Load Profiles of Selected Major Household Appliances and Their Demand Response Opportunities

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***Abstract*—Electrical power consumption data and load profiles of major household appliances are crucial elements for demand response studies. This paper discusses load profiles of selected major household appliances in the U.S., including two clothes washers, two clothes dryers, two air conditioners, an electric water heater, an electric oven, a dishwasher, and two refrigerators. Their electrical power consumption data measured in one-second intervals, together with one-minute data (averaged over 60 one-second readings), are provided in an online data repository (URL: www.ari.vt.edu/research-data/). The data were gathered from two homes in Virginia and Maryland during July–October 2012. In this paper, demand response opportunities provided by these appliances are also discussed.**

***Index Terms*—Appliance power consumption data, demand response, load profiles, major household appliances.**

I. Introduction

DESPITE THE fact that large commercial and industrial customers provide majority of demand response (DR) opportunities in today's environment, Federal Energy Regulatory Commission (FERC) indicates that the residential sector has the most untapped demand response potential. With the advent of smart grid technologies, full DR participation from residential customers is expected to provide roughly half of the total peak demand reduction potential in the U.S. [1].

To enable demand response in the residential sector, home energy management algorithms are needed. Many recent publications present a variety of algorithms for appliance-level demand response [2]–[8]. In most studies, appliance power consumption is considered to be constant at its rated power without any cycling or variation during its operation. The main reason underlying the flat appliance power consumption assumption is the lack of knowledge about detailed appliance operating characteristics, and most importantly the lack of publicly available measurement data. Variation in appliance power consumption is an intrinsic characteristic of most major household appliances, such as washing machines, clothes dryers, dishwashers, air conditioners, and refrigerators. Using realistic load profiles of individual appliances for such studies will lead to more accurate research findings and analyses.

To date, there are only a few comprehensive sources of energy use data at a household level. These include a free forum for the public to share their energy usage data developed by Lawrence Berkeley National Laboratory (LBNL) [9]; a publicly available data set called Reference Energy Disaggregation Data Set (REDD) [10]; and the data from Pacific Northwest GridWise testbed demonstration projects [11].

For the forum developed by LBNL, the public can share time-series power consumption data of selected household appliances. However, most data available in the LBNL library are for low-wattage appliances, such as gas-based clothes dryers, fans, and light bulbs. In addition, the LBNL data are of varying time intervals (1-second, 1-minute, 5-minute, etc.) obtained from different individuals using assorted measuring devices, which may not be calibrated to provide consistent results. This inconsistency prevents the use of this data from analyzing DR opportunities of different appliances. The REDD data set contains detailed power usage information from several homes. The data available for each home includes current and voltage measurements from the whole house and each individual circuit. The data are logged at a frequency of about once a second for a main circuit panel and once every three seconds for each circuit [12]. In this data set, when a circuit supplies different types of appliances, it is categorized by its main type of appliance. This indicates that electrical load profiles of individual appliances may not always be available. For the data set from Pacific Northwest GridWise testbed projects, selected appliance data are not available in high resolutions, i.e., one-minute intervals or less, which may not be granular enough to allow comprehensive DR analysis at the appliance level. Apart from these three libraries, very few other publications discuss operating characteristics of household appliances based on real-world measurement data [13]–[15]. In these papers, load profiles of a very limited number of appliances are discussed.

With the advent of the smart grid, detailed appliance-level power consumption data is crucial for DR studies. This paper bridges the gap of data unavailability by providing load profiles and associated raw data of selected major household appliances measured in two U.S. households. These include 11 major appliances of the following types: washing machine, clothes dryer, air conditioner, electric water heater, electric oven, dishwasher and refrigerator. For each individual appliance, time-se-

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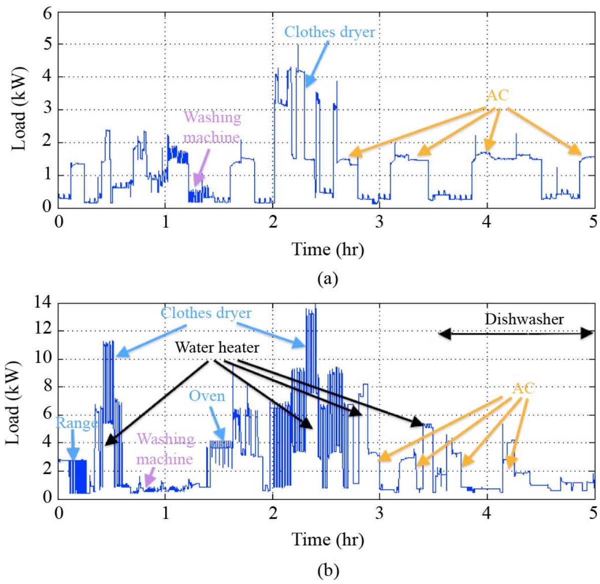

Fig. 1. Household load profile (kW) between 11am and 4pm: (a) House 1: 1200 sq ft; and (b) House 2: 2500 sq ft.

ries power measurements are obtained in one-second intervals. Opportunities to perform DR for these major household appliances are also evaluated.

The value of this work lies in one-second appliance operating characteristics, and associated raw data (in both one-second and one-minute intervals). These data sets are made available at www.ari.vt.edu/research-data. A sample data set in one-minute intervals is presented in the Appendix. These data sets can serve as a basis for researchers in the smart grid community to develop, analyze and validate realistic DR algorithms, enable appliance-level load modeling methods, load identification, and household load forecasting methodologies.

II. Importance of Demand Response (DR) Implementation for Residential Customers

Fig. 1 illustrates examples of household load profiles measured from two selected houses in the U.S. House 1 (1200 sq ft) represents a very small house. All appliances in this house, except the water heater and the stove/oven, run on electricity. House 2 (2500 sq ft) represents a typical American single-family home. All appliances in this house run on electricity.

