Simulation Study of Transactive Control Strategies for Residential HVAC Systems

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***Abstract*—Demand response (DR) is a popular alternative to the control of generation assets in balancing energy production and consumption in the electric grid. The end-use electrical demand can be adjusted based on real-time electricity prices, known as price-based DR. A means to enable automatic price-based DR is to implement a transactive controller, in which energy consuming devices respond to the market price signal and reduce their power consumption. In this paper, two transactive control strategies, i.e., with and without pre-cooling, are simulated to analyze their effectiveness in controlling residential HVAC systems. Their ability to perform peak demand reduction and save money on electricity bills is evaluated for one home and a group of 100 homes. The study is carried out using the GridLAB-D simulation tool.**

***Index Terms*—Transactive control, HVAC control, energy market, GRIDLAB-D.**

NOMENCLATURE

ki	:	The slope of the transactive controller when the electricity price is above the average (k1) and below the average (k2);
P_{avg}	:	The 24-hour average electricity price (c/kWh);
$P_{current}$	:	The current market price of electricity (c/kWh);
$range_{high}$	:	The maximum allowable temperature increase from the desired temperature set point (°F);
$range_{low}$	:	The maximum allowable temperature decrease from the desired temperature set point (negative °F);
$T_{adjusted}$	:	The actual HVAC temperature set point set by the controller (°F) ;
$T_{desired}$	:	The desired temperature set point as per the schedule (°F);
T_{indoor}	:	The indoor temperature of a house (°F);
T_{max}	:	The maximum allowable setpoint (°F);
T_{min}	:	The minimum allowable setpoint (°F);
σ	:	The 24-hour standard deviation of the market price.

I. INTRODUCTION

According to the Energy Information Administration (EIA), residential buildings consume approximately 38% of the total electricity consumption in the U.S. However they are largely untouched by commercial building energy management solutions due to cost constrains. There has been considerable research on providing a hardware solution for home energy management (HEM) [1]–[3] and design of various HEM strategies[4], [5]. However, previous work either provides the basic control, or employs a set of complex rules to achieve energy savings.

Recently, a new form of control based on monetary incentives called the transactive control, has been investigated, which has a simple control concept but yet inherently provides cost savings [6]. This forms a part of the broader concept of a transactive network, which is a network of energy consuming devices, energy producing devices and other energy related service providing entities that interact to perform market-based transactions [7].

The Olympic Peninsula project [8] and the Pacific Northwest Smart Grid Demonstration project [9], [10] located in Washington State and Oregon, USA, have field-demonstrated the viability of transactive control for both commercial and residential consumers, and laid the groundwork for further research in this field. The transactive control algorithm originally presented in [6] is simple and easy to implement which makes it attractive for implementation in low cost hardware. There has been some studies [11], [12] demonstrating the viability of this form of control, however an extensive performance comparison of different transactive control algorithms is lacking and is the focus of this paper.

II. TRANSACTIVE CONTROL STRATEGIES

We perform analysis of two variations (strategies) of the transactive control algorithm discussed previously and study its impact on the operation of residential HVAC systems. For this form of control, the heating or cooling set point of the thermostat is adjusted linearly based on the market price signal.

Fig. 1 illustrates the operation of the passive transactive controller for strategy 1 (without pre-cooling). For this strategy, the controller chooses the cooling set point ($T_{adjusted}$) based on the current market price ($P_{current}$), the market price statistics (average and standard deviation), and the user-chosen slopes of the transactive control line (k1). While the controller will choose the higher cooling set point as the market price increases, it will not allow the cooling set point to go below the desired temperature ($T_{desired}$) as the market price decreases below P_{avg} (i.e., precooling is not allowed). A homeowner who is more willing to trade comfort for cost savings should select a steeper k1 slope while a homeowner who wants to maintain comfort except for very high prices should choose a shallower k1 slope. This can be achieved by providing a comfort versus savings slider to the customers as carried out in [10]. The other parameter for the control is the maximum (T_{max}) temperature limit, which is the maximum indoor temperature that a homeowner is willing to bear. Irrespective of the price, set points will not be adjusted above this limit.

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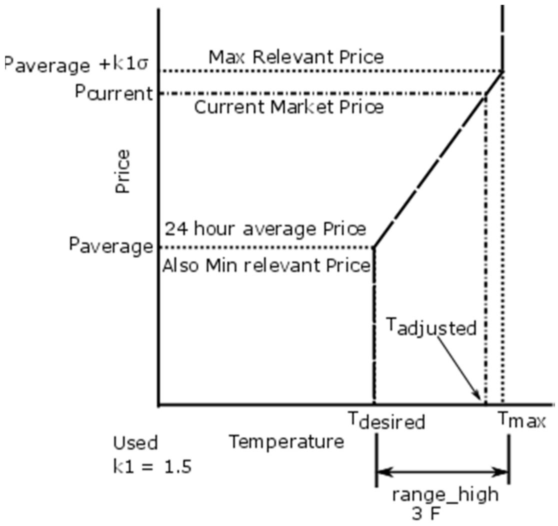

Fig. 1. Transactive control strategy 1 (without pre-cooling).

Fig. 2 illustrates the passive transactive controller for strategy 2 (with pre-cooling). In addition to allowing the adjusted temperature to go above the desired temperature set point when the market price is high, this controller allows