NATIONAL RENEWABLE ENERGY LABORATORY

Laboratory Testing of Demand-Response Enabled Household Appliances

B. Sparn, X. Jin, and L. Earle

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Technical Report
NREL/TP-5500-60383
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Prepared under Task No. BE12.0203

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List of Acronyms

ACM	appliance communication module
AHEM	Automated Home Energy Management
AMI	Advanced Metering Infrastructure
DR	demand response
DSM	demand-side management
GE	General Electric
HPWH	heat pump water heater
HSP	House Simulation Protocol
NREL	National Renewable Energy Laboratory
TOU	time of use

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1 Introduction

With the advent of the Advanced Metering Infrastructure (AMI) systems that are capable of two-way communications between the utility grid and a building, the Automated Home Energy Management (AHEM) industry has made a significant effort to develop capabilities that allow residential building systems to respond to utility demand events by temporarily reducing their electricity use. Major appliance manufacturers are following suit by developing Home Area Network-tied appliance suites that can take signals from the home's "smart meter," a.k.a. AMI meter, and adjust their run cycles accordingly. For example, during a peak event a refrigerator could delay a defrost cycle for several hours, or the clothes dryer may run at a lower heat setting so that the power requirement is much lower but clothes take longer to dry. Household appliances can use numerous strategies to respond to demand-side management (DSM) opportunities, which could substantially reduce electricity bills for the residents, depending on the pricing structures used by the utilities to incent these types of responses. However, these systems and infrastructures are very new, and have not been broadly tested in real-world scenarios.

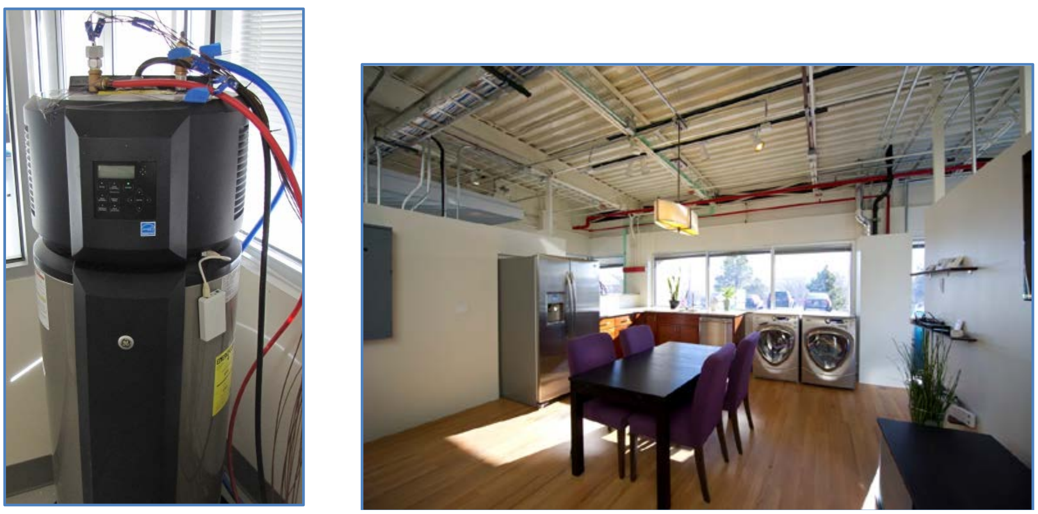
Homeowners and utilities have strong incentives to facilitate efficient DSM. Electricity prices and supply reliability are important to residential customers, and are closely tied to the operational practices of the electric utility and how it handles peak demand issues. The service providers are most likely primarily concerned with meeting the requirements of public utility commissions (and earnings if investor-owned), but dissatisfied ratepayers pose business and regulatory risks. Grid-connected appliances can help all parties by automatically shifting energy use out of peak hours to level loads and maintaining ratepayer satisfaction with their utilities through supply reliability and cash incentives (National Action Plan for Energy Efficiency, 2010). The first step to quantifying these end effects is to test these systems and their responses in simulated demand-response (DR) conditions while monitoring energy use and overall system performance[1].

[1] NREL is not a certified appliance testing or rating laboratory. The results described in this report are focused on enabling simulation of appliance interactions with whole buildings and the utility grid, and should not be used to establish compliance with efficiency standards.

2 Description of Smart Appliance Test Articles

2.1 General Electric Profile Smart Appliances

We studied a suite of General Electric (GE) Profile appliances that have been enabled with GE's Brillion[2] technology as part of the Nucleus home energy management system. This is the first set of coordinating demand-responsive major appliances to enter the US market. These smart appliances can respond to utility signals from the smart meter and report their energy use to the occupants. The appliances installed in the laboratory include a dishwasher, a clothes washer and dryer, a refrigerator, and a heat pump water heater (HPWH). Each appliance has an Ethernet port where an appliance communication module (ACM) connects, as shown in Figure 2 and Figure 3. The ACM receives signals from the Nucleus, which is the central controller for this energy management system. The Nucleus communicates with the home's AMI meter, or can be controlled by the homeowners via the home manager website, and passes that information to the appliances. More details about the Nucleus energy manager, the home manager website, and the different DR controls for each appliance are given in the next section.



NREL Image Gallery 25539, 20207
Credit: Bethany Sparn, Dennis Schroeder

Figure 1. GE's GeoSpring hybrid HPWH (L) and Profile smart appliances (R). Each appliance can report its own energy use and respond to utility price signals via the Nucleus home energy management system.

[2] www.geappliances.com/home-energy-manager/appliance-energy-consumption.htm

Figure 2. GE Brillion appliance communication module

NREL Image Gallery 25540, 25541
Credit: Lieko Earle, Bethany Sparn

Figure 3. The smart refrigerator with the ACM connected via an Ethernet cable

2.2 General Electric Nucleus Energy Manager

The home energy network relies on the Nucleus energy manager, which plugs into a standard 120-V receptacle and wirelessly communicates with the home's smart meter, appliances, in-home display, and other devices via Zigbee Smart Energy Protocol. Zigbee Smart Energy Protocol is a wireless communication protocol specifically designed for AHEM and smart grid products (Zigbee Smart Energy Overview). See Figure 4 for a diagram of the Nucleus and the communication network as part of the Nucleus home energy management system.

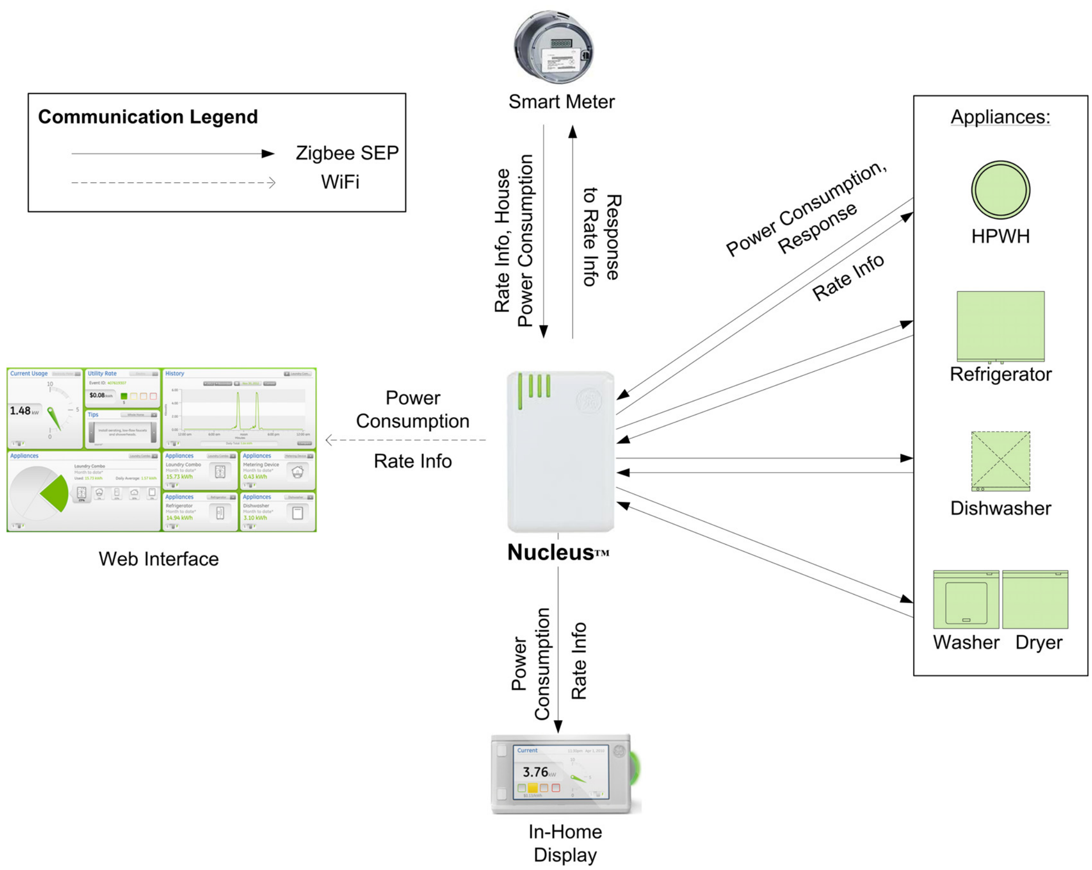


Figure 4. Communication paths for the Nucleus home energy management system

The Nucleus receives current electricity pricing information from the home's AMI meter and sends that information to the appliances. The price information triggers different energy-reducing controls for each appliance. The response of the appliances, whether the users accepted the energy reducing controls, is reported to the Nucleus and then back up the chain to the electric utility via the AMI meter. At regular intervals, each appliance reports its electrical power consumption back to the Nucleus via the ACM. The whole-house electrical power consumption is measured by the smart meter; those data are also reported to the Nucleus. These data are displayed and updated every 15 s on a Web-based dashboard (see Figure 5) on a computer or smart phone that is connected to the Nucleus via WiFi or LAN. The same information can also be displayed on an in-home display.