As shown in Fig. 1(a), major appliances in operation in House 1 at the time of the measurement were a clothes washer, a clothes dryer and a window air conditioner. As shown in Fig. 1(b), major appliances in operation in House 2 at the time of the measurement were an electric range/oven, a washing machine, a clothes dryer, a water heater, a dishwasher, and a central air conditioning unit. Other background loads, such as lighting, computers, and a refrigerator were also running in both houses during the measurements.

It is interesting to note that peak loads of two houses of different sizes with different appliance ownerships, ratings and usage patterns can vary significantly from 5 kW for a 1200 sq ft house to 14 kW for a 2500 sq ft house. Information about appliance ratings and their operating characteristics are discussed in further details in subsequent sections.

TABLE I
Appliance Models and Their Ratings

Appliance	Model	Rating
Clothes washer	- GE WSM2420D3WW	120/240V 21A
	- LG WM2016CW	120V 60Hz 5A
Clothes dryer	- GE WSM2420D3WW	120/208V 60Hz 16A
	- LG DLE2516W	120/240V 60Hz 26A
Air conditioner	- LG LW1212ER	115V 12,000 BTU
	- Bryant Heating and Cooling Systems 697CN030-B	208/230V 1PH 60Hz Comp: RLA 14.2A Fan: 1/5HP
Water heater	- E52-50R-045DV (50 gal)	240V 4500W
Range/oven	- Kenmore 790.91312013	120/240V 10kW
Dishwasher	- Kenmore 665.13242K900	120V 60Hz 9.6A
Refrigerator	- Hotpoint HTR16ABSRWW	120V 60Hz 12A 15.6-cuft top freezer
	- Maytag MSD2641KEW	115V 60Hz 9.4A 25.6-cuft side-by-side

In a typical U.S. distribution network setting, a 25 kVA distribution transformer serves three to seven homes in a neighborhood. If there are more than three homes that have similar load profiles to that shown in Fig. 1(b), the distribution transformer can potentially be overloaded. This problem can become exacerbated for neighborhoods with electricity-only supply, i.e., no gas supply, and with a cluster of electric vehicles. To prevent transformer overloading and defer necessary upgrades of distribution transformers and switchgears, demand response (DR) can be performed at an appliance level. In order to enable DR at customer premises, it is necessary to understand operating characteristics and load profiles of each major appliance. Subsequent sections discuss these points with real 1-second measurements, and analyze DR opportunities at the appliance level based on appliance operating characteristics and their electrical load profiles.

III. Appliances Under Study and Measurement Devices

This section describes selected appliances under study and measurement methods.

A. Appliances Under Study

Power consumption data of selected appliances presented in this paper are measured from two households located in Virginia and Maryland. Major electrical appliances reported in House 1 are a stacked clothes washer/clothes dryer unit, a wall-unit air conditioner and a refrigerator. Major electrical appliances available in House 2 are a front-load washing machine, a clothes dryer, a central air conditioner, an electric water heater, an electric range/oven, a dishwasher, and a refrigerator. Therefore, there are a total of 11 appliances under study. Table I summarizes these appliances in terms of their model numbers and ratings.

B. Measurement Devices

Two measurement devices were used in this study, namely the energy detective device (TED), and EXTECH true RMS power analyzer data logger. TED is designed to measure electrical power consumption of the entire house (up to 200 A in rating) by installing it in a circuit breaker panel. EXTECH is designed to measure power consumption of a single appliance (with rating of up to 2000 VA) by plugging in an appliance directly to the EXTECH device. Both devices are capable of measuring power consumption and power factor data in one-second intervals. In this study, TED was used to measure

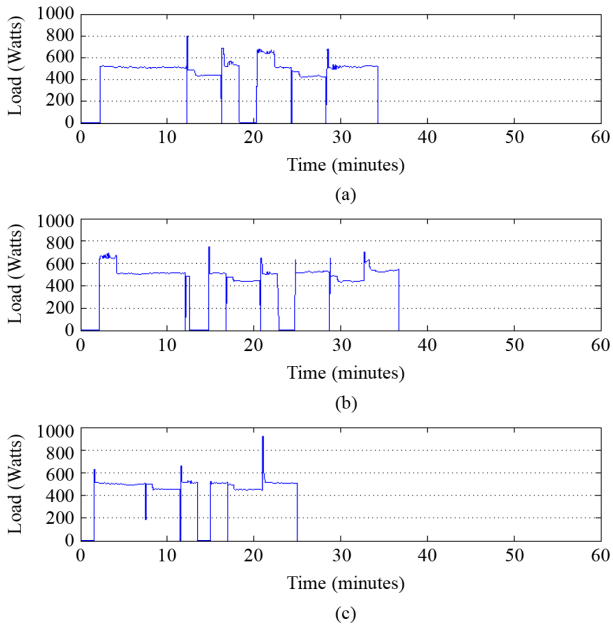

Fig. 2. Load profiles of the GE WSM2420D3WW clothes washer: (a) normal wash cycle; (b) permanent press cycle; and (c) delicates cycle.

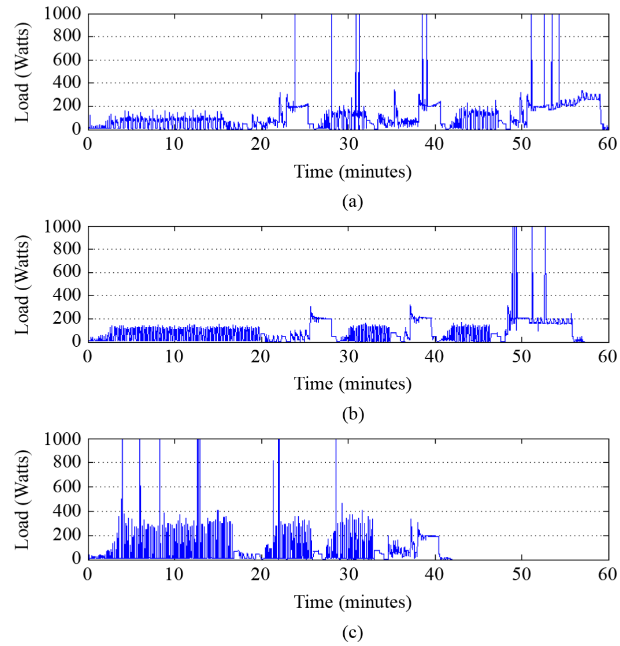

Fig. 3. Load profiles of the LG WM2016CW clothes washer: (a) normal wash cycle; (b) permanent press cycle; and (c) delicates cycle.

