An Algorithm for Intelligent Home Energy Management and Demand Response Analysis

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***Abstract*—A home energy management (HEM) system is an integral part of a smart grid that can potentially enable demand response applications for residential customers. This paper presents an intelligent HEM algorithm for managing high power consumption household appliances with simulation for demand response (DR) analysis. The proposed algorithm manages household loads according to their preset priority and guarantees the total household power consumption below certain levels. A simulation tool is developed to showcase the applicability of the proposed algorithm in performing DR at an appliance level. This paper demonstrates that the tool can be used to analyze DR potentials for residential customers. Given the lack of understanding about DR potentials in this market, this work serves as an essential stepping-stone toward providing an insight into how much DR can be performed for residential customers.**

***Index Terms*—Customer choice, demand response (DR), home energy management (HEM), load priority, smart appliance.**

I. Introduction

OVER THE PAST several decades, electric power systems have encountered more frequent stress conditions due to ever-increasing electricity demand [1]. Transmission line outages have been a common cause of system stress conditions, which are likely to occur during critical peak hours. Such events will cause a supply-limit situation where cascading failures and large-area blackouts are possible. Demand response (DR) has been envisioned to deal with such unexpected supply-limit events by selectively curtailing system loads, whereby regaining balance between electricity supply and demand [2]. DR also plays an important role in load shifting that can help increase reliability and efficiency in operation.

In the United States, many DR programs are widely implemented by commercial and industrial customers. These are mainly interruptible load, direct load control, real-time pricing and time-of-use programs [3]. On the other hand, very few DR programs are in use today for residential customers. Majority of them are direct load control programs for water heaters. Some of them are time-of-use, critical peak pricing and real-time pricing programs. This paper focuses on DR for residential customers as opposed to commercial ones because DR in commercial markets are mature, and are already being served by third-party providers. In addition, with an introduction of electric vehicles in residential markets, DR can be performed within a home to avoid any potential distribution transformer overloading problems [4].

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In the context of a residential home, three types of DR automation levels exist: a) manual DR; b) semi-automated DR; and c) fully automated DR [5]. The fully automated DR is the most popular automation type that can be achieved by a home energy management (HEM) System. An HEM system is responsible for monitoring and managing the operation of in-home appliances, and providing load shifting and shedding according to a specified set of requirements. Different algorithms and models [6]–[10] can be used, depending on load types and requirements of DR programs available in different regions. Various HEM hardware applications are proposed in [11], [12]. Several papers in the literature focus on controlling low power consumption appliances, such as refrigerators, coffee makers, lighting, and other plug loads. These appliances are not suitable for demand response as they have no significant impact on the overall household power consumption. Issues of optimal appliance scheduling to minimize household energy consumption are also the topic of previous work [13], [14]. However, such scheduling will incur a wait time for operation of each appliance.

This paper presents the development of an HEM algorithm for managing household power-intensive appliances. These are: space cooling units, water heaters, clothes dryers and electric vehicles (EV). They range in size from 2 kW for a space cooling unit to 3.3–9.6 kW for an EV. The highlight of the proposed HEM algorithm is its ability to control selected appliances and keep the total household power consumption below a certain limit, while considering customer preferences and allowing the customer more flexibility to operate their appliances. In this paper, a simulation tool is also developed and used to simulate DR events to showcase the applicability of the proposed HEM algorithm. Overall, research findings are expected to provide an insight into the level of load curtailments possible for residential customers, which can be interpreted as DR potentials in residential markets with automated DR.

II. The Proposed HEM Algorithm

An HEM system plays a crucial role in achieving automated DR within a house, as most residential customers do not have time, nor proactive enough to perform DR manually. An effective HEM system should provide load shifting and shedding ability when needed with the least impact on customer lifestyle during a DR event.

A. A Demand Response (DR) Event

A DR event is defined as a period during which the customer demand needs to be curtailed to alleviate a system stress condition. Customers who participate in a DR program can be informed of a DR event by an external signal from a utility via their smart meters. For our study, we assume that the external signal received by the HEM system is in a form of a demand curtailment request (kW) and duration (hours). Fig. 1 illustrates the proposed HEM framework.

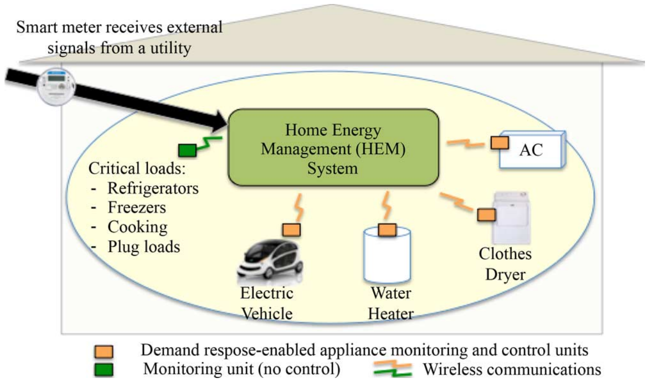

Fig. 1. The HEM architecture.

TABLE I
EXAMPLE OF LOAD PRIORITY AND PREFERENCE SETTINGS IN A HOUSE

Appliance	Load Priority	Homeowner Preference
Water Heater	1	Water Temperature: 110-120°*F*
Space Cooling Unit	2	Room Temperature: 76°*F* (±2°*F*)
Clothes Dryer	3	Finish the job by midnight Maximum OFF time: 30 mins Minimum ON time: 30 mins
EV (Level 2 charging w/ 240V single phase)	4	Fully charged by 8 AM Minimum charge time: 30 mins

As the HEM receives the external signal, which includes demand curtailment request and duration, its algorithm is designed to guarantee the total household power consumption below the specified demand limit level (kW) during the specified duration (hours). This demand limit level can vary every 15 min or every hour depending on system requirements. High power consumption appliances to be controlled are space cooling units, clothes dryers, water heaters, and electric vehicles. Critical loads are to be served at all time. The proposed HEM algorithm allows the homeowner to operate their appliances when needed as long as the total household consumption remains below the specified limit during a DR event. At the same time, it takes into account load priority and customer comfort preference.