Figure 5. The Nucleus Web interface dashboard displays appliance and whole-house energy use and current electricity prices

In a typical installation, the Nucleus system would receive price signals from the local utility via the home’s smart meter. To test the response of the appliances to higher electricity prices in the laboratory, the Nucleus Web interface was used to set up a tiered price schedule. The time-of-use (TOU) price scheduler allows for four levels of pricing: Low, Medium, High, and Critical (see Figure 6).

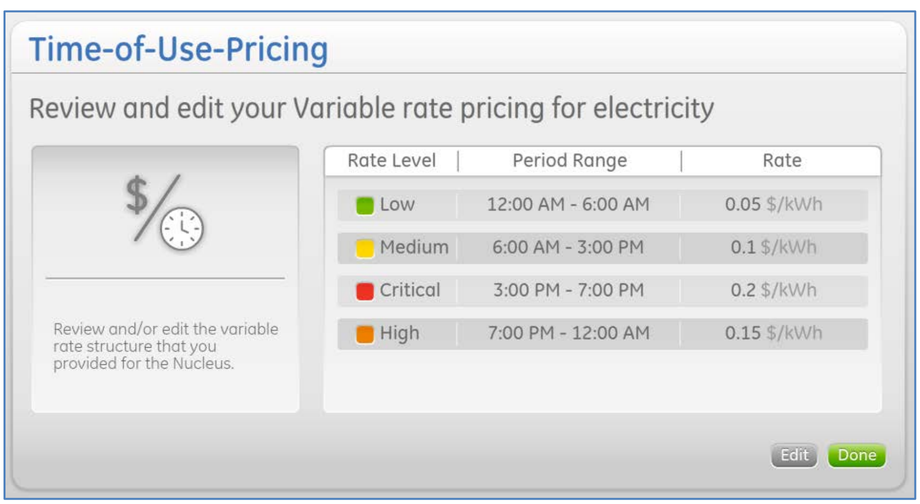


Figure 6. TOU price schedule that can be configured using Nucleus energy manager

All the appliances operate normally in the Low and Medium price periods, except that the HPWH uses the Heat Pump Only mode exclusively during the Medium price periods (See Sparn, Hudon, and Christensen (2011) for more information about the HPWH operating modes). The automatic adjustments to operation are made in the High and Critical price periods. When the cost of electricity hits the High or Critical threshold, the appliances are all sent signals to conserve energy. The controls for the appliances in both High and Critical price periods are shown in Table 1. GE provided basic information about the operational modes of each appliance in the different price. Our laboratory testing verified these modes and the impact they have on energy use profiles of the appliances.

Table 1. Summary of GE Smart Appliances and Their Energy Management Options

Appliance	Energy Management Controls	
	"High" Price Response	**"Critical" Price Response**
Dishwasher	Delay wash cycle, then turn off heat dry	Same as High Price Response
Clothes Washer	Delay wash cycle, then use Low Energy wash setting	Same as High Price Response
Clothes Dryer	Delay dry cycle, then use Low Energy dry setting	Same as High Price Response
Refrigerator-Freezer	Delay defrost cycle, raise freezer set point by 4°F	Delay defrost cycle, raise freezer set point by 4°F, disable sweat heaters and dim lighting
HPWH	Operate in heat pump only mode and reduce hot water set point temperature to 110°F	Operate in heat pump only mode and reduce hot water set point temperature to 100°F

The dishwasher, washer, and dryer behave the same in High and Critical price periods: delaying the cycle until after the High or Critical price period has ended is the default control. If the user overrides the delay, the appliances will then run in a lower energy mode. The user can override that option as well and run the appliances in any operating mode. The user can override these modes by using the appliance control panel. For the dishwasher, the lower energy cycle is a normal wash cycle but with the heated dry feature turned off. For the clothes washer, a cold wash is used with an extra-high speed spin cycle. The extra-high spin cycle can actually cause an increase in energy over a more typical wash load, but removing more water will reduce the energy consumed by the dryer. The dryer also has a low energy cycle that takes longer and uses more tumbling than hot air.

Unlike the appliances with user-initiated cycles, how to override the controls for the refrigerator and water heaters is not obvious to the user. Several controls are changed for the refrigerator during the High price periods: its defrost cycle is delayed and the freezer temperature set point is raised by 4°F. When a Critical price period starts, the High price controls are implemented, lights are dimmed, and the anti-sweat heaters are disabled. The HPWH restricts its operating mode to Heat Pump only mode when the electricity price falls into Medium, High, or Critical price categories. During the High price periods, the set point is set to 110°F and is lowered to 100°F during Critical price periods.

3 Testing Approach

We conducted a series of tests to evaluate the whole-house peak demand and estimated annual energy saving benefits of the integrated appliance suite. Although GE provided basic information about the different controls that are automatically employed for different pricing signals, we found no documentation that detailed exactly what the controls would do. Simulated utility pricing signals were created to test the appliances on a regular schedule. GE engineers helped make this capability available to us.

Our high-level research questions are:

- Which specific energy management modes are triggered for each appliance that receives a High- or Critical-price signal from the utility? Do any unexpected system interactions result from their responses?
- How does the daily energy use change for each appliance when subjected to peak pricing events? Do the controls for one appliance affect the energy use of any other appliances?
- Does the Nucleus system reliably enable communication between the meter and the appliances, and does it report accurate energy use for each device? The appliances and the Nucleus are all in the same room during the laboratory testing, so there are no obstacles to interrupt communications.

Our appliance-specific research questions are:

Dishwasher:

- If the cycle is delayed, how is the new schedule determined? Can the user change when the delayed cycle will run?
- Does the dishwasher offer any energy-saving features beyond turning off the "heat dry?"

Clothes Washer:

- If the cycle is delayed, how is the new schedule determined?
- How do the "e-mode" settings affect the energy use characteristics of the cycle?

Clothes Dryer:

- If the cycle is delayed, how is the new schedule determined?
- How do the "e-mode" settings affect the energy use characteristics of the cycle? If a lower heat setting is used, how much longer does it take to dry clothes?

Refrigerator-Freezer:

- How much energy use can be avoided during High price periods when defrost is delayed and the freezer set point temperature is raised by 4°F, if implemented for only a short period of time? Does this control just delay energy use or does it reduce energy consumption?

- Similarly, do the controls implemented for Critical pricing save energy or just delay energy consumption?

Heat Pump Water Heater:

- How does the lowered set point affect the energy use characteristics of the water heater?
- Under typical water draw conditions, does lowering the set point during peak hours simply shift the water heating load, or does it offer energy savings?
- If the High/Critical price periods are long (some utilities have high pricing from 10:00 a.m. to 10:00 p.m., for example) the likelihood of large hot water draws during the peak hours increases. How can we quantify the savings achieved associated with longer peak periods?

A standard appliance operation method was used to compare the system's performance under different utility scenarios. The appliances were operated first without any controls imposed (Low electricity cost all day). This process established the baseline energy consumption and cycle characteristics. All the appliances were realistically operated; simulated occupancy was imposed if necessary. The appliance-specific procedures are discussed in detail in the following sections. We then repeated the same procedures and schedules (if applicable) when running the appliances with High and Critical prices imposed for several hours each day.

The test space's temperature was set to 72°F during the day and 68°F at night for the winter months when these tests took place.

3.1 Appliance Baseline Operation

3.1.1 Dishwasher

The baseline load for the dishwasher was the "normal" wash cycle. A baseline test was performed with the Heat Dry setting turned on and another was run with the Heat Dry turned off. For each cycle, a set of eight place settings, including dinner plates, salad plates, bowls, mugs, and silverware, were soiled with tomato sauce and loaded into the dishwasher. The dishes had to be soiled consistently between the different cycles because this dishwasher uses "soil sensing" to determine when the cycle will end.[3] Dishwasher detergent was used with each load (see Figure 7 and Figure 8).

[3] This was a convenient method but is not consistent with the more rigorous soiling procedure specified by the ANSI/AHAM DW–1 standard.

Figure 7. A plate soiled with a teaspoon of tomato sauce

NREL Image Gallery 25542, 25543
Credit: Bethany Sparn

Figure 8. The dishwasher loaded with eight place settings of soiled dishes

3.1.2 Clothes Washer and Dryer

Two baseline cycles were run: one with cold water and another with hot water. Both were set to the "normal load" cycle with the soil setting at "normal" and spin setting on "medium." A standard laundry load was created using 7 lb of white tee shirts, which were weighed before and after the cycle to determine the amount of water in left in the fabric after the cycle (Figure 9 and Figure 10). The size of the load was based on the "large" load defined by 10 CFR 430 Subpart B, Appendix J for the testing of clothes washers (Department of Energy, 2011). The load size was taken from the standard U.S. Department of Energy (DOE) testing procedures, but none of the other test requirements were followed because those test procedures were designed for a different purpose. Detergent was used with every load.

