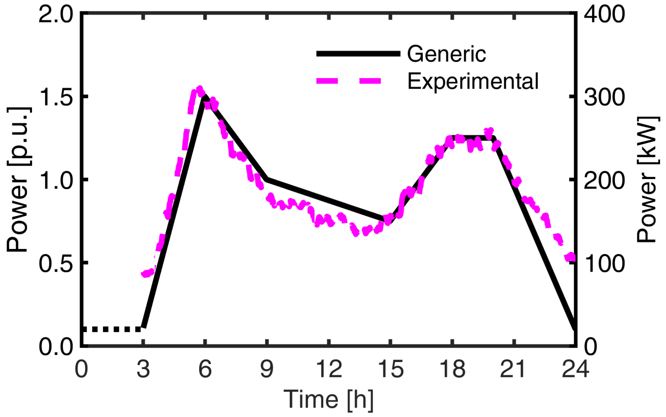

Fig. 4. Example day aggregated power transfer. The aggregated generic profile was developed based on data retrieved from 450 EWHs.

In another experimental study conducted in the approximately the same time frame, a different group of researchers from Oak ridge National Lab considered a field pilot demonstrator that involves only 50 EWHs [4]. The results from such limited number of samples somewhat follow the trend noted in our proposed generic load curve, but the variations are much larger due to limited aggregation effect. In this study, a systematic search was carried out to recursively reducing the number of EWHs until the trend established by the full data was still obvious. To this end, only workdays with more than 450 EWHs online were analyzed. The generic EWH power curve of the selected workdays is presented in Fig. 4.

The measured power profile from 450 EWHs were used to develop an aggregated generic load profile to represent the typical power flow for multiple EWHs (Fig. 4). The estimated standby loss in the early morning was low because of the improved insulation [4]. This proposed aggregated generic EWH load curve can be employed for estimating expected morning

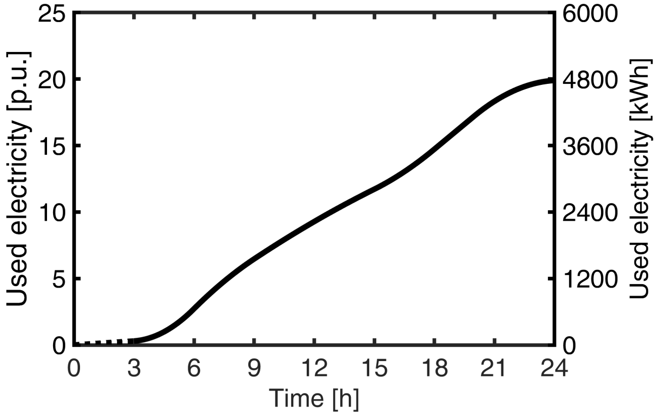

Fig. 5. Example day EWH cummulated energy. The average daily electricity usage for each EWH is approximately 11kWh.

Table I
THE P.U. VALUE OF AVERAGE EWH POWER

Hour	0	3	6	9	15	18	20	24
Power [p.u.]	0.1	0.33	1.5	1	0.75	1.25	1.25	0.33

and evening peak demands as well as evaluate the anticipated standby losses from multiple EWHs. This techniques uses the least amount of data points to develop an aggregated generic curve that can be used for the modeling of aggregated EWH load (Table I). Based on the aggregated generic curve the cumulative energy for the 450 EWHs considered was recorded as 5,016kWh for the example day evaluated (Fig. 5). Hence, the average daily electricity usage for each EWH can be computed as 11kWh. In this approach, the per-unit base value for the proposed aggregated generic curve is defined as:

$$P_{base} = \frac{E \cdot N}{T}, \tag{1}$$

where, E is the average daily electricity usage; N, the total number of EWHs; and T, the duration in hours.

The equivalent thermal model is used to establish the daily hot water usage in the study. The water temperature is mostly determined by the input electric power, the standby heat loss, and the hot water draw activities. These three major factors are included in the heat transfer function of the water temperature, as follows,

$$C\frac{\mathrm{d}\theta_T(t)}{\mathrm{d}t} = S(t)P_H(t) - \frac{1}{R}[\theta_T(t) - \theta_A] - \rho c_p W(t)\left[\theta_T(t) - \theta_{W,C}\right], \tag{2}$$

where C is the equivalent capacitance; $S(t)$, the ON/OFF status; defined respectively as:

$$C = V \cdot \rho \cdot c_p. \tag{3}$$

Table II
PARAMETERS FOR THE EQUIVALENT EWH MODEL.