B. Load Priority and Customer Comfort Preference

The first step before the proposed HEM algorithm can operate is for a homeowner to set their load priority and comfort preference. An example of load priority and preference settings is shown in Table I.

As shown for this house, the water heater is of the highest priority. This is followed by the space cooling unit, the clothes dryer, and the electric vehicle. Comfort level settings can be specified for each appliance. For the water heater, the hot water temperature preference can be set, e.g., between 110–120 °F. For the space cooling unit, the room temperature preference can be specified, e.g., between 74–78 °F. For the clothes dryer, a homeowner can specify its complete time, maximum heating coils OFF time and minimum heating coils ON time. For the EV, a homeowner can specify the EV fully charge time, e.g., by 8 A.M.

C. The HEM Control Strategy by Appliance Type

The specified demand limit is the important factor to determine the status of appliances in the algorithm. Any violation in the demand limit will result in turning OFF selected appliances according to their priority. Customer preference settings are allowed to be violated from the least important loads to the most important ones to guarantee the requested demand limit. The operation of each appliance and its associated HEM control algorithm are summarized below.

1) Electric Water Heater (WH) Operation: A hot water temperature set point is specified with a temperature tolerance. When the hot water temperature falls below the minimum required temperature ($T_{WH,s} - \Delta T_{WH}$), WH heating coils are ON. After the hot water temperature reaches the set point, WH heating coils are OFF. If the hot water temperature is within the preset comfort range ($T_{WH,s} - \Delta T_{WH} \leq T_{WH.n} \leq T_{WH.s}$), the heating coils will keep their previous status. See (1).

$$S_{WH,n} = \begin{cases} 0, & T_{WH,n} > T_{WH,s} \\ 1, & T_{WH,n} < T_{WH,s} - \Delta T_{WH} \\ S_{WH,n-1}, & T_{WH,s} - \Delta T_{WH} \leq T_{WH,n} \\ & \quad \leq T_{WH,s} \end{cases} \tag{1}$$

where:

$T_{WH,s}$	hot water temperature set point (°F);
ΔT_{WH}	temperature tolerance (°F);
$T_{WH,n}$	hot water temperature in time interval n(°F);
$S_{WH,n}$	WH status in time interval $n(0 = \text{OFF}; 1 = \text{ON})$.

HEM Control Strategy for WH: If the demand limit is imposed on this house and the water heater is ON, the HEM is allowed to turn OFF the water heater as needed according to the preset load priority. If the water heater has the highest priority, it will be the last one to be turned OFF.

2) Space Cooling Unit (AC) Operation: A room temperature set point is specified with a dead band. When the room temperature exceeds the maximum allowable temperature ($T_{AC,s} + \Delta T_{AC}$), the space cooling unit is ON and the room temperature will gradually decrease. When the room temperature is below $T_{AC,s} - \Delta T_{AC}$, the space cooling unit is OFF. If the room temperature is within the preset comfort range ($T_{AC,s} - \Delta T_{AC} \leq T_{AC,n} \leq T_{AC,s} + \Delta T_{AC}$), the space cooling unit will keep its previous status. See (2).

$$S_{AC,n} = \begin{cases} 0, & T_{AC,n} < T_{AC,s} - \Delta T_{AC} \\ 1, & T_{AC,n} > T_{AC,s} + \Delta T_{AC} \\ S_{AC,n-1} & T_{AC,s} - \Delta T_{AC} \leq T_{AC,n} \\ & \quad \leq T_{AC,s} + \Delta T_{AC} \end{cases} \tag{2}$$

where:

$T_{AC,s}$	room temperature set point (°F);
ΔT_{AC}	deadband (°F);
$T_{AC,n}$	room temperature in time interval n(°F);
$S_{AC,n}$	AC status in time interval $n(0 = \text{OFF}; 1 = \text{ON})$.

HEM Control Strategy for AC: If the demand limit is imposed on this house and the space cooling unit is ON, the HEM is allowed to turn OFF the space cooling unit as needed according to the preset load priority. If the comfort setting is violated (i.e., room temperature exceeds the preset level), the space cooling unit will be forced ON to keep the room temperature within the comfort range, given that the total household consumption does not exceed the limit.

3) Clothes Dryer (CD) Operation: A clothes dryer consists of a rotating tumbler and heating coils. The power consumption of the motor part is usually in the range of several hundred watts (e.g., 300 watts), while that of the heating coils can be several kilowatts (e.g., 4 kW). The clothes dryer will be turned ON as long as the accumulated ON time is less than the required ON time to complete a clothes drying job. When the accumulated ON time reaches the required ON time, the clothes dryer will be turned OFF. See (3).

$$S_{CD,n} = \begin{cases} 0, & CT_n \geq CT_{\max} \\ 1, & CT_n < CT_{\max} \end{cases} \tag{3}$$

where:

CT_n	clothes dryer's accumulated ON time (minutes);
$CT_{\max}$	clothes dryer's required ON time (minutes);
$S_{CD,n}$	clothes dryer status $(0 = \mathrm{OFF}; 1 = \mathrm{ON})$.