Figure 9. A standard load of laundry is weighed before being washed

NREL Image Gallery 25544, 25545
Credit: Bethany Sparn

Figure 10. The GE Profile clothes washer and dryer with the standard load of tee shirts in the washer

Following the baseline loads for the clothes washer, baseline loads for the dryer were run on the "normal" load setting with the dryness set to "normal dry" and dry sensor set to "dry." The standard laundry load of 7 lb of white tee shirts was dried after the wash cycle completed. As with the clothes washer, the load of laundry was weighed before and after the drying cycle to determine the amount of water removed by the dry cycle. The dryer returned the load of laundry to its original 7 lb after each dryer cycle.

3.1.3 Refrigerator-Freezer

The temperature settings on the refrigerator and freezer were 37°F and 0°F, respectively, per the manufacturer's default. Thermal mass was installed in the refrigerator and freezer in the form of 32 bottles of water (a total of ~4.2 gal of water) and two 10-lb bags of ice, respectively. Provided thermal insulation is adequate and sealing around the gaskets is reliable, the dominant heat load for a refrigerator consists of room-temperature foods and liquids into the cooled compartments. For example, 1 gal of room-temperature[4] water will introduce about 80 Wh of heat to a refrigerator at 37°F. To freeze 0.25 gallon of room-temperature water, 110 Wh need to be removed from the freezer at 0°F. To simulate the heat added to the refrigerator and freezer, a known load was applied on a schedule with the use of a 60-W string of incandescent lights placed inside the refrigerator and freezer compartments and operated on a timer switch (Figure 11 and Figure 12):

- Refrigerator lights on 8:00 a.m. to 8:30 a.m. and 6:00 p.m. to 7:00 p.m.
- Freezer lights on 10:00 p.m. to 10:30 p.m.

The load schedule for the refrigerator is equivalent to putting 0.375 gal of water in the refrigerator in the morning and 0.75 gal in the evening. The simulated load for the freezer is proportional to the heat removed when freezing a cup of water (0.063 gal). The daily refrigerator energy use profile shown in the Building America House Simulation Protocol (HSP) is mostly flat with a small bump in the morning and a slightly larger bump in the evening (Hendron & Engebrecht, 2010). The light schedule used to simulate daily loads is based on this HSP profile.

[4] Room temperature is defined as 71°F per the HSP (Hendron & Engebrecht, 2010).

Figure 11. GE Profile side-by-side refrigerator and freezer

NREL Image Gallery 25546, 25547
Credit: Bethany Sparn

Figure 12. The inside of the refrigerator and freezer including the thermal mass (water bottles and ice) and incandescent light strings uses to simulate load

3.1.4 Heat Pump Water Heater

The water heater temperature set point is 120°F, per Building America HSP. A solenoid valve actuated by the data acquisition system conducted automated water draws based on the HSP standard for hot water draws. A total of approximately 65 gal/day was broken up into 24 draw events with an overall draw profile consistent with the HSP; large-volume draws are clustered around the morning and evening hours (see Figure 13). While the draw profile was running, no other appliances were drawing hot water.

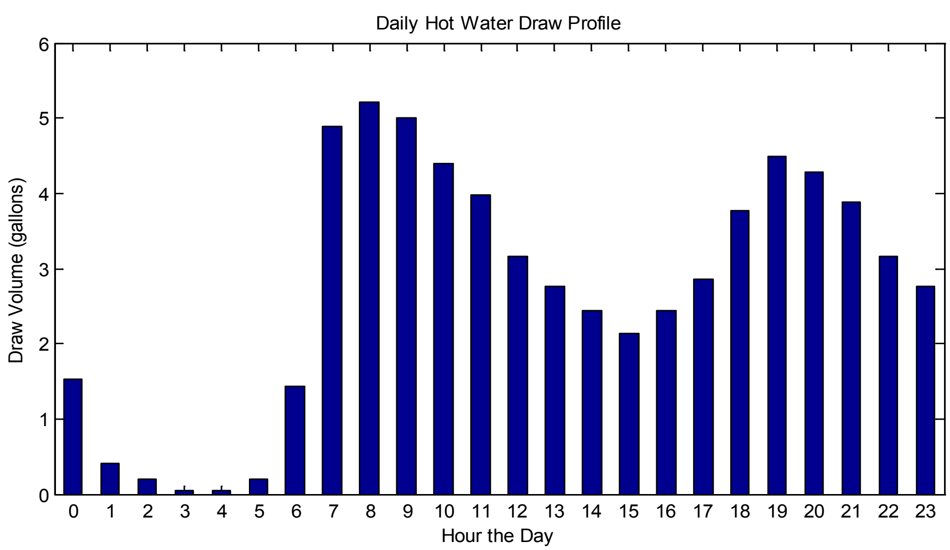


Figure 13. Hourly hot water draw profile used to simulate daily use of the HPWH

3.2 Operation With High and Critical Controls

Once the baseline measurements were completed, a pricing schedule was implemented in the Nucleus home manager that imposed load-shifting controls during peak hours. The hours used for peak pricing vary significantly between utilities around the country (see Table 6), so we chose 2:00 p.m. to 8:00 p.m. as our High price hours to be conservative. Many utilities have longer peak price times, but they typically include the 2:00 p.m. to 8:00 p.m. period. The longer the peak hours, the greater the energy savings, so shorter peak hours were chosen so that our results would indicate a lower limit on achievable savings.

To test the High price controls, the High price period was set to occur during the 2:00 p.m. to 8:00 p.m. period. All other times, the appliances were allowed to behave per their Low price settings. Similarly, during the Critical price testing, the 2:00 p.m. to 8:00 p.m. period was set to Critical pricing. A price schedule for the High and Critical price tests is shown in Figure 14.

Hour of Day

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
High:	Low														High						Low			
Critical:	Low														Critical						Low			

Figure 14. The pricing schedule used for the High and Critical price tests

The appliances were allowed to be used "normally" (from the occupant's perspective) in the peak hours, and automatic changes in cycle behavior caused by the pricing signals were recorded. This schedule was primarily needed for the appliances that run continuously during the day: the refrigerator and the HPWH. The other appliances were run during the peak hours to test their response to the different price signals. The refrigerator and HPWH were run in each scenario (baseline, High price and Critical price) for 6 or 7 days continuously to ensure that normal fluctuations were captured. The different cycles for the dishwasher, washer, and dryer were also repeated at least three times. The repeated cycles or days of testing ensure that our results are representative of normal operation. This test procedure was designed to answer the appliance-specific research questions found in Section 3.

3.3 Data Acquisition

For most of the appliances, gathering power consumption data was the most important measurement. Power consumption profiles of individual appliances were individually monitored. The power consumption (and a variety of the other related parameters) for each circuit are monitored using a Dent PowerScout 18 Power Meter, which has the capacity to monitor up to 18 individual circuits with current transformers and voltage taps. The PowerScout measures real, apparent, and reactive power and energy, but for the data shown in this report it is all real power. The accuracy of the power measurement is better than ± 1% per the manufacturer specifications (Dent Instruments, 2010). Power measurements were collected every 10 s.

In addition to power consumption, water temperature was measured at the water heater inlet and outlet as well as in water supply lines at the sink and dishwasher. All temperature measurements were taken with T-type thermocouples with an accuracy of ± 0.5°C, per manufacturer specifications. Flow rate was measured at the same places that temperature was measured, using an in-line turbine flow meter with an accuracy of ± 1.5% of reading. The data acquisition system also controlled the solenoid valve used to implement the hourly draw profile for the HPWH.

4 Results[5]

The energy consumption results reported for each appliance was measured using the Dent Powerscout, a true RMS power and energy meter produced by Dent Instruments. The systematic error per the manufacturer's specifications is +/-1% of the measurement. Where appliance cycles were repeated we found that any uncertainty due to instrument systematics was negligible compared to the variability in energy use between repeated cycles.

4.1 Dishwasher

Two baseline cycles were run for the dishwasher: One with heat dry turned on and another with it turned off. The default control imposed during the peak price period is to delay the cycle until the price drops. No specific time delay is imposed; the dishwasher waits until the price signal coming from the Nucleus changes to Low or Medium and then runs the cycle that was selected earlier. The user can also manually delay a wash cycle by up to 24 h. The energy consumption of the different cycles is summarized in Table 2; the uncertainty is based on the standard deviation between repeated cycles. This small variability can be attributed to power meter measurement accuracy as well as slight power consumption variations between multiple cycles.

Table 2. Energy Use Summary for Dishwasher

Cycle	Cycle Energy Use (kWh)
Baseline: No Heat Dry	0.46 ± 0.01
Baseline: Heat Dry	0.67 ± 0.01
High/Critical	0.46 ± 0.01

If the user rejects the first option to delay the cycle, the cycle will run with the heat dry turned off. (The user can also override this and run a wash cycle with the heat dry option.) Avoiding the heat dry portion of the cycle reduced energy consumption by approximately 200 Wh per cycle, or about 30%. There is no difference between a cycle where the user manually turned off the heat dry feature and a cycle where the high electricity prices automatically turned off the heat dry. This was expected and verifies that the peak pricing controls turn off only the heat dry feature (see top versus bottom graph, Figure 15).

[5] When relevant to the DR controls, we consulted with GE engineers to decipher what the appliances are doing based on their power consumption traces. We will not delve into the details of each appliance's operation.