Parameter	Value or unit
Density of water ρ	993 $^{kg}/_{m^3}$
Specific heat capacity of water c_p	4,179 $^{J}/_{kg°C}$
Room air temperature θ_A	22 °C
Temperature of cold water $\theta_{W,C}$	10 °C
Rated EWH heating rate P_H	4.5 kW
Water tank volume V	50 gallon
Equivalent resistance R	1400 $^{°C}/_{kW}$
Water temperature in the tank θ_T	°C
Hot water draw W	m^3/s

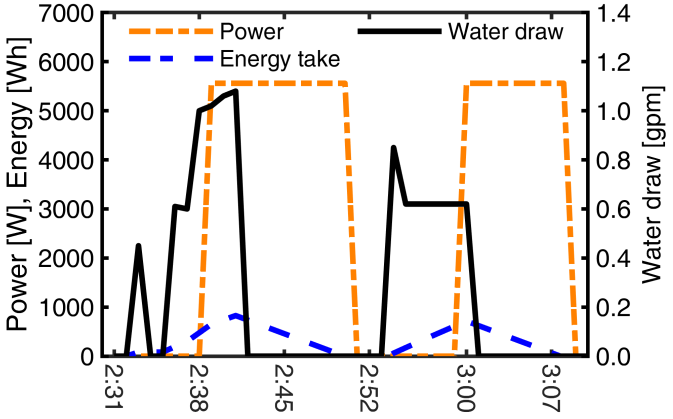

Fig. 6. Simulation results obtained based on (2). The data compares satisfactorily with the experimental results from the NREL test published in the EPRI report [12].

$$S(t) = \begin{cases} 0, & \text{if } S(t-1) = 1 \;\&\; \theta_T(t) \geq \theta_H(t) \\ 1, & \text{if } S(t-1) = 0 \;\&\; \theta_T(t) \leq \theta_L(t) \\ S(t-1), & \text{otherwise,} \end{cases} \tag{4}$$

where θ_L and θ_H are the lower and upper band of the water tank temperature. The definitions of other parameters are listed in Table. II. It is worth noting that the water temperature in the tank θ_T and the hot water draw W have only their units listed in the table.

The performance test of a CTA-2045 equipped A. O. Smith water heater was conducted by National Renewable Energy Laboratory (NREL) and reported by Electric Power Research Institute (EPRI) [12]. The case of "Normal Operation" from the report was used for the validation of the parameter values listed in Table. II, apart from the "Rated EWH heating rate P_H, which was set to 5.5kW only for this validation. The simulation results, which were plotted in the same style as the report, show satisfactory results (Fig. 6). The term "Energy take" reflects the temperature of the water tank.

When the working status and power of the EWH and the tank temperature are known, (2) can be re-written to calculate

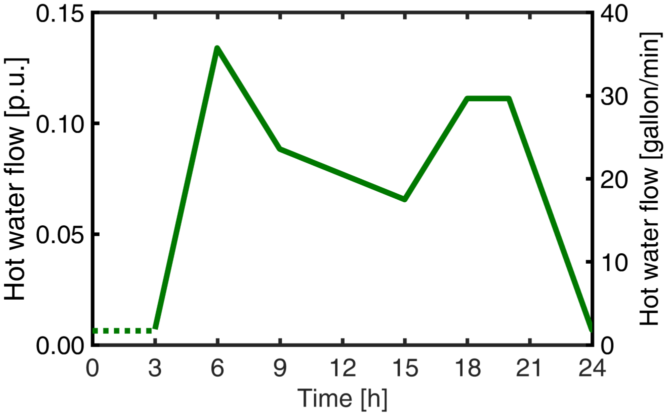

Fig. 7. The calculated total daily hot water draw for 450 EWHs. The total daily hot water usage was 27,427 gallons for 450 EWHs, an average of 61 gallons.

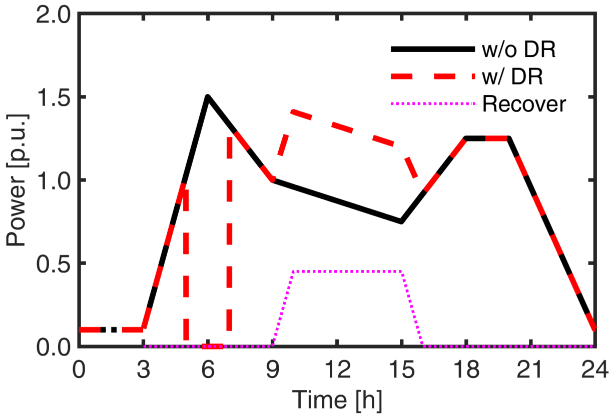

Fig. 8. Example demand response for aggregated electric water heater. This approach demonstrates how the peak demand at the early hour of the day (5:00–7:00) can be shifted to some time around midday (9:00–16:00), when solar generation is relatively high.

the hot water usage:

$$W(t) = \frac{S(t)P(t) - \frac{1}{R}[\theta_T(t) - \theta_A]}{\rho c_p\,[\theta_T(t) - \theta_{W,C}]}. \qquad (5)$$

In the study, it is assumed that the average temperature of all the water tanks is constant. When $\theta_T(t) = 125F$, $S(t) = 1$, and EWH power $P(t)$ was replaced with the value of aggregated eneric curve from Fig. 4, the aggregated hot water draw was calculated using (5) and is shown in Fig. 7. The daily hot water draw for each EWH was 61 gallons.