one-second power consumption and power factor data of appliances that are hardwired to circuit breaker panels. These include the stacked clothes washer/dryer unit (GE WSM2420D3WW), the front-loading clothes dryer unit (LG DLE2516W), the central air conditioner (Bryant 697CN030-B), the water heater, the range/oven, and the dishwasher. EXTECH was used to measure one-second power consumption and power factor data of other appliances that can be plugged in to a 120 V standard outlet. These are the front-load washing machine (LG WM2016CW), the wall-unit AC and the two refrigerators. Both TED and EXTECH devices were calibrated before conducting any measurements to ensure that their readings are comparable.

IV. Load Profiles of Major Appliances Under Test

This section illustrates load profiles of major appliances under test captured in one-second intervals.

A. Washing Machines

Load profiles of two clothes washers are measured: one is the bottom unit of the stacked washer/dryer unit (GE WSM 2420D3WW); and the other is the front-load washer (LG WM2016CW). These are illustrated in Figs. 2 and 3, respectively.

Figs. 2(a) –2(c) show load profiles of the GE WSM 2420D3 WW unit when operating in three wash settings: normal, permanent press and delicates. The washer has three cycles of operation: wash, rinse, and spin. The washer starts its wash cycle by filling in the water during the first 1–1.5 minutes. During water fill times, the washer consumes 4–8 watts. Various washing speeds are observed during a wash cycle, consuming between 430–688 W. Wash times are different for three wash settings. The spray rinse cycle follows the wash cycle. During this cycle, the washer also spins at different speeds. Then, the last cycle is spin. The power consumption during the spin cycle is roughly 500–540 W. The power factor (PF) data of the washer were recorded between 0.55–0.59.

Figs. 3(a)–3(c) illustrate load profiles of the front load LG WM2016CW washer for the same three wash settings: normal, permanent press, and delicates. This is a high-efficiency washer model, which appears to consume much less power than the GE WSM 2420D3WW washer with much more complicated operating characteristics. Similar to the GE one, this front load washer starts its wash cycle by filling in the water, during which the washer consumes 4–50 W. As the water fills in, the washer also starts rotating. It can be seen that during the first couple minutes of operation, its power consumption is low, and keeps on increasing. This reflects an increasing motor load as the water level increases. Frequent variations in motor speeds (i.e., every 30 seconds) are observed during the wash cycle, during which the washer consumes 4–350 W. Based on several washer runs, peak power consumption during the wash cycle varies from 150 W to 350 W depending on the laundry load size. The wash cycle is followed by the rinse cycle, which consumes 45–76 W. The last cycle is the spin cycle, during which the washer consumes 190–300 W. The power factor (PF) during its operation ranges between 0.13 and 0.69.

Note that with the high-efficiency washer such as the LG WM2016CW, the wash time can be longer than one hour if the amount of detergent used is high compared to the amount of washload to process.

B. Electric Clothes Dryer

Load profiles of two electric clothes dryers are measured: one is the top unit of the stacked washer/dryer unit (GE WSM 2420D3WW); and the other is the LG dryer (LG DLE2516W).

Figs. 4(a)–4(c) shows load profiles of the GE WSM 2420D3 WW dryer unit for three drying modes: auto-regular, auto-permanent press, and timed (30 minutes). Similarly, Figs. 5(a)–5(c) shows load profiles of the LG DLF2516W dryer unit for three drying modes: auto-regular, delicates, and timed (30 minutes). It can be seen that the GE stacked washer/dryer unit has a power consumption of about 2.95 kW at 1.0 PF for all operating cycles when heating coils operate; and about 185 W at 0.44–0.47

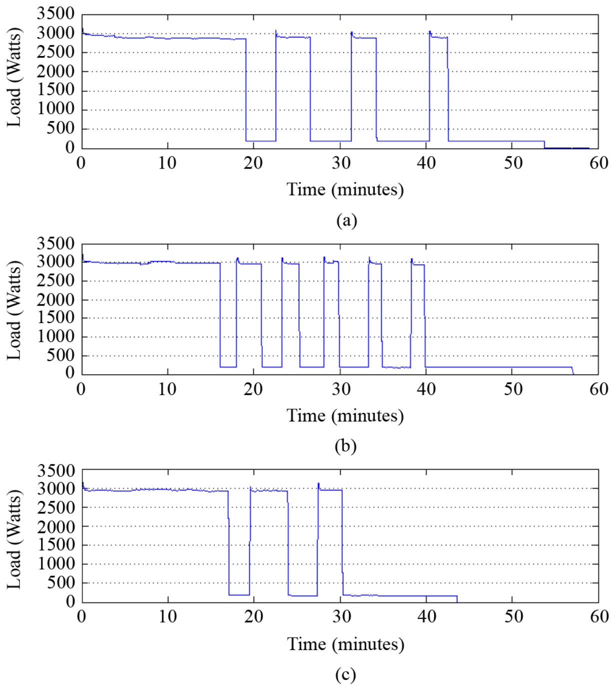

Fig. 4. Load profiles of the GE WSM2420D3WW clothes dryer: (a) auto-regular; (b) auto-permanent press; (c) 30-minute timed drying cycles.