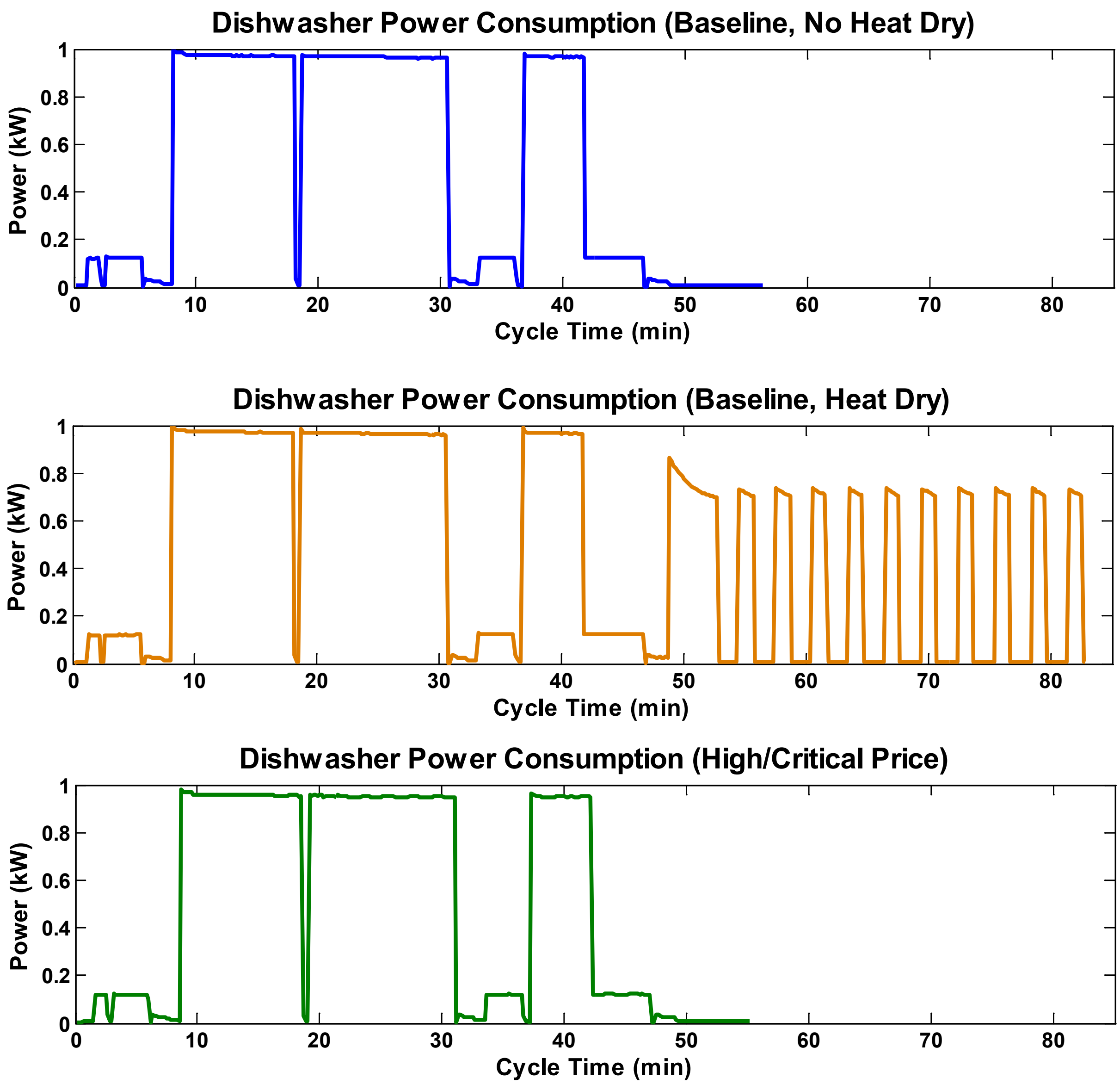


Figure 15. Comparison of dishwasher power consumption

4.2 Clothes Washer and Dryer

The clothes washer and dryer are separate appliances, but the energy use of the washer affects the dryer. If the washer uses more energy to spin the wet clothes faster and longer, less water needs to be removed by the dryer. A single communication module was used for the two appliances. For these reasons, we will discuss the results from washer and dryer together.

Two baseline cycles were performed with the washer and dryer: one with a cold wash cycle and another with a hot wash cycle. The energy use of the washer for the two cycles was nearly identical, but the additional energy used by the water heater to provide the hot water made the hot baseline cycle more energy intensive. In order to measure the water heating energy associated with the hot cycle, three back-to-back cycles were run. That was the number of cycles necessary to trigger the water heater to reheat the tank, after starting from a fully heated tank.

The total energy used by the HPWH to reheat the tank, divided by 3, gave us the hot water energy consumed by a single hot wash cycle: 0.24 kWh. Starting with a load of laundry weighing 7.0 lb, after going through a wash cycle with medium spin speed, the wet load weighed 11.3 lb for both the cold and hot cycles. The dryer cycles that followed the cold and hot baseline washer cycles were also nearly identical, as expected. After the dryer cycle, the load returned to 7.0 lb.

When the electricity price reaches the High or Critical level, both the washer and dryer automatically delay the cycles. As with the dishwasher, the washer and dryer will delay their cycles for as long as the Nucleus sends them a High or Critical price signal. However, the user can override that default and then will be presented with the option to run the washer in the "e-Wash" mode and run the dryer in the "e-Dry" mode. (The user still has the option to override the e-Wash and e-Dry modes and wash or dry as usual.) The e-Wash mode is a cold water cycle that uses the extra-high spin speed. The extra-high spin speed removed more water from the clothes, with the load weighing 10.8 lb after the e-Wash cycle. The e-Wash mode actually increases the energy used per wash cycle compared to the baseline cold water load because of the extra-high spin speed. However, more water is removed from the clothes and the e-Dry mode is more energy efficient, so the net energy used by the washer and dryer together is reduced by the controls imposed by the higher electricity prices, as shown in Table 3. The washer cycles were repeated and the energy use was found to be very consistent between cycles. The standard deviation is small relative to the level of precision of the measurements.

Table 3. Energy Use Summary for Washer and Dryer Cycles

Cycle	Washer Energy Use (kWh)	Hot Water Energy Use (kWh)	Dryer Energy Use (kWh)	Total Cycle (kWh)
Baseline: Hot Wash + Dry	0.20	0.24	2.72 ± 0.05	3.19
Baseline: Cold Wash + Dry	0.21	0	2.72 ± 0.05	2.96
High/Critical: e-Wash + e-Dry	0.26	0	1.84 ± 0.05	2.29

The power use profile of the e-Dry cycle looks very different than the standard dryer cycle. The cycle appears to spend the first 20 min of the cycle tumbling the clothes, followed by about 45 min of tumbling with bursts of hot air. This cycle takes about 30 min longer than the standard cycle but it reduces the cycle energy use by 32%. The baseline dryer cycles were repeated and the standard deviation is reported. We have only a single measurement for the e-Dry cycle, but we estimate that the level of uncertainty is similar to that for the baseline cycles.

Note that the e-Wash and e-Dry modes are available to users at all times, not just when electricity is high. Using a higher washer spin speed along with the e-Dry mode takes an hour longer than a standard load, but reduces the energy required to complete the laundry load (see Figure 16 and Figure 17).