The per unit hot water draw was calculated based on (5), with $\theta_T(t) = 125F$, $S(t) = 1$, and the EWH power $P(t)$ replaced by the value from Fig. 4. The aggregated generic hot water draw shown in Fig. 7 stands for the representative user behavior and does not change when the DR is implemented.

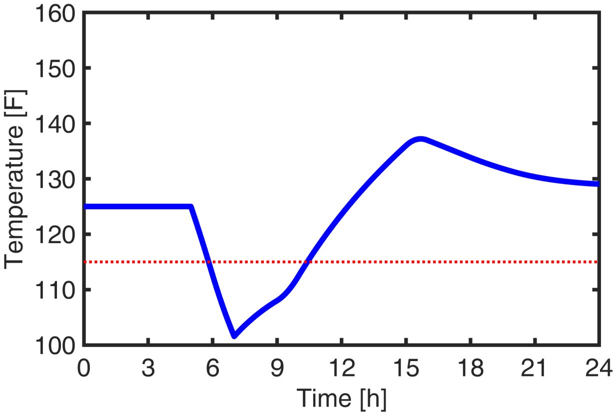

Fig. 9. The average tank temperature for the EWHs participating in demand response. The red dotted line marks the common preference of 115°F. The example shows a significant reduction in tank temperature in the early hours for the extreme condition when all the EWH were turned off. The recovery around midday means EWHs can be used as storage for surplus PV power.

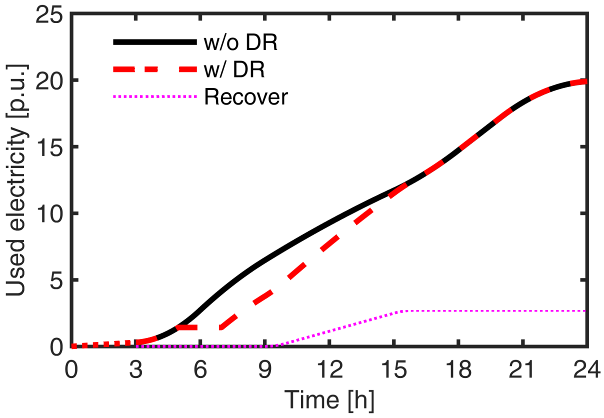

Fig. 10. Accumulated electricity usage of the EWH. from 5:00–7:00, the used electricity remained the same in the DR case. In the afternoon, the electricity usage caught up with the w/o DR case.

IV. EXAMPLE CASES OF DEMAND RESPONSE (DR)

The objective of demand response is to shed the EWH load at critical time, and recover during the midday, as follows:

$$P_D(t) = \begin{cases} 0, & \text{if } t \in T_D \\ P_O(t) + P_R(t), & \text{if } t \in T_R, \end{cases} \qquad (6)$$

where P_D is the aggregated EWH load with DR; P_R, the aggregated recover power; P_O, the original aggregated EWH load without DR; T_D, the set of time when DR is required; T_R, the set of time when recovery is required. It is worth noting that not all EHWs will turn on during the recovery. Therefore, it is assumed that $P_O(t) + P_R(t) < P \cdot N$.

An example demand response with $T_D = [5:00, 7:00]$ and $T_R = [9:00, 16:00]$ is shown in Fig. 8. The fixed hot water flow from Fig. 7 was used for the DR study. When the EWH's load was shed in the morning, the water temperature in the tank dropped (Fig. 9). The example case in Fig. 9 shows the maximum load reduction case scenario, which will result in the temperature being too low. In which case some of the EWH will not meet the customer comfort. A practical home energy management would put the customer comfort as priority and avoid the tank temperature being too low. The tank temperature increased in the midday as the EWH started to recover from 9:00. In this example, it is assumed that the total electricity usage for the w/ and w/o DR cases are equal (Fig. 10).

V. CONCLUSION

The proposed aggregated generic curves for the residential EWH load and the hot water usage in this paper are the first of its kind to the best of the authors‘ knowledge. The aggregated generic curves were obtained based on two years of experimental data from approximately 800 users collected by the industrial collaborator, A.O. Smith. While monitoring the temperature in the tank, this load curve may be employed by EWHs for multiple applications including establishing peak demand, power variation, daily energy profile and unit utilization factor.

The detailed technical benefits of the example aggregated generic curve were demonstrated through a demand response program, in which the operation of the EWH was regulated to reduce the peak power and store surplus solar generation. In this approach, the residential setup was considered as a virtual power plant with the EWH regarded as a "uni-directional" energy storage operating within customer predefined water tank temperature limits.

ACKNOWLEDGMENT

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