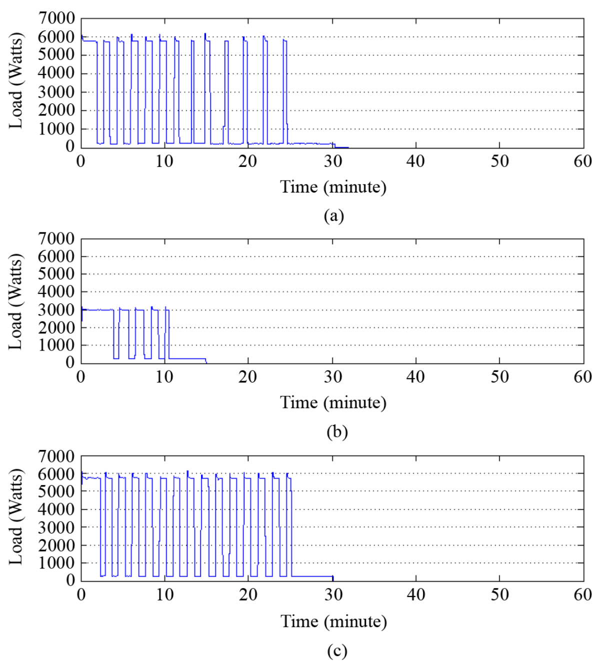

Fig. 5. Load profiles of the LG DLE2516W clothes dryer: (a) auto-regular; (b) delicates; and (c) 30-minute timed drying cycles.

PF when the dryer tumbles without heat. The LG dryer unit is a much larger capacity electric dryer than the GE unit under study. It has the power consumption of about 5.76 kW at 1.0 PF for auto-regular and timed modes; and about 3 kW for the delicates cycle. When the dryer tumbles without heat, the dryer consumes about 226 W at 0.44–0.47 PF. Observations show that the first ON cycle is always the longest, following by several subsequences ON/OFF cycles depending on laundry loads. This is because, in a typical clothes dryer, an automatic dry control system is used to sense the air temperature in the dryer drum.

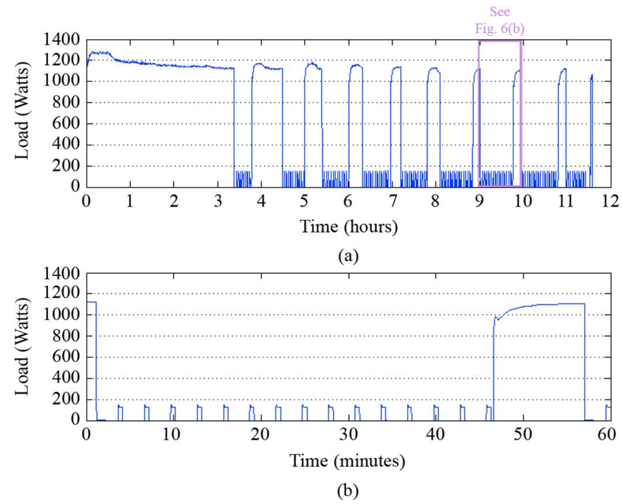

Fig. 6. Load profiles of the wall AC unit: (a) captured for a 12-hour period; and (b) zoomed for a one-hour period (between hours 9 and 10).

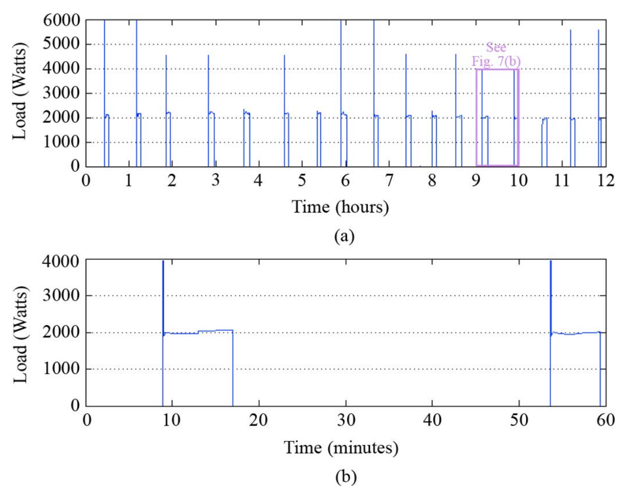

Fig. 7. Load profiles of the central AC unit: (a) captured for a 12-hour period; and (b) zoomed for a one-hour period (between hours 9 and 10).

For all drying cycles, dryers tumble without heat during the last five to ten minutes of operation.

The measured data shown in Figs. 4(c) and 5(c) demonstrate the dryer's load profiles when the timer is set at 30 minutes. Several ON/OFF cycles are also present for the timed cycle. It is interesting to see that the drying function completion time in the timed drying mode varies from manufacturer to manufacturer, and from model to model. For the GE stacked dryer unit, heating coils are OFF at exactly 30 minutes and the dryer continues to operate without heat during the last 10–15 minutes, while for the LG unit, the dryer stops its operation exactly after 30 minutes.

C. Air Conditioner (AC)

Load profiles of two types of AC units were captured during our experiment, namely a wall AC unit (LG LW1212 ER) and a central AC unit (Bryant 697CN030-B). Operations of both AC units were captured for 12 hours. These are illustrated in Fig. 6 for the wall AC unit and Fig. 7 for the central AC unit.

Fig. 6(a) illustrates operating characteristics of the wall AC unit for 12 hours from $t = 0$ (when the wall AC unit was manually started) to $t = 12$ (shortly after the unit was manually turned off between hours 11 and 12). Fig. 6(b) shows the

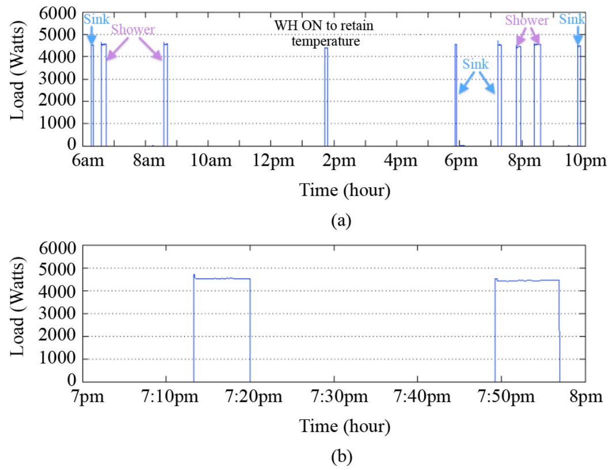

Fig. 8. Load profiles of the 50-gallon water heater, showing (a) its 14-hour operation; (b) its 1-hour operation between 7 P.M. and 8 P.M. on the same day.