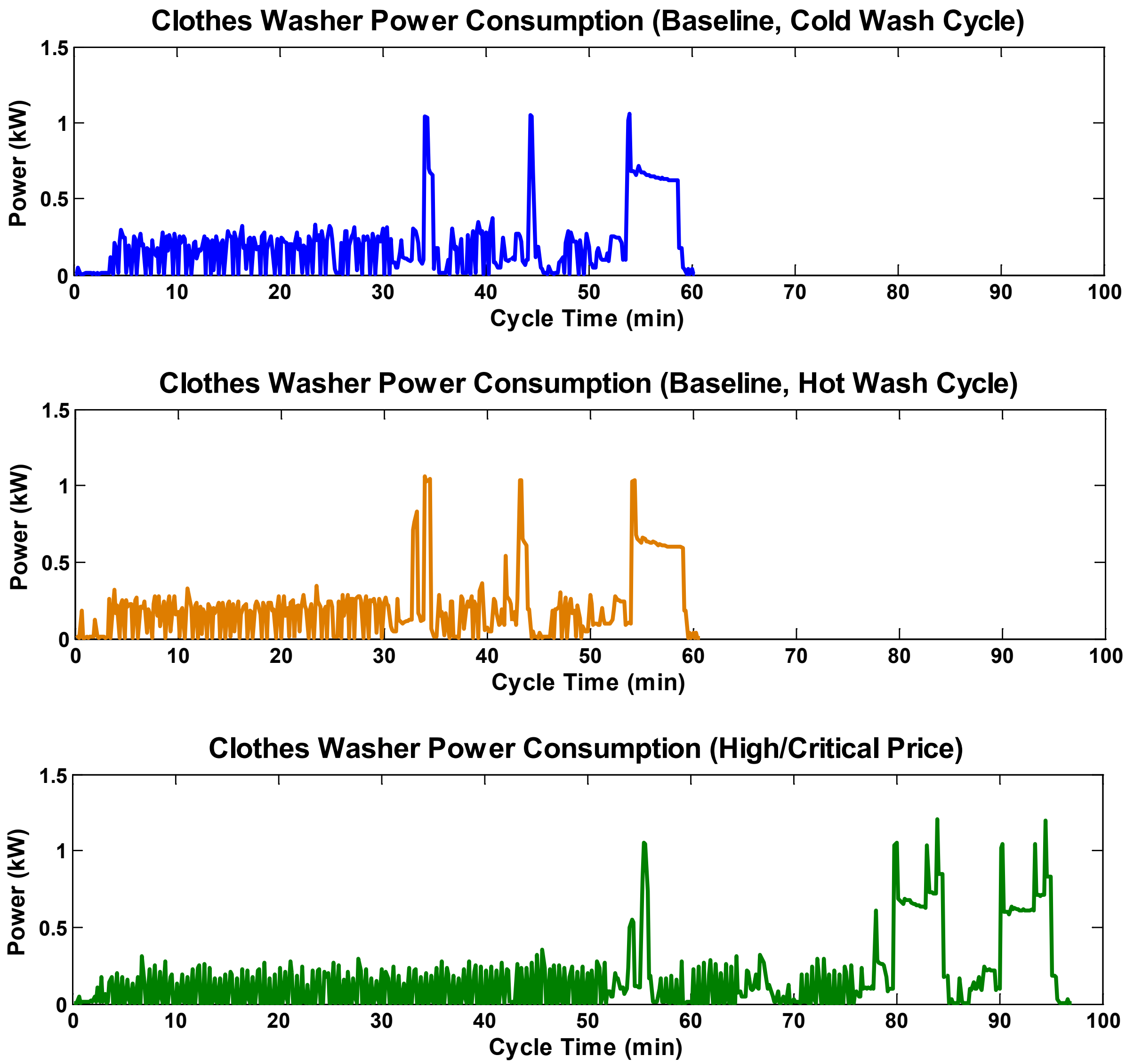


Figure 16. Comparison of clothes washer power consumption

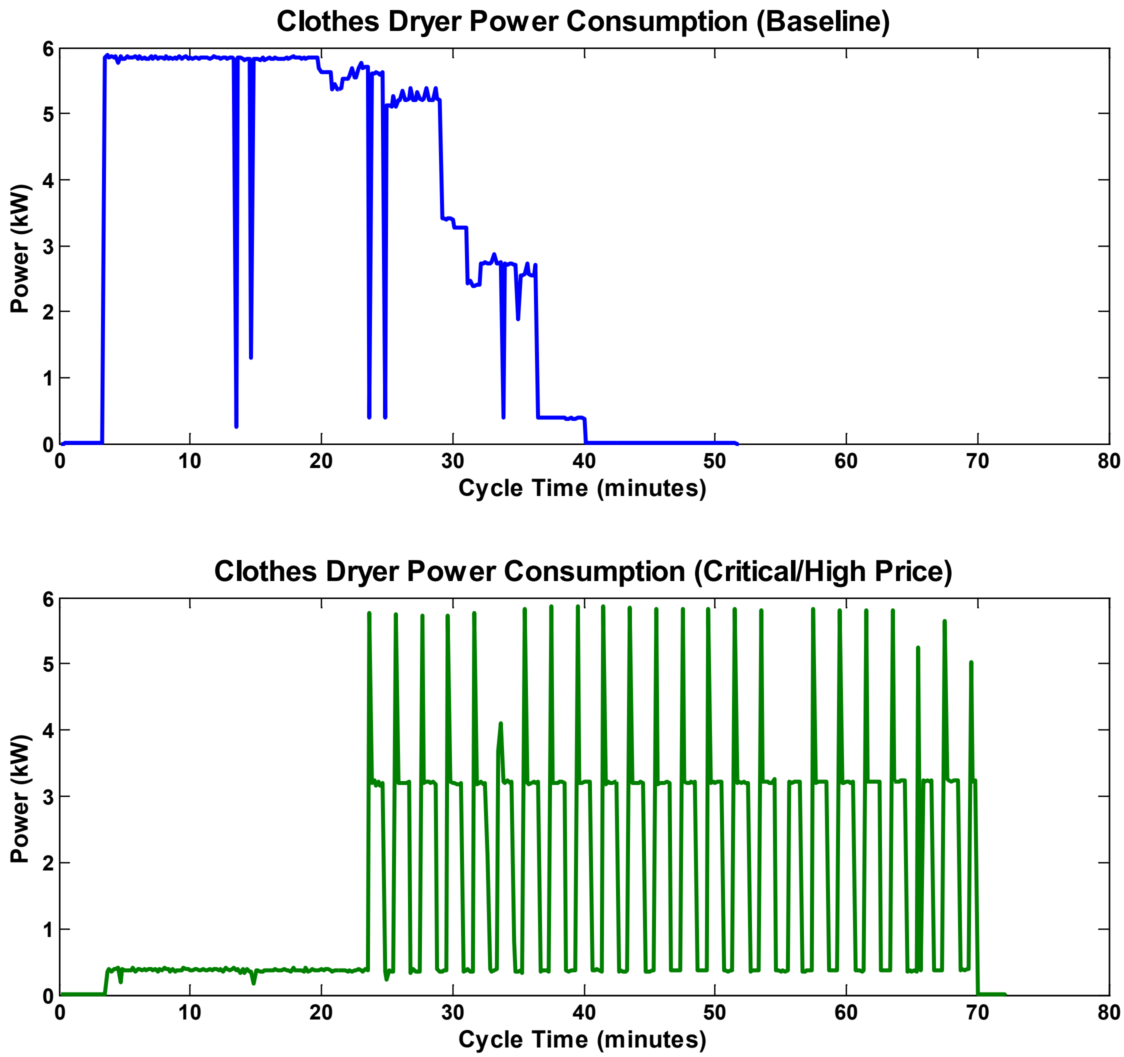


Figure 17. Comparison of clothes dryer power consumption

4.3 Refrigerator-Freezer

To simulate typical use of the refrigerator and freezer, water bottles and bags of ice were stored as thermal mass in the refrigerator and freezer, respectively. A 60-W string of incandescent lights was also distributed throughout the refrigerator and freezer and was turned on a twice a day for the refrigerator and once for the freezer to simulate the additional load imposed when room temperature items are added to the refrigerator and freezer.

The High and Critical price period signals sent by the Nucleus imposed energy-reducing controls on the refrigerator and freezer between 2:00 p.m. and 8:00 p.m. The regular cooling cycles continued during the peak price period but appear to be somewhat delayed and abbreviated (probably because the set point of the freezer was higher). Based on our simulated use of the refrigerator, the defrost cycle was observed only every 3 or 4 days, but it may operate more often in an actual home with larger latent loads. Because the defrost cycle was so infrequent, it was not affected by the High and Critical price period controls. Since the defrost cycle was so infrequent, it was not affected by the High and Critical price period controls. The data shown in Table 4 includes several days of data for each price structure, but in all cases the defrost cycle turned on during one day, which is why the uncertainty for the daily energy use is relatively high compared to the other appliances. The defrost heater never came on during peak hours, so the variation in energy use during that time is smaller.

The DR controls for the refrigerator-freezer do not make a significant impact on total energy use, but they do help with peak load reduction. The High price controls reduce the peak energy consumption by 16% and the Critical price controls reduce peak load by 22% (see Table 4 and Figure 18).

Table 4. Energy Use Summary for Refrigerator

	Daily Energy Use (kWh)	Peak Energy Use (kWh)
Baseline	1.20 ± 0.12	0.32 ± 0.01
High Price	1.21 ± 0.10	0.27 ± 0.05
Critical Price	1.18 ± 0.16	0.24 ± 0.02