HEM Control Strategy for CD: Our HEM controls the clothes dryer by turning OFF its heating coils, while leaving the motor part running. This is to ensure that the clothes dryer can resume its operation without homeowner intervention. If the demand limit is imposed on this house and the clothes dryer is ON, the HEM is allowed to control the clothes dryer as needed according to the preset load priority. The clothes dryer ON time limit, e.g., 30 min, can be specified to ensure that the clothes dryer operates for at least a certain duration before it can be controlled OFF. The heating coil OFF time limit can also be specified to prevent excessive heat loss during the clothes dryer operation. However, these comfort level settings are allowed to be violated if any loads of higher priority need to operate to maintain the preset comfort ranges.

4) Electric Vehicle (EV) Operation: Once plugged in, an EV will be charged until its battery's state of charge (SOC_n) reaches the maximum state of charge $(SOC_{\max})$. See (4).

$$S_{EV,n} = \begin{cases} 0, & SOC_n \geq SOC_{\max} \\ 1, & SOC_n < SOC_{\max} \end{cases} \tag{4}$$

where:

SOC_n	battery state of charge in time interval n (%);
$SOC_{\max}$	maximum battery state of charge (%);
$S_{EV,n}$	EV status in time interval $n (0 = \mathrm{OFF}; 1 = \mathrm{ON})$.

HEM Control Algorithm for EV: In our algorithm, the EV is allowed to be partially charged as soon as it is plugged in regardless of its priority without violating the demand limit. This will allow the homeowner to have the privilege to use the car earlier if needed. In certain circumstances when other appliances of higher priority need to operate, the EV charging may be placed on hold. However, if the HEM system foresees that the EV charging cannot be completed by the time specified by the homeowner, the EV will be allowed to start charging earlier than scheduled by changing its priority.

D. The HEM Load Management Algorithm

In each time interval, the proposed HEM algorithm starts by gathering information, which include the status and power consumption of all appliances, load priority and customer preference settings, water and room temperatures, as well as the demand limit and its associated duration. Then, the HEM algorithm checks for comfort level violations, which include: a) water temperatures for the WH; b) room temperatures for the space cooling unit; c) the required ON time, the maximum OFF time and the minimum ON time for the clothes dryer; and d) the fully charge time and the minimum charge time requested for the EV. See Fig. 2. If there is a comfort level violation, the HEM decides on the status of each appliance based on the requested demand limit level. See Fig. 3.

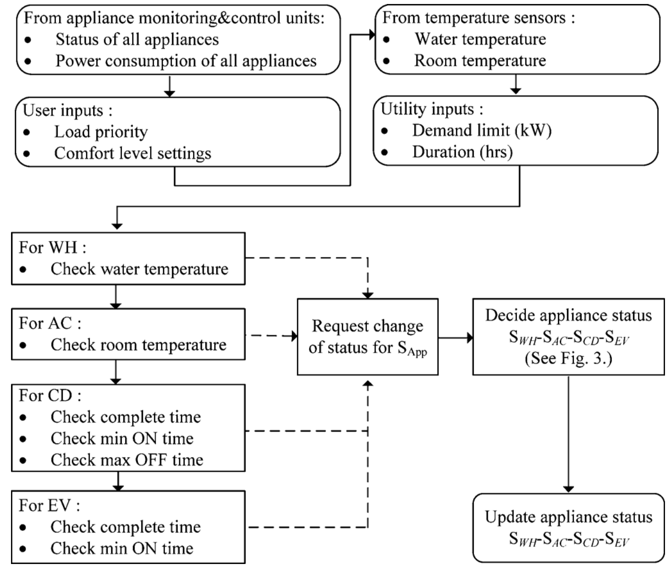

Fig. 2. HEM algorithm flow chart (part I)–overall algorithm. Note that S_{APP} is the status of appliance APP that has the comfort level violation.

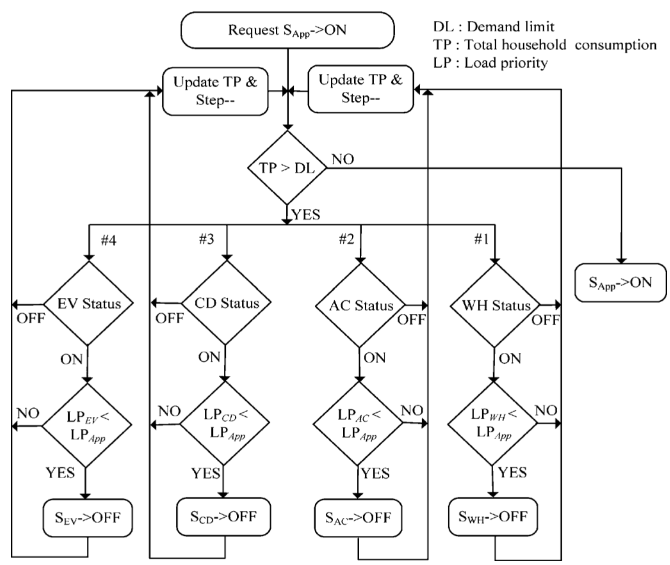

Fig. 3. HEM algorithm flow chart (part II)—HEM decision-making process, assuming the load priority is as follows: $\mathrm{WH} > \mathrm{AC} > \mathrm{CD} > \mathrm{EV}$.