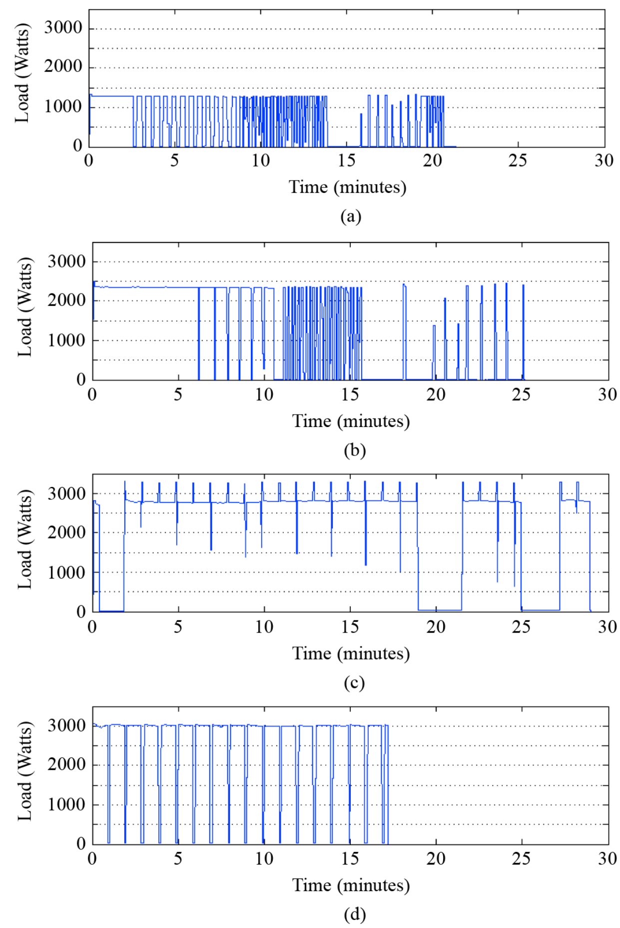

Fig. 9. Load profiles of an electric range/oven: (a) small burner; (b) large burner; (c) bake at $450\ ^{\circ}F$; and (d) broil.

zoomed version of the wall AC operation during the one-hour period between hours 9 and 10. This measurement was captured in July 2012 starting at around 7 P.M. when the homeowner arrived home from work and manually started the AC. The one-second measurement indicates that the wall AC unit consumes between 1.10 and 1.25 kW when the compressor was ON. At the beginning, the compressor operates for over three hours to bring the room temperature down to its set point. The length of compressor operation depends on ambient temperature as compared to the AC temperature set point. It can be seen that during compressor OFF durations, the AC fan (measured at 120–150W) turns ON and OFF several times to circulate the air in the house. The average AC fan ON time is 30 seconds, and OFF time is 2.5 minutes. See Fig. 6(b). The wall AC unit's power factor is recorded at 0.95–0.97 during the compressor operation, and 1.0 during the fan only operation.

Fig. 7(a) illustrates operating characteristics of the central AC unit for 12 hours form $t = 0$ to $t = 12$. Fig. 7(b) shows the zoomed version of the central AC operation during the one-hour period between hours 9 and 10. This measurement was captured in September 2012 starting from 10 A.M. to 10 P.M.. The one-second measurement as shown indicates that the central AC unit consumes between 1.84 to 2.34kW with the power factor of 0.90–0.92 during its operation. The fan for the central AC unit is supplied by a separate circuit. The fan consumes about 250 watts at 0.54–0.56 PF (not shown), which comes on about 30 seconds after the AC starts, and goes off 30–60 seconds after the AC stops.

D. Electric Water Heater (WH)

One-second electrical power measurement of a 50-gallon electric WH unit (E52–50R-045DV) was captured during our experiment. The WH operation was monitored for 14 hours from 6 A.M. to 10 P.M., as shown in Fig. 8(a). Fig. 8(b) expands the WH load profile between 7 P.M. and 8 P.M. on the same day. The WH consumes approximately constant power at about 4.5kW at a PF of 1.0 during its operation.

Based on our observation for this particular case, the 50-gallon WH unit is ON after about five minutes of hot water usage from a combination of showers, dish washing at a kitchen sink and clothes washing by a washing machine. For the load profile as shown in Fig. 8(a), WH operations at around 6 A.M., 6 P.M., 7 P.M., and 10 P.M. were due to hot water usage in the kitchen sink; and WH operations at around 6:30 A.M., 8:30 A.M., 8 P.M., and 8:30 P.M. were from showers. The 50-gallon WH unit also operates once in a while to maintain the water temperature in the tank even without hot water consumption. This happened at about 2 P.M. in this case. For this particular case, WH operation duration is approximately six minutes to maintain the water temperature inside the tank. For other uses, the WH operation duration can range from three minutes to 15 minutes. This can vary, depending on the amount (and duration) of hot water drawn, hot water temperature set point, and the water inlet temperature.

E. Electric Range/Oven

Load profiles of an electric range/oven (Kenmore 790.9131 2013) are shown in Fig. 9. This electric range/oven has four cooktop burners: two small and two large; and an oven, which allows a homeowner to bake or broil the food.

Electric power consumption of a small cooktop burner and a large one was captured as illustrated in Figs. 9(a) and 9(b), respectively. For the small cooktop burner, the control knob was set to the high-heat setting during the first nine minutes. Then, the knob was set to the medium-heat setting for the next five minutes. Lastly the knob was set at the low-heat setting. It can be seen that after the burner was turned ON, a radiant element operates to heat the food. The power consumption of

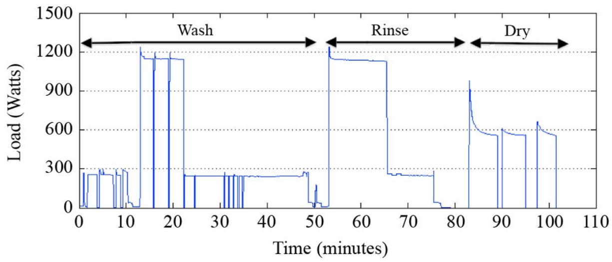

Fig. 10. Load profile of a dishwasher.