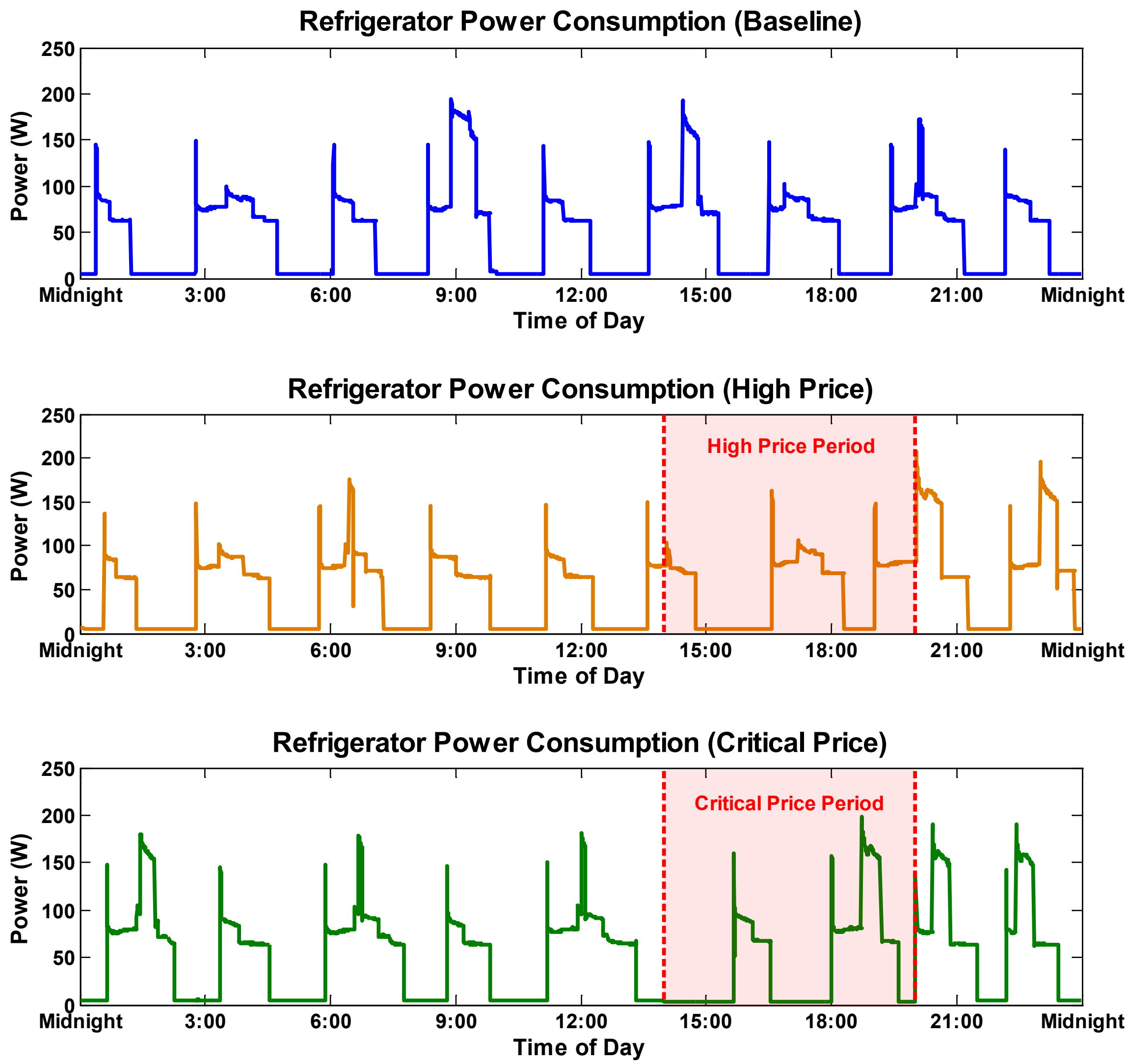


Figure 18. Comparison of refrigerator power consumption

4.4 Heat Pump Water Heater

To test the water heater, a 24-h draw profile was employed to simulate hot water draws over the course of an entire day. The baseline test was performed with the set point at 120°F in Hybrid Mode, which uses the heat pump primarily, but can also revert to the electric resistance elements if necessary. The tests of the High and Critical price periods imposed lower set points, but only during the higher price period of 2:00 p.m. to 8:00 p.m.

The lower set points were applied for only a short period of time, so the controls effectively imposed a heating delay rather than lowering the daily energy consumption. There was a small reduction in daily energy use, as shown in Table 5, but peak shifting was a larger effect. During the peak period, any call for hot water would be at a reduced set point. As soon as the peak period was over, the heat pump would bring the whole tank back up to 120°F. If the peak period were much longer or more hot water were used during this period, the reduced set point might lead to significant energy savings, but that was not observed during these tests. Once in the Low price period, nothing prevents the backup electric resistance heaters from turning on, but that did not happen during our tests. If that were to happen, it could greatly increase the daily hot water energy use.

Each price schedule was repeated for at least six days and the variation in the daily energy use and the energy use during the peak period are reported in Table 5. Similarly, the standard deviation for the daily draw volume is given.

Table 5. Energy Use Summary for HPWH

	Daily Energy Use (kWh)	Peak Energy Use (kWh)	Daily Draw Volume (gal)
Baseline	3.58 ± 0.31	1.08 ± 0.14	65.9 ± 0.2
High Price	3.12 ± 0.33	0.30 ± 0.31	66.8 ± 0.4
Critical Price	3.21 ± 0.20	0.03 ± 0.02	67.7 ± 2.0

During the peak period for High and Critical pricing, the set point was reduced so the outlet temperature also decreased. The minimum mixed temperature per the HSP is 110°F. During the five days that the Baseline schedule was employed, the outlet temperature dipped below 110°F briefly, totaling less than 0.5 gal. The minimum outlet temperature was observed to be 105°F. When the High price period was imposed for five days, slightly more water was delivered below the 110°F threshold, 1.8 gal, with a minimum temperature of 105°F. That volume accounts for less than 0.5% of the hot water delivered during the High price test. When the peak period price was increased to the Critical price, more water was delivered below the required mixed temperature: 54.5 gal, accounting for 13.3% of the hot water volume delivered. However, the minimum temperature dipped to 102°F, which does not meet Building America's comfort standards, but may not have a large impact in a real house. All the draws that did not meet the 110°F requirement occurred late in the evening, 8:00 p.m. to 9:00 p.m., when the hot water is typically going to sinks or the dishwasher. Also, the hourly draw profile imposed the full 8:00 p.m. draw at the top of the hour, right when the heat pump turned back on. If the draws were spread out over the hour, as might be more realistic, the output temperature would have been higher as the heat pump would have had more time to recover (see Figure 19.

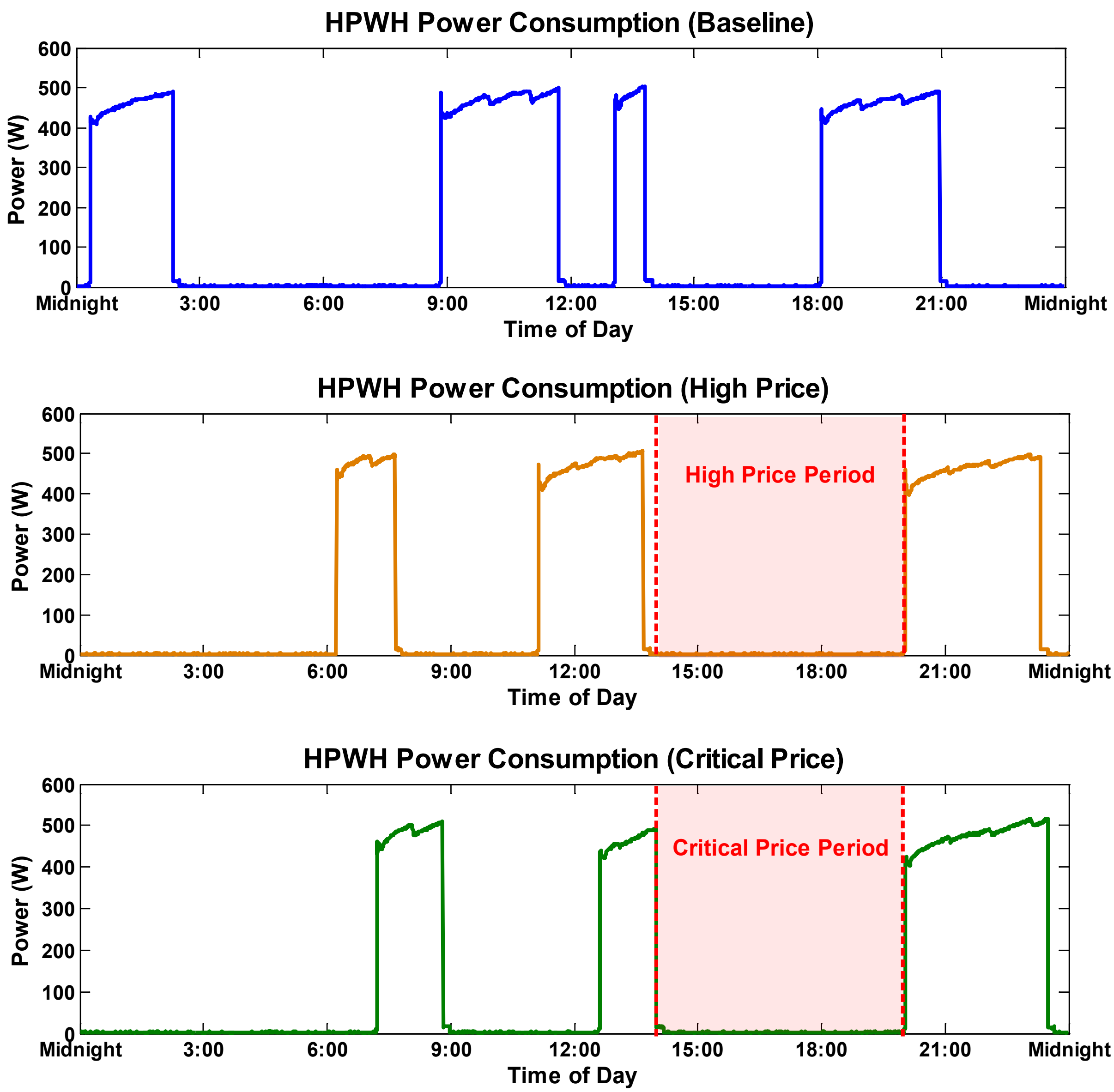


Figure 19. Comparison of HPWH power consumption

4.5 Nucleus Energy Management System

We simulated utility peak events by sending artificial electricity rates to the Nucleus energy management system, which then sent the pricing signals to the appliances.

The energy management software also collected estimated power consumption data from each appliance. These data were compared to the power data collected by the PowerScout power meter. Power consumption for the appliances as reported to the Nucleus energy management system followed the same trend as the power data collected at the circuit breaker level. However, it is intended to be used by homeowners to increase their energy use awareness. The power consumption data measured by the Nucleus system tended to be off by about 10% relative to the circuit breaker power meters. The Nucleus system is geared toward providing home occupants with near-real time estimates and is not designed to be a highly accurate measurement system. It is successful at its intended purpose, but it should not be considered as a substitute for research-grade monitoring equipment.