After the decision is made, the HEM sends control signals to change the selected appliance status. The total household power consumption is compared with the requested demand limit. If the household consumption is lower than the demand limit, no action is taken if there is no comfort level violation. However, with the comfort level violation of appliance APP (S_{APP}), the HEM will force the selected appliance ON to minimize the comfort level violation. If the household consumption is greater than the demand limit and there is no comfort level violation, the HEM will turn OFF the lowest priority loads, in this case starting

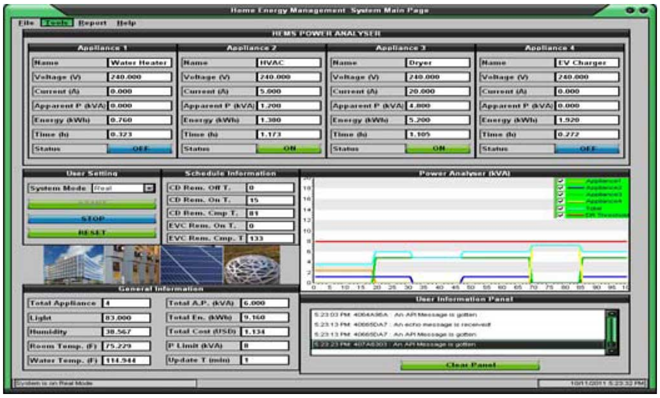

Fig. 4. The developed HEM dashboard.

with the EV, the clothes dryer and the space cooling unit, to keep the total power consumption below the demand limit. If the household consumption is greater than the demand limit and there is a comfort level violation of the appliance app, then the HEM will compare the priority of all ON appliances with the priority of this appliance, starting from the lowest priority loads to the highest one. If the priority of the appliance APP is greater than any other appliances that are ON, the HEM will shut OFF the lower priority loads until the appliance APP can be turned ON and the total power consumption is below the demand limit.

III. The HEM Software Implementation

A simulation tool is developed in C++ that consists of the proposed HEM algorithm (discussed in the previous section), the HEM graphic user interface (GUI) and DR-enabled load models (discussed below).

A. HEM Graphical User Interface (GUI)

The HEM graphical user interface (GUI) is developed as a part of the proposed HEM software as shown in Fig. 4.

It serves as a dashboard for customers to monitor appliance status, appliance power consumption, total household power consumption, the requested demand limit, room temperatures, hot water temperatures and other comfort preference status. Customers can use the dashboard to change their load priority and preference settings. All parameters shown on the dashboard is updated at 1-min intervals.

B. DR-Enabled Load Models

DR-enabled load models of a WH, a space cooling, a clothes dryer, and an EV are implemented according to [15]. This is to allow us to analyze the impact of the proposed algorithm on overall household power consumption and appliance management. Load model highlights are summarized below.

1) Electric Water Heater (WH) Load Model: The power consumption of the WH is at its rated power when it is ON, and is zero when it is OFF. See (5).

$$p_{WH,n} = P_{WH} \cdot S'_{WH,n} \tag{5}$$

where:

$p_{WH,n}$	WH power consumption in time interval n (kW);
P_{WH}	WH rated power (kW);
$S'_{WH,n}$	HEM control signal for WH, $0 = \mathrm{OFF}, 1 = \mathrm{ON}$.

According to [15], time series hot water temperatures are determined a function of the amount of hot water draw, inlet temperatures, WH power consumption, tank size, tank heat resistance and the hot water temperature set point.

2) Space Cooling (AC) Load Model: For the space cooling load model, the power consumption of the space cooling is at its rated power when it is ON, and is zero when it is OFF. See (6).

$$p_{AC,n} = P_{AC} \cdot S'_{AC,n} \tag{6}$$

where:

$p_{AC,n}$	AC power consumption in time interval n (kW);
P_{AC}	AC rated power (kW);
$S'_{AC,n}$	HEM control signal for AC, $0 = \mathrm{OFF}, 1 = \mathrm{ON}$.

According to [15], room temperatures in each time interval is calculated a function of house size, house heat resistance, the number of people in the house, the unit size, ambient temperatures and the room temperature set point.

3) Clothes Dryer (CD) Load Model: The power consumption of a typical clothes dryer includes the motor part and the heating coils. Using (7), the rated power of the clothes dryer is calculated for each time interval n.

$$p_{CD,n} = P_h \cdot S'_{CD,n} + P_m \cdot T_{CD,n} \tag{7}$$

where:

$p_{CD,n}$	CD power consumption in time interval n (kW);
P_h	CD heating rated power (kW);
P_m	CD motor rated power (kW);
$S'_{CD,n}$	HEM control signal for CD heating coils in time interval n, $0 = \mathrm{OFF}, 1 = \mathrm{ON}$;
$T_{CD,n}$	operation status of the clothes dryer in time interval n, $T_{CD,n} = 0$ before CD operates and after it finishes its job, $T_{CD,n} = 1$ during CD operation.

4) Electric Vehicle (EV) Load Model: The load model of EV is designed according to basic battery charging data. Using (8), the rated charging power of the EV is calculated for each time interval n. The battery state of charge is calculated based on the relationship presented in [15]. Note that this study considers a fixed EV charging rate—which is the charging profile in the charging station on the market today—and the HEM controls EV charging by switching ON/OFF the charger.

$$p_{EV,n} = P_{EV} \cdot S'_{EV,n} \tag{8}$$

where:

$p_{EV,n}$	EV charge power in time interval n (kW);
P_{EV}	EV rated power (kW);
$S'_{EV,n}$	HEM control signal for EV, $0 = \mathrm{OFF}, 1 = \mathrm{ON}$.