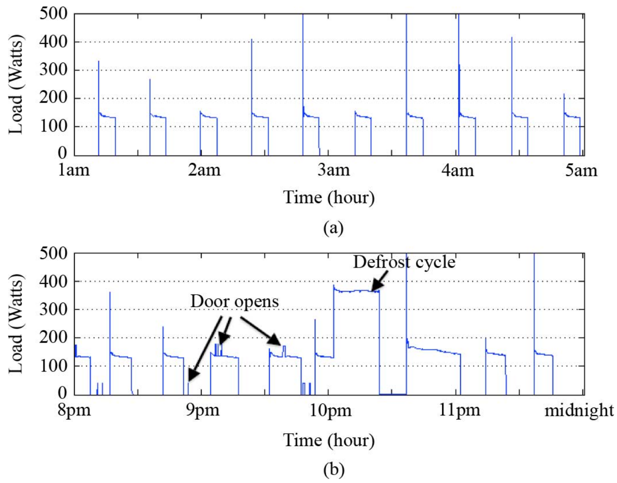

Fig. 11. Load profiles of the top-freezer refrigerator unit: (a) no activity; and (b) with door opens and a defrost cycle.

this small burner is about 1.3 kW at 0.95 PF. The radiant element cycles ON/OFF once the right temperature is reached. More frequent cycles with shorter ON periods were observed when the knob was changed to lower heat settings. For the large cooktop burner, similar heat settings were set, i.e., changing from high-heat to medium-heat setting at minute 11, and from medium-heat to low-heat setting at minute 16. Similar operating characteristics are observed. The power consumption of this large burner is about 2.3 kW at 0.95 PF.

Figs. 9(c) and 9(d) illustrate oven characteristics when bake and broil settings are selected, respectively. For the bake setting, the oven power consumption is roughly 2.8 kW at 0.98 PF. Notice that there are periodic brief 400-watt increases during the operation. This seems to be the operation of a thermal switch. The temperature was set at 450 °F, and it took about 19 minutes for the oven to reach the set temperature, after which the oven operates in an ON/OFF cycle until it is turned OFF. For the broil setting, radiant heat from the upper broil element in the oven is used, and its power consumption is approximately 3.0 kW at 0.98 PF. The heating element operates in a periodic cycle with 50-second ON and 10-second OFF, until the oven is turned OFF.

F. Dishwasher

Load profile of a dishwasher (Kenmore 665.13242K900) was captured during our experiment, as shown in Fig. 10. The dishwasher operated for about 105 minutes.

The dishwasher has three main operating cycles: wash, rinse and dry. As shown in Fig. 10, the first 50 minutes are associated with the wash cycle. The rinse cycle follows from minutes 50 to 80. Then, the last is the dry cycle.

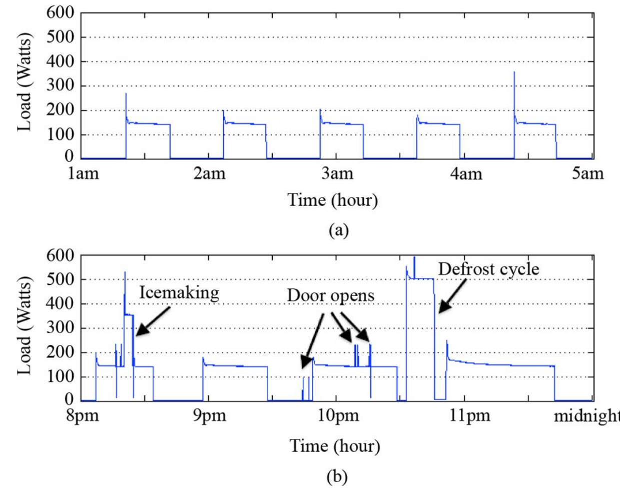

Fig. 12. Load profiles of the side-by-side refrigerator unit: (a) no activity; and (b) with door opens, an ice-making cycle and a defrost cycle.

The first 10 minutes of operation during the wash cycle belong to the pre-wash phase. Pre-wash involves filling in water and shooting the water through jets to get dishes clean. The dishwasher consumes 250–300 watts at 0.62–0.65 PF. Then, the real wash cycle begins when the water is heated by the heating element inside the dishwasher until the water temperature reaches the proper temperature, i.e., 115 ° F in this case. During heating the water, the dishwasher consumes about 1180 watts at 1.0 PF. Then, the hot water is sprayed to clean dishes. A series of pauses during the wash cycle are observed. The dishwasher then drains dirty water, consuming about 36-44 watts.

The rinse cycle that follows starts by filling in water and heating the water to the proper temperature, i.e., 135 ° F for this particular dishwasher. Then, the dishwasher sprays water on dishes to rinse them. The water is then drained; and the dry cycle starts. During the dry cycle, the dishwasher consumes about 600 watts at 1.0 PF.

G. Refrigerators

One-second measurements of two refrigerators (Hotpoint, 15.6-cuft top freezer and Maytag, 25.6-cuft side-by-side) were recorded for five consecutive days.

Fig. 11 presents load profiles of the Hotpoint refrigerator for two specific periods. One is between 1 A.M. and 5 A.M. when there is no refrigerator activity, as shown in Fig. 11(a). The other is between 8 P.M. and midnight with several refrigerator door opens and a defrost cycle, as shown in Fig. 11(b).

For this refrigerator model, the power consumption during its ON mode is about 135 watts (at 0.992–0.999 PF), and there is no power consumption during its OFF mode. Without refrigerator door open, a typical ON time is about 7.5 minutes and a typical OFF time is about 17 minutes. High spikes can be expected during transitions from OFF to ON stages.