5 Cost-Effectiveness Discussion

The primary objective of this technology is to facilitate effective DSM by helping people use less electricity during periods of high demand, and thus save money. Large-scale rollouts of AMI meters are enabling more utilities to implement TOU pricing. If appliances can automatically adjust their electricity consumption during the High price periods, consumers will save money on their utility bills, even if the result is simply peak shifting and not a reduction in total energy use over the full day.

The amount of money that consumers can save is highly dependent on the TOU schedule and rates. Most utilities have started offering TOU pricing as an optional rate structure for people with an AMI meter installed, but the rate schedules that have been implemented vary widely. Table 6 shows the current residential TOU summer schedules for the nine largest utilities that offer a two-tiered TOU schedule. The peak hours tend to cover the entire evening but the time that the peak period begins varies by up to 7 h. There is also great diversity in the on-peak and off-peak rates, which will have a large impact on the cost to the consumer. The rates shown here represent only the time-dependent portion of the rate paid by the consumer. All the utilities charge some sort of flat monthly fee; at least one, Duke Energy, also charges a monthly fee that is tied to the peak power consumption of the household. The analysis presented here focuses only on how appliance controls tied to time-based rates can affect the customer bills.

Table 6. Residential TOU Schedules for Some Large Utilities Around the Country

Utility	Service Area	Summer On-Peak Time (Weekdays Only)	Electricity Rates ($/kWh)	
			On-Peak	Off-Peak
Florida Power & Light[6]	Florida	12:00 p.m. – 9:00 p.m.	0.0843	(0.0375)
Consolidated Edison[7]	New York City	10:00 a.m. – 10:00 p.m.	0.3027	0.0116
Georgia Power Co.[8]	Georgia	2:00 p.m. – 7:00 p.m.	0.2032	0.0459
Detroit Edison[9]	Detroit	11:00 a.m. – 7:00 p.m.	0.1236	0.0416
Public Service Electric & Gas[10]	New Jersey	7:00 a.m. – 9:00 p.m.	0.2443	0.1184
Duke Energy Corp[11]	IN, OH, KY, NC, SC, FL	1:00 p.m. – 7:00 p.m.	0.0673	0.0563
Consumer Energy Co[12]	Michigan	11:00 a.m. – 7:00 p.m.	0.1070	0.0769
AEP Columbus Southern[13]	Ohio	1:00 p.m. – 7:00 p.m.	0.2734	0.0313
Alabama Power[14]	Alabama	1:00 p.m. – 7:00 p.m.	0.2500	0.0500

It is unclear if these rates and schedules will remain the same if and when TOU rates change from being optional to being mandatory.

[6] www.fpl.com/rates/pdf/electric_tariff_section8.pdf. Accessed August 15, 2013.
[7] www.coned.com/documents/elecPSC10/SCs.pdf. Accessed August 15, 2013.
[8] www.georgiapower.com/pricing/files/rates-and-schedules/2.20_tou-reo-7.pdf. Accessed August 15, 2013.
[9] www2.dteenergy.com/wps/portal/dte/residential/billingPayment/details/Rate%20Selector. Accessed August 15, 2013.
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[14] www.alabamapower.com/residential/pricing-rates/pdf/RTA_Energy.pdf. Accessed August 15, 2013.

To illustrate the achievable cost savings, the appliance-specific results are combined with the TOU schedules from Duke Energy and Alabama Power. These utilities have a 6-h peak period, similar to what we used, but the on-peak and off-peak prices vary widely. Duke Energy has electricity rates that are both low and only about $0.01/kWh apart, whereas Alabama Power has a much higher peak price that is five times the cost of the off-peak rate. As with other utilities, the actual cost to consumers includes the electricity rate and other fees. Duke Energy charges a flat monthly fee and a peak power fee that is tied to the on-peak power demand; Alabama Power charges a flat monthly rate. For this exercise, we focused on the energy costs related to the TOU rates; however, we acknowledge that the base rates for the two utilities are different and difficult to compare because they are structured differently.

Table 7 and Table 8 take the energy consumption results from our laboratory testing and apply the TOU pricing schedules from Duke Energy and Alabama Power to show a range of cost savings that are possible when participating in TOU rate programs. Table 7 includes the results for the refrigerator and HPWH, the two appliances that run constantly. The first two columns of data, the daily average energy use and the average energy use during the peak hours, are taken from the laboratory results. The average energy use during peak refers to the energy used during our simulated peak period of 2:00 p.m. to 8:00 p.m. Energy used during the peak hours is charged the peak energy rate for both utilities; the remaining energy used each day is charged to the off-peak rate. The daily cost for Duke Energy and Alabama Power is calculated in this fashion. These TOU rate schedules are applied during summer months only, June 1 to September 30, and only on weekdays, which comes to 86 days for the 2013 calendar year. The summer cost is calculated by multiplying the daily cost by 86 days.

Table 7. TOU Price Comparison for Refrigerator and HPWH

		Daily Average (kWh)	Average During Peak (kWh)	Duke Energy TOU Schedule		Alabama Power TOU Schedule	
				Daily Cost ($)	Summer Cost[15] ($)	Daily Cost ($)	Summer Cost[15] ($)
Refrigerator-Freezer	Baseline	1.20	0.32	0.071	6.11	0.124	10.66
	High	1.21	0.27	0.071	6.11	0.115	9.89
	Critical	1.18	0.24	0.069	5.93	0.107	9.20
HPWH	Baseline	3.58	1.08	0.213	18.32	0.395	33.97
	High	3.12	0.30	0.179	15.39	0.216	18.58
	Critical	3.21	0.03	0.181	15.57	0.167	14.36

[15] TOU schedule applies from June 1 to September 30 and on weekdays only. The daily cost was multiplied by 86 days to get the cost for the whole summer.

Table 8. TOU Price Comparison for Dishwasher and Clothes Washer and Dryer

			Duke Energy TOU Schedule				Alabama Power TOU Schedule			
			Peak Cost ($)		Delayed Cost ($)		Peak Cost ($)		Delayed Cost ($)	
		Cycle (kWh)	Cycle	Summer[16]	Cycle	Summer[16]	Cycle	Summer[16]	Cycle	Summer[16]
Dishwasher	Baseline: Heat Dry	0.68	0.046	**3.96**	0.038	3.27	0.170	**14.62**	0.034	2.92
Dishwasher	No Heat Dry	0.46	0.031	2.67	0.026	**2.24**	0.115	9.89	0.023	**1.98**
Washer/ Dryer	Baseline: Hot + Dry	3.20	0.215	**18.49**	0.180	15.48	0.800	**68.80**	0.16	13.76
Washer/ Dryer	Baseline: Cold + Dry	2.95	0.199	17.11	0.166	14.28	0.738	63.47	0.148	12.73
Washer/ Dryer	e-Wash + e-Dry	2.28	0.153	13.16	0.128	**11.01**	0.570	49.02	0.114	**9.80**

There are a number of results in Table 7 to point out. The Duke Energy TOU schedule has lower electricity rates, without a large difference between on-peak and off-peak prices. As a result, the cost savings are much lower when the appliances are asked to conserve energy during peak hours. For instance, the HPWH is able to basically avoid heating during the peak period when operating under the Critical price controls, but that does not translate into significant savings. The HPWH operating as usual in the Baseline schedule costs $18.32 for the entire summer, compared to $15.57 for the summer if the Critical controls are imposed during peak hours. In contrast, the drastic difference in on-peak and off-peak costs for Alabama Power leads to larger potential for savings and a stronger incentive to shift energy use out of the peak period. The same HPWH responding to Critical price controls during peak hours costs $14.36 for the summer under Alabama Power's TOU schedule, a large savings relative to the baseline case that cost $33.97 without the peak-shifting controls.

In general, the refrigerator uses less energy per day than the HPWH and it cannot shift its energy use out of the peak period entirely so the price-based controls have a smaller effect on energy use and cost to the consumers. As a result, the refrigerator is probably not a cost-effective DR-enabled appliance. The refrigerator is relatively energy efficient and would thus be hard to improve.

Table 8 is a similar comparison of how different TOU rates affect the cost to operate the dishwasher, washer, and dryer. These appliances are not continuously run, so there are more options for how they can be operated relative to the peak period. The cycle energy shown in the first column comes from the laboratory testing. There is a baseline cycle (or in the case of the washer/dryer combo – two baseline cycles) and a low energy cycle. The user could run the baseline cycle during peak, which would typically be the most expensive option, or to delay the baseline cycle so that it would run during off-peak hours. The user could also choose the lower energy cycle during peak hours or delay the lower energy cycle until off-peak hours. There is a

[16] Summer cost determined by assuming 1 cycle per day for 86 days. The TOU schedules shown here apply between June 1 and September 30, on weekdays only.

cost to run each cycle during peak hours (Peak Cost) and off-peak hours (Delayed Cost). The most expensive and least expensive cycle options are bolded for each appliance and each utility, as those values will be used to calculate the maximum potential cost savings.

Similar to the results for the refrigerator and HPWH, the TOU rate schedules change the magnitude of savings that are possible with the dishwasher and the washer and dryer. The TOU rates may also affect the decisions a user would make during peak hours. For example, if a Duke Energy customer were deciding how to operate a dishwasher, the cost difference between delaying the cycle until off-peak hours and running the lower energy cycle during peak favors running the lower energy cycle during peak. There is little difference in cost, but it is slightly cheaper to run the "No Heat Dry" cycle during peak. However, the same situation with Alabama Power's rates would heavily favor delaying the cycle until off-peak. The greatest savings that can be achieved with any TOU schedule is to do both: select the low energy cycle and delay the cycle until after the peak period.