IV. Demand Response Case Studies

This section demonstrates the applicability of the developed simulation tool in managing high power consumption appliances and analyzing how much load curtailments are possible for residential customers. A hottest summer day in August is

TABLE II
PARAMETERS OF THE HOUSE UNDER STUDY

Parameter	Value	Unit
House size	2000+500 basement	sq ft
A_{floor}, $A_{ceiling}$, A_{wall}, A_{window}	2000, 2000, 2600, 520	sq ft
$R_{ceiling}$, R_{wall}, R_{window}	49, 13, 2	ft^2*°F/(btu/h)
Number of people	3	people
Capacity of the AC unit	34,000	BTU
AC temperature set point	76°F ± 2°F	°F
AC power consumption	2.352	kW
Ambient temperature	A hottest day in August [17]	°F
Water heater (WH) tank size	80	gallons
WH tank R-value	18	ft^2*°F/(btu/h)
WH temperature set point	110°F -120°F	°F
WH power consumption	4.5	kW
Water consumption	Real water consumption data from IEA [18]	gallons/min
Clothes dryer (CD) power consumption	4.0 kW (0.3kW motor, 3.7kW heating coil)	kW
CD start time/operation duration	6:00 pm, need 90 minutes to complete its operation	-
Electric vehicle (EV) power consumption	3.3kW for a recommended charge rate of Volt [19]	kW
EV start time/charge duration	5:30pm, need 145 minutes to fully charge the EV	-
Load priority	WH > AC > CD > EV	-
Critical loads	Data from RELOAD [20], vary every hour between 1.1kW and 1.7kW during 5-10pm	

used as a basis for the presented case studies as a DR event is most likely to occur during such operating conditions.

A. House and Appliance Parameter Assumptions

A 2500-square feet home is taken as a case study. This is an average single-family home size in the United States [16]. Table II summarizes parameters used to model this house, which include house structure and appliance characteristics. For this house, the load priority is set as follows: a water heater has higher priority than a space cooling unit; a space cooling unit has higher priority than a clothes dryer; and a clothes dryer has higher priority than an electric vehicle. For the comfort level setting, the hot water temperature should be between $110-120\ ^{\circ}\mathrm{F}$; the room temperature should be between $74-78\ ^{\circ}\mathrm{F}$; the clothes dryer should finish its job by midnight; and the EV should finish charging by 8 A.M.

B. Simulation Results

Fig. 5 illustrates the performance of the proposed HEM algorithm in managing high power consumption appliances and keeping the total household consumption below selected demand limit levels (i.e., 8, 6, and 4 kW) between 5–10 P.M. Fig. 5 displays household consumption between 5 P.M.–1 A.M. as no demand response function occurs outside this time frame.

In the base case scenario with no demand limit as shown in Fig. 5(a), there are some hot water drawn events around 7 P.M. and 10 P.M.—notice the tank water temperature drops. The large water draw event at around 10 P.M. makes the hot water temperature drops quickly below the threshold. The water heater then operates to bring the water temperature back within the preset comfort range. Note that the water temperature comfort range $(110-120\ ^{\circ}\mathrm{F})$ can be naturally violated during a large water draw event. The space cooling unit cycles ON and OFF to maintain the room temperature within the preset comfort level, i.e., $74-78\ ^{\circ}\mathrm{F}$. As soon as the homeowner arrives home, he plugs in his Chevy Volt at 5:30 P.M., and operates the clothes dryer at 6 P.M. As shown, the total power consumption of this house increases to about 11 kW between 6–7:30 P.M. Note that this level of power consumption may introduce the risk of distribution transformer overloading [21].

In this paper, it is assumed that during a residential customers' evening peak period (between 5 P.M. and 10 P.M.) a demand limit is imposed on this house. Note that this demand limit level can vary every 15 min or every hour depending on system requirements, but for the purpose of this study, a demand limit is assumed to be fixed. Also, 10 P.M. is assumed to be the end of the DR event. This is to follow the end of the summer time-of-use period specified by an electric utility in Virginia.

Figs. 5(b)–5(d) depict the simulation results when household loads are managed below 8 kW, 6 kW, and 4 kW demand limits, respectively, between 5–10 P.M.

With the 8 kW demand limit as shown in Fig. 5(b), the load shifting period starts from 6 P.M. to 7:30 P.M., and the load compensation period ends at around 9:30 P.M. During the 8 kW-limit DR event, the space cooling unit (2.3 kW) can operate together with either the clothes dryer (4 kW) or the EV (3.3 kW) and critical loads. Note that the critical load power consumption (not shown in Fig. 5) varies every hour between 1.1 kW and 1.7 kW between 5 P.M. and 10 P.M. As the clothes dryer has higher priority than the EV, the EV charging is on hold as soon as the clothes dryer starts. The clothes dryer then cycles with the EV every 30 min until its job is complete. This is due to our preference setting and the way our HEM algorithm is designed to allow the EV to be partially charged as soon as it is plugged in. Also notice that when the clothes dryer gets controlled, the motor part (0.3 kW) keeps on running, while the heating coils (3.7 kW) are shut OFF.

With the 6 kW limit as shown in Fig. 5(c), the load shifting period also starts from 6 P.M. to 7:30 P.M. Since the larger amount of loads need to be shifted, the load compensation period ends just before midnight. As the clothes dryer has higher priority than the EV, charging EV is deferred as soon as the clothes dryer starts; and the clothes dryer cycles with the space cooling unit because the 6 kW limit will be violated if both the space cooling unit (2.3 kW) and the clothes dryer (4 kW) are running at the same time with critical loads. EV is deferred until after the clothes dryer finishes its job.