When the refrigerator door is open, its power consumption is increased by 40 watts due to the incandescent light bulb inside the refrigerator. This is shown in Fig. 11(b) at about 8 P.M., 8:15 P.M., 8:50 P.M., 9:10 P.M., 9:40 P.M., and 9:50 P.M.. Notice that opening the refrigerator door will prolong subsequent refrigerator ON durations. A defrost cycle happened at about 10:05 P.M., when the refrigerator power consumption increases to about 365 watts (at 1.0 PF). A typical defrost cycle for this refrigerator lasts about 20 minutes, and happens every 30–40

TABLE II
DEMAND RESPONSE OPPORTUNITIES FOR SELECTED MAJOR APPLIANCES

Appliance type	Appliance model number	(a) Average peak power consumption in a cycle (watts)	(b) Average min power consumption if DR is performed (watts)	(c) Load reduction potential (watts)	(d) Load reduction potential (%)	(e) Possible interruption/ deferral period (min)	(f) DR potenti al	(g) DR potential rank
House 1								
Clothes washer	GE WSM2420D3WW	580	0	580	100%	None/ Up to several hours	Low	3
Clothes dryer	GE WSM2420D3WW	2,950	185	2,760- 2,950	94%- 100%	Up to 30 minutes/ Up to several hours	High	1
Air conditioner	LG LW1212ER	1,150	0	1,150	100%	Vary	Med	2
Refrigerator	HTR16ABSRWW	365/135	0	365	100%	Up to several hours (defrost cycle)	Low	4
House 2								
Clothes washer	LG WM2016CW	200	0	200	100%	None/ Up to several hours	Low	6
Clothes dryer	LG DLE2516W	5,760	226	5,534- 5,760	96%- 100%	Up to 30 minutes/ Up to several hours	High	1
Air conditioner	Bryant 697CN030-B	2,000	0	2,000	100%	Vary	Med	3
Water heater	E52-50R-045DV (50 gal)	4,500	0	4,500	100%	Vary	High	2
Range/oven	Kenmore 790.91312013	1,300-3,000	0	None	None	None	None	None
Dishwasher	Kenmore 665.13242K900	1,180	0	1,180	100%	None/ Up to several hours	Med	4
Refrigerator	MSD2641KEW	500/145	0	500	100%	Up to several hours (defrost cycle)	Low	5

hours. As shown in Fig. 11(b), a refrigerator defrost cycle will follow by a long refrigerator operating duration.

Fig. 12 illustrates load profiles of the Maytag refrigerator for the same two periods. Note that this Maytag refrigerator is a side-by-side unit with a built-in icemaker. Fig. 12(a) shows the refrigerator operation without any activities. Fig. 12(b) shows the refrigerator operation with a defrost cycle, an ice making cycle and door opens. For this refrigerator model, the power consumption during its ON mode is about 145 watts (at 0.989–0.992 PF), and that during the OFF mode is about 2.7 watts to supply electronic devices. Without refrigerator door opens, a typical ON time for this refrigerator is about 20 minutes and a typical OFF time is about 25 minutes. This refrigerator appears to have a much longer ON time than the one shown in Fig. 11. One reason could be that this is a much larger capacity refrigerator (i.e., 25.6 cu ft vs 15.6 cu ft).

This Maytag refrigerator has a freezer on the left side and a fridge on the right side. There is one 45-watt incandescent light bulb inside the freezer, and two 45-watt bulbs inside the fridge. Hence, the power consumption increases by 45 watts when the freezer's door is open; and by 90 watts when the fridge's door open. An ice making cycle will add about 200–250 watts more, which can be seen in Fig. 12(b) at around 8:20 P.M.. A defrost cycle at about 10:30 P.M. indicates the electric power consumption of about 500 watts (at 1.0 PF). A typical defrost cycle for this refrigerator lasts about 13 minutes. As shown in Fig. 12(b), a refrigerator defrost cycle will follow by a long refrigerator operating duration, i.e., 50 minutes in this case.

V. DISCUSSION ON DR OPPORTUNITIES

This section summarizes operating characteristics of appliances under study. It also discusses opportunities for these appliances to participate in a demand response (DR) program, along with operation constraints for different appliances to reduce customers' comfort level violation.

A. DR Opportunities for Selected Major Appliances

Table II compares power consumption, peak power reduction potential, possible interruption/deferral period and DR potential of selected appliances in two households. Possible interruption/deferral periods as presented in column (e) estimate the duration that a specific appliance can be interrupted/deferred without impacting consumer convenience.

For House 1, as far as the peak power consumption is concerned—as shown in Table II column (a)—the appliance that has the highest power consumption is the electric clothes dryer. This is followed by the wall AC unit, the clothes washer, and lastly the refrigerator. For House 2, two appliances that have the highest power consumption are the electric clothes dryer (5.76 kW) and the electric water heater (4.5 kW). These are followed by the electric oven, the central AC unit, the dishwasher, the refrigerator, and lastly the washing machine. Observations for these two houses of different sizes point out that:

- *An electric clothes dryer offers the highest DR opportunity*. This is because deferring or interrupting clothes drying loads can reduce the overall household power consumption by a significant amount. In today's environment, it is possible to interrupt a clothes dryer operation by disconnecting its heating coils while letting the dryer tumble without heat. External hardware devices can now be acquired [16] to enable such a control. For the case of two houses under study, demand reduction potential is 2760 watts for a stacked washer/dryer unit; or 5534 watts for a front-load dryer unit when a clothes dryer's heating coils are disconnected. The interruption period should not be more than 30 minutes to prevent excessive heat loss. Deferring a clothes dryer start time is also possible with selected smart clothes dryer models. Possible deferral periods can be up to several hours depending on how quickly a customer would like his/her clothes drying job to finish.
- *Electric water heaters, if present in a house, can offer the second highest peak power reduction potential*. Electric water heaters are well known for their demand response potential in direct load control programs. The PJM interconnection has a pilot project underway to demonstrate water heater participation in PJM's energy and regulation markets [17]. To allow controlling a water heater without affecting customer comfort, monitoring the water temper-

ature inside the water heater tank is necessary. Then, a DR implementation can be performed to allow interrupting water heater operation only when the hot water temperature is within a limit preset by a homeowner, i.e., 110-120 $^\circ F$. In this case, as soon as the hot water temperature falls below a specified threshold, the water heater should resume its operation.