The cost to operate the dishwasher, washer, and dryer over a full summer depends on how often people use them. The Building America HSP assumes one cycle per day for the dishwasher, clothes washer, and dryer (Hendron & Engebrecht, 2010), so that was used to extrapolate the per-cycle costs to summer-long costs to run the dishwasher, washer, and dryer. As with the analysis for the refrigerator and HPWH, the TOU price is applied to 86 days for the summer. Assuming that people run their dishwasher and washer and dryer every weekday during the summer may overestimate how often those appliances are run, but it can be used to establish an upper bound for the savings that could be achieved. As previously stated, the maximum cost savings occurs when the user shifts from running the most energy-intensive cycle during peak to the low energy cycle during off-peak hours. The costs for those options are bolded in Table 8, with the maximum cost corresponding to running the baseline cycle during peak hours and minimum cost occurring when the lower energy cycle is delayed to off-peak hours.

Combining the results from all the appliances evaluated during this study, the maximum summer savings that could be achieved by a person using this suite of appliances living in the Duke Energy territory is $12.31 compared to a maximum of $92.71 for someone in the Alabama Power jurisdiction. The cheapest options for the two utilities are nearly identical: $34.57 for Duke Energy and $35.34 for Alabama Power. To assess whether these products can be cost effective, we considered the costs of the Brillion products only, a total of $530 for the Nucleus and four communication modules. With the Alabama Power TOU rates and a maximum savings of about $90 per summer, it would take about 6 years to recoup the cost of the Brillion products. This does not include the cost to buy new appliances or any other additional costs for installation. Even without considering those costs, this may be a little longer than most consumers are willing to wait, but the payback period could be shortened if the cost of electricity rose further. In contrast, the simple payback period using the maximum savings that can be achieved using Duke Energy rates is 44 years. This is much too long to be a cost-effective solution for homeowners.

Many factors, including the number of people in a household, appliance use patterns, and TOU schedule, can affect the potential cost savings associated with DR appliances. If all that was known about a home is that its service provider has the infrastructure in place to enable the appliance controls described here, it would be difficult to determine if the Brillion system would be a cost-effective solution. While it is no guarantee for cost effectiveness, a household that is flexible with its appliance use and subject to a TOU schedule with significantly higher on-peak prices will derive the most benefit out of DR-enabled appliances.

One potentially negative consequence with these particular control strategies is that a peak is created later in the day, as all the home's appliances turn back on after the official peak period is over. The HPWH, dishwasher, washer, and dryer all are controlled to delay operation until the price drops back to off-peak levels, which could create a smaller, later peak. The main driver for peak loads, air conditioners, would still peak late in the afternoon as people return to hot homes, but simply delaying the operation of the other major appliances may not be the best solution. Appliance manufacturers may be able to build in more sophisticated controls that would allow their appliances to stagger their operation to avoid the late peak.

6 Conclusions

This project was intended to evaluate a new technology and answer a broad range of questions. The main questions that we wanted to answer with these laboratory tests were: What do the appliances do in response to different price signals? and Do DR controls save energy or just shift energy out of the peak period? Beyond those most basic questions, there are numerous questions about potential cost savings when used with TOU pricing, cost effectiveness, and how all these results will vary with different users. Key findings are summarized below:

1. **Not all appliances are suited to DR controls.** Refrigerators are a good example of this: a refrigerator cannot completely shift its load to off-peak hours and newer refrigerators are already very energy efficient. As a result, potential cost savings are very low, regardless of the TOU rates imposed.
2. **The utility's TOU schedule and rates will have a large impact on the cost effectiveness of DR appliance technology and how willing people will be to participate.** TOU rates are supposed to reflect the actual cost of electricity and encourage people to use electricity when it is cheaper. If the financial incentive is very small, people will likely be less motivated to change their behavior or buy appliances that can help manage their energy use automatically.
3. **Even with a TOU rate schedule with very high on-peak prices and very low off-peak prices, the cost effectiveness of the GE DR appliances varies.** Currently, the GE appliances with DR capabilities are high-end and expensive. If you consider the cost of the Brillion products only, a total of $530 for the Nucleus and four communication modules, cost effectiveness becomes more attainable. The results combined with Alabama Power TOU rates projects maximum savings of about $90 per summer, meaning that it would take about 6 years to recoup the cost of the Brillion products. In contrast, the smaller summer savings for Duke Energy, around $12, leads to a simple payback period of more than 44 years.
4. **Generally, the DR controls can be replicated manually without expensive communication hardware.** The settings for the dishwasher and washer and dryer that produced the largest savings are always available, as is the ability to delay cycles. It is less convenient to change the set point for the HPWH for a few hours during the day, but it can be done. The only appliance that employed controls that are not accessible to the consumer is the refrigerator, and those controls did not have a large impact on peak energy load. Consumers are really paying for convenience with the DR products, as they would not have to keep track of their rate schedule and actively reduce consumption during peak hours.
5. **Despite enthusiasm for smart grid projects and TOU pricing, full implementation is still years away.** GE and other appliance manufacturers began to develop DR-enabled appliances in response to the Energy Policy Act of 2005 (U.S. Demand Response Coordinating Committee, 2008). For DR appliances to be functional, they need to receive price signals from a smart meter. Not all smart meters have a Zigbee radio installed that is needed to communicate with anything in the house, including the appliances. Smart meter rollout projects also have been delayed for a variety of reasons, including high costs and poor public reception. Utilities still plan to move their customers over to

mandatory TOU rates, but they all must have AMI meters before then. Until all these pieces fall into place, homes have AMI meters with Zigbee radios (or other consumer-facing communication) and TOU rates are mandatory, consumers will have little incentive to invest in DR-enabled appliances.

The results in this report demonstrate that the energy and cost savings achievable with this set of GE appliances can vary significantly depending on the utility's TOU schedule. The time and duration of the peak period and the rates imposed during on-peak and off-peak hours affect the results for whether the appliance control system is cost effective. There are still questions regarding how the length of the on-peak period will affect daily energy use and thus cost savings. Some utilities are employing very long peak periods, some twice as long as the 6-h period that was tested here, and that could affect the conclusions for the refrigerator and HPWH.

Other appliance manufacturers are working on similar suites of DR-enabled appliances, which will certainly employ different control strategies to reduce energy consumption during peak hours. Those appliances would need to be tested in a similar manner to know if the results seen with the GE appliances can be applied to other brands. For the time being, it appears that smart appliance technology has developed ahead of the change in the utility market that it was intended to address. Utilities are definitely moving toward required TOU rates, but more cautiously than initially anticipated. As a result, other appliance manufacturers may hold off production of similar DR-enabled appliances.

This type of technology could also be applied to the management of on-site renewable energy and energy storage devices. Plug-in electric vehicles represent a large load that has the potential to compound peak load issues if people come home from work and plug in their cars at the same time that air conditioners are working their hardest (Taylor, Maitra, Alexander, Brooks, & Duvall, 2009). A simple management system could ensure that charging does not begin until the peak period has ended. A more sophisticated control system could allow the electric vehicle to charge during peak as long as the home's photovoltaic system was supplying that energy.

6.1 Future Work

Once the market/utility structure is better positioned to support DR-enabled appliances, further research is needed to investigate the cost and performance characteristics of this technology. Following are topics that would be worth exploring:

The duration of the peak period imposed by the TOU schedule has the largest effect on the HPWH and refrigerator. A number of optional TOU schedules have very long peak periods, up to 12 h. The longer the peak period, the greater the energy savings for the HPWH, because the standby losses are reduced. However, occupants may be unhappy with their hot water set to only 100°F for long periods of the day. Would there be any effect on the performance of the refrigerator with a longer peak period, both in terms of energy savings and comfort? Would a longer TOU period make the refrigerator a better candidate for DR controls or worse?

Space conditioning systems can also be DR-enabled. The effect of controlling the thermostat based on pricing structures is best addressed by field-testing in real homes.

Ultimately grid-scale modeling will be required to understand the system-wide implications of DR-enabled appliances if they are to become widely adopted. Scenarios will increase in complexity with broader penetration of rooftop photovoltaics and electric vehicles. Results of this type of modeling would provide detailed information on the load-leveling capabilities of this class of technology to utility DSM programs, which may motivate utilities to implement appropriate TOU structures to incentivize consumer participation, creating a bigger market for these appliances.

Which strategies can be employed by manufacturers, occupants, and utilities to integrate smart appliances successfully into DSM programs? This class of technology is currently optimized to shift peak load in response to the needs of the utilities, but we would like to see more emphasis placed on saving energy while shifting peak. This can be accomplished with a combination of strategies targeting different stakeholders. As with all AHEM systems, it is important to ask what improvements can be made to the control algorithms that improve consumer comfort and convenience while saving energy. If grid-connected appliances become more common, there could be additional incentives for the appliance manufacturers to design controls that both help the utilities by reducing peak and help the consumers by reducing overall energy use, such as a special version of an ENERGY STAR® label that conveys the emphasis on saving overall energy. There is significant value to the utility if these appliances can help shift peak and that value will likely be passed on to consumers in the form of rebates or TOU price structures. However, oversight of utility rate structures should discourage programs that result in peak shifting only, especially if such programs result in an overall increase in energy use. As the utility environment moves toward rate structures based on the actual cost of energy, customers can benefit by taking advantage of smart appliances and other AHEM technology that helps them manage their energy use.

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