At the 4 kW demand limit as shown in Fig. 5(d), we can notice the comfort level violation—room temperature goes up to $95\ ^{\circ}\mathrm{F}$ between 6:30–7 P.M. This is because the HEM tries to meet the requested demand limit by deferring loads according to their priority, i.e., deferring the EV, then the clothes dryer and lastly the space cooling unit. During 6–7:30 P.M., the space cooling unit should have been operated to maintain the preset room temperature. However, as the critical load consumption is high during that period (i.e., 1.5–1.7 kW), the space cooling unit has to be shut OFF. In this case, critical loads (1.5–1.7 kW) are operated together with the motor part of the clothes dryer (0.3 kW). Therefore, there is no room for AC operation (2.3 kW) while maintaining the total household load below 4 kW limit. Also the result indicates that this demand limit requirement is so low that it creates a much higher peak during an off-peak period after the DR event ends.

C. Result Discussions and Observations

Two interesting observations can be made:

1) The proposed HEM algorithm can effectively keep the total household power consumption below the demand limit requirement by managing selected power-intensive loads according to their priority, while trying to satisfy

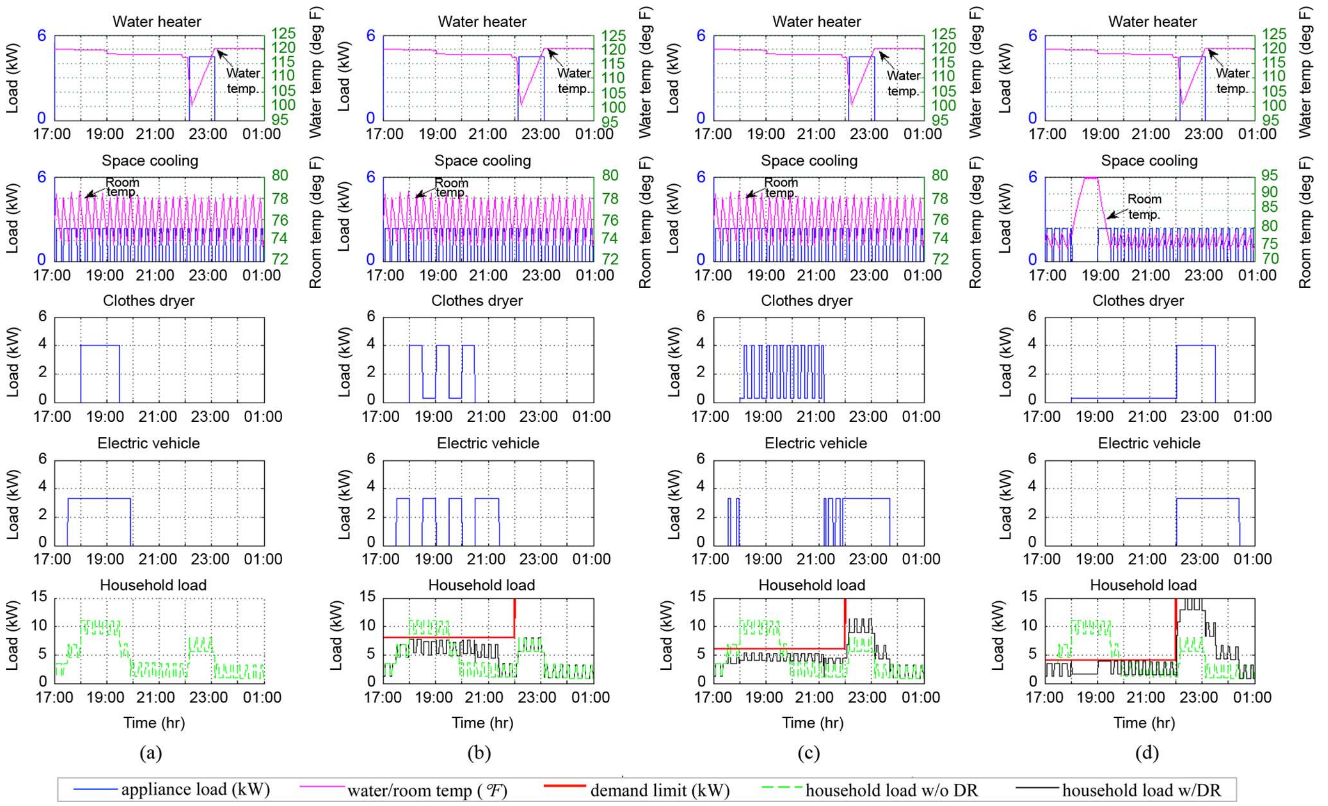

Fig. 5. Demand response simulation for a 2500 sq ft home with all four appliances (WH, AC, CD, EV) and a large hot water draw event at around 10 P.M. (a) No demand limit. (b) 8 kW limit from 5 pP.M.–10 P.M. (c) 6 kW limit from 5 P.M.–10 P.M. (d) 4 kW limit from 5 P.M.–10 P.M.

the preset comfort level settings. However, if the demand limit is lower than a certain value, some customer comfort must be sacrificed, i.e., room temperature violation; and

2) A low demand limit level may result in an adverse effect by creating a new peak during an off-peak period after a DR event ends. This may damage a distribution transformer serving this local area, and should be avoided at all costs.

Two observations indicated above imply that, in any DR event, the demand limit level to be assigned to each house should be carefully chosen; and it should be above a certain value. This is in order to prevent either: a) a comfort level violation; or b) a high load compensation after a DR period ends. Hence, it is worthwhile to investigate the lowest possible demand limit level that can be assigned to a house before any violation can occur. This is discussed in the next subsection.

D. Constraints on Demand Limits

The lowest possible demand limit for a particular house will vary according to:

— rated power (kW) and type of appliances in a house;
— appliance usage patterns, including water draw profiles, EV plug-in time, and clothes dryer start time;
— comfort level settings, i.e., room temperature set point, water temperature set point, clothes dryer complete time, and EV charge complete time;
— house parameters and ambient temperatures;
— duration and start time of a DR event.