- *AC units offer somewhat medium DR potential* as performing AC control on a residential AC unit can reduce at least 1 kW of peak power consumption for a window unit, and 2–4 kW for a central AC unit. At present, a central AC unit can participate in AC cycling programs in response to signals sent by a utility [18]. With new technologies, a wall AC unit can also be controlled [19]. A more realistic way of controlling air conditioners is underway by adjusting the AC temperature set point [20]. In this case, demand response can be performed on an AC unit while simultaneously maintaining customer comfort preference. For example, a customer may specify his/her comfort range, e.g., room temperature can go up by 5 $^\circ F$ from the original set point during a DR event. As long as the room temperature is within this specific range, the operation of an AC unit can be interrupted.
- *Demand response can also be performed on dishwashers*, which can offer about 1 kW demand reduction potential if deferred. Some dishwasher models available in the market today offer an ability to defer their start time. Potential deferral periods can be up to several hours depending on customer preference. However, if a dishwasher is in operation, it should not be interrupted, as some dishwasher models may not be able to resume their operation after the interruption.
- *Clothes washers and refrigerators have low demand response potential* because of the following two reasons. One, their power consumption is not as high. Two, there is yet no external hardware device available that can enable their DR functions. Thus customers need to replace existing appliances with emerging DR-enabled smart appliances, which is unlikely. With the smart appliance concept, selected appliance manufacturers envision a smart washer with a delayed start time, delayed rinse cycle, or spin cycle. A smart refrigerator is also envisioned with delayed defrost cycle, and perhaps modification of run time during peak demand.
- *Electric ranges/ovens have no DR potential*. These are the loads that should not be controlled, as it will significantly impact customer convenience.

To take into account load priority and customer comfort preference in managing household loads, an intelligent home energy management algorithm will be needed. Operation of these appliances should also be cycling with each other based on the preset load priority to avoid customer comfort violation. Such an algorithm, along with its hardware demonstration in a laboratory environment, have been proposed by the authors in [21], [22].

VI. Conclusion

This paper presents electricity load profiles of selected major household appliances in one-second resolution, and provides their raw data in one-second and one-minute resolutions. It also discusses DR potential for these major household appliances. The main contribution of this paper lies in the set of high-resolution data at an appliance level—which are intended for use by university and industry researchers to develop realistic load models, analyze various DR algorithms for home energy management and thus ultimately gaining an insight into how individual appliance operation can be controlled for an emerging DR program.

Appendix A
Sample Raw Power Consumption Data (Watts) in 1-Minute Intervals

Index	Washer – Normal wash (WSM2420D3WW)	Washer – Delicates (WSM2420D3WW)	Washer – Normal wash (LG WM 2016CW)	Washer – Delicates (LG WM 2016CW)	Dryer – Auto-regular (WSM 2420D3WW)	Dryer – AutoPerm (WSM 2420D3WW)	Dryer – Auto-regular (LG DLE 2516W)	Dryer – Delicates (LG DLE 2516W)	Wall AC – hours 9-10 (LG LW 1212ER)	Central AC –hours 9-10 (Bryant 697 CN030-B)	Water heater (E52-50R-045DV)	Range/oven – Large burner (790.91312013)	Range/oven – Bake (790.91312013)	Range/oven – Broil (790.91312013)	Dishwasher (665.13242K900)	Refrigerator – 10-11pm (HTR16ABSRWW)	Refrigerator – 10-11pm (MSD2641KEW)
1	6	4	17	12	2846	2901	5511	2834	1121	0	0	2254	941	2666	27	218	144
2	5	243	14	15	2951	3009	5470	3004	172	0	0	2352	480	2749	78	370	144
3	383	510	33	31	2944	2991	1519	3006	1	0	0	2354	2814	2583	256	367	143
4	518	503	43	86	2933	2979	2731	2731	45	0	0	2352	2816	2588	214	366	143
5	514	501	65	72	2897	2981	3983	1460	21	0	0	2344	2755	2589	191	363	143
6	513	495	57	108	2888	2982	879	2266	1	0	0	2337	2800	2588	262	364	142
7	510	497	55	71	2888	2970	4692	1695	44	0	0	2199	2766	2584	254	364	142
8	509	473	55	63	2901	2968	2036	1787	22	0	0	1959	2805	2724	133	364	142
9	510	467	59	100	2897	3022	2897	1880	1	263	0	2139	2729	2578	209	364	175
10	513	456	67	67	2880	3028	3772	999	44	1974	0	1959	2772	2718	206	364	149
11	513	457	65	75	2876	3018	1335	1605	23	1968	0	1325	2838	2702	116	366	173
12	511	478	58	85	2883	2986	3202	273	1	1968	0	998	2793	2561	18	367	141
13	501	519	55	143	2875	2985	228	274	42	1968	0	1032	2850	2566	53	367	142
14	446	249	66	63	2873	2987	2076	273	24	2023	3039	1229	2795	2575	1172	366	142
15	439	13	66	85	2881	2977	1190	257	1	2023	4525	1348	2849	2814	1147	367	142
16	443	509	69	69	2878	2987	2623	0	42	2057	4527	865	2759	2571	882	367	151
17	528	491	23	58	2860	512	224	0	27	2057	4529	4	2849	2571	1153	367	142
18	550	482	18	48	2852	189	2711	0	1	0	4531	2	2776	507	1146	365	142
19	128	451	31	18	2856	2948	224	0	40	0	4526	402	2605	0	1147	364	142
20	4	451	56	28	446	2958	3035	0	27	0	4523	169	32	0	922	363	142

* A complete data set is available at www.ari.vt.edu/research-data/.

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