As the water temperature comfort range can be naturally violated during a large water draw event, we are only interested to find the lowest possible demand limit before either a room temperature violation or a high load compensation can occur in

TABLE III
LOWEST POSSIBLE DEMAND LIMITS BEFORE ANY VIOLATION OCCURS FOR HOUSES W/ DIFFERENT APPLIANCE OWNERSHIP AND USAGE PATTERNS

Simulation scenarios for the 2500 sqft home	Appliances				Lowest possible demand limit before any violation can occur	Type of Violation	
	Space cooling	Clothes dryer	Water heater	EV		T_{room} violation	Compensation
Case 1: 10pm water draw, w/ EV	√	√	√	√	7.0kW	-	⊗
Case 2: 10pm water draw, w/o EV	√	√	√	-	5.4kW	-	⊗
Case 3: 7pm water draw, w/ EV	√	√	√	√	8.6kW	⊗	-
Case 4: 7pm water draw, w/o EV	√	√	√	-	8.6kW	⊗	-
Case 5: no WH w/EV	√	√	-	√	4.7kW	-	⊗
Case 6: no WH w/o EV	√	√	-	-	4.0kW	⊗	-

different scenarios. We are looking at a typical 2500 sq ft American house that has selected types of high power consumption appliances. See Table III. Some houses have all four appliances (WH, space cooling unit, clothes dryer, and EV)—cases 1 and 3; some have no EV—cases 2, 4, and 6; and the others have gas water heater, i.e., no electric water heater—cases 5 and 6.

To simulate the worst case scenarios, it is assumed that the usage of these appliances occurs during the peak evening hours, i.e., EV plug-in time at 5:30 P.M. and clothes dryer start time at 6 P.M. We consider two hot water draw profiles: one has a large hot water draw event at around 10 P.M.—cases 1 and 2; the other has a large water draw event at around 7 P.M.—cases 3 and 4. It is assumed that the DR event occurs between 5 P.M.–10 P.M. Note that cases 1 and 2 are to showcase the (worst-case) compensation (load rebound) effect when all deferred loads operate together with the water heater after the DR event ends; and cases

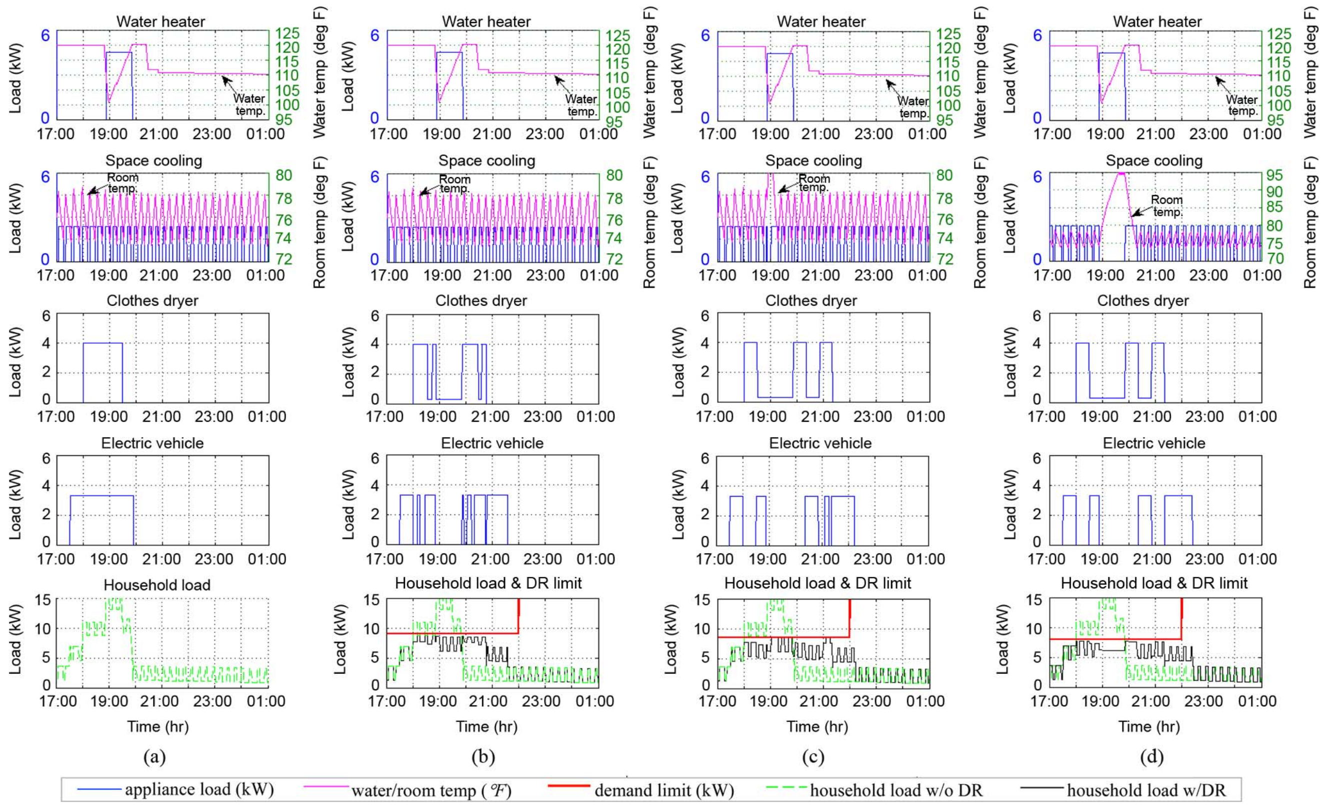

Fig. 6. Demand response simulation for a 2500 sq ft home with all four appliances (WH, AC, CD, EV) and a large hot water draw event at around 7 P.M. (a) No demand limit. (b) 9 kW limit from 5 P.M.–10 P.M. (c) 8.5 kW limit from 5 P.M.–10 P.M. (d) 8 kW limit from 5 P.M.–10 P.M.

3 and 4 are to showcase the (worst case) operation of all appliances during a DR event. All simulation scenarios use a typical summer room temperature set point of $76\ ^\circ\mathrm{F} \pm 2\ ^\circ\mathrm{F}$, and consider the hottest summer day in August. Table III summarizes the lowest possible demand limit levels before either a room temperature violation or high load compensation can occur in all simulation scenarios mentioned above.

The simulation results for case 1 are shown in Fig. 5. In this case, the lowest possible demand limit before the violation is at around 7 kW and the violation is high load compensation after the DR event ends. The 7 kW limit can be derived from the power consumption of the space cooling unit (2.3 kW) that should be able to run at the same time as EV (3.3 kW) and critical loads. At the 7 kW limit, the clothes dryer can cycle with the space cooling unit, and therefore, neither EV nor clothes dryer will be deferred. See Fig. 5(b) when the demand limit is at 8 kW—no violation, and Fig. 5(c) and 5(d) when the demand limits go below 7 kW—high load compensation after the DR event. Case 1 at the 7 kW limit has no temperature violation problem because the water heater does not operate during the DR event between 5–10 P.M.

The DR simulation for case 3 is illustrated in Fig. 6 with a large water draw event at 7 P.M. As the water heater operates during the DR event, the demand limit must be higher than that in case 1 to avoid any comfort level violation. In this case, the lowest possible demand limit has to be at least 8.6 kW, i.e., the power consumption of WH (4.5 kW), space cooling unit (2.3 kW), motor load of the clothes dryer (0.3 kW) and critical loads, to avoid the room temperature violation. At this limit, the EV and the clothes dryer are already deferred, and the next load to be shed is space cooling if the demand limit goes lower than 8.6 kW. Fig. 6(b) illustrates that for a 9 kW demand limit there is no comfort level violation. Fig. 6(c)–6(d) indicate that the lower the demand limit is below this threshold, i.e., 8.6 kW, the higher the risk of comfort level violation is present.

In case 4, it is interesting to see that the same house without EV still has the lowest possible demand limit before the room temperature violation at 8.6 kW. This is because the high power consumption of the water heater is a major factor contributing to the room temperature violation. As WH operates at 7 P.M., the space cooling unit's operation has to be postponed if the demand limit is lower than 8.6 kW. Therefore, during this period, the room temperature will exceed the maximum acceptable temperature.

In case 2 for the same house without EV but has high water usage after the DR event ends, the lowest possible demand limit is 5.4 kW and the violation is high load compensation after the DR event. The 5.4 kW limit can be derived from the power consumption of the clothes dryer (4.0 kW) that should be able to run at the same time as critical loads (and cycling with the space cooling unit) to avoid deferring the clothes drying load. The clothes dryer operation has to be deferred to after 10 P.M. At that time, it will run together with the water heater, the space cooling unit and critical loads, which will result in the total load after 10 P.M. of about 12 kW ($\mathrm{WH}\ 4.5\ \mathrm{kW} + \mathrm{AC}\ 2.3\ \mathrm{kW} + \mathrm{CD}\ 4\ \mathrm{kW} + \mathrm{critical}$ loads).

For the houses with no electric water heater, the results indicate that they have lower demand limit levels before violating either the comfort level or creating high off-peak demand after the DR event. See cases 5 and 6 in Table III.

E. Implications on DR Potential Analysis

By comparing cases 1 and 2 with cases 3 and 4—it is the same house but the water heater operates at different times, one can conclude that the comfort level violation can be reached sooner than the high load compensation violation (when we lower the demand limit requested).

By comparing cases 3 and 4—when the water heater operates together with all other appliances at around 7 P.M., it is observed that regardless of the presence of EV, the demand limit to avoid the comfort level violation is pretty high, i.e., 8.6 kW. This implies low DR potentials if customer comfort levels are to be satisfied. However, by sacrificing some comfort levels, DR potentials can increase. That is, it will reach the next constraint, which is the high load compensation violation that should be avoided at all costs.

By comparing cases 1 and 2—when the water heater operates after the DR event at around 10 P.M., it can be concluded that without EV, DR potentials increase and can further increase for the house without an electric water heater (see cases 5 and 6).

V. Conclusions

This paper presents an intelligent home energy management (HEM) algorithm for demand response applications. Simulation results show that the proposed HEM algorithm can proactively and effectively control and manage the appliance operation to keep the total household consumption below a specified demand limit. The proposed HEM algorithm takes into account both load priority and customer comfort level settings.

Simulation results indicate that at a low demand limit level, although the HEM is able to keep the total household demand below the limit, customers may need to sacrifice their comfort level to some extent (i.e., room temperature exceeds the preference setting). Also, it is possible that a DR event could create a high off-peak demand due to load compensation. This implies that there is a limit on how much DR can be performed. This paper analyzes this limit and demonstrates that DR potential is a function of customer comfort preference and the demand limit level that does not cause high load compensation after a DR event. It is expected that the results of work can benefit electric distribution utilities and DR aggregators in providing an insight into the limits and potentials of DR available in residential markets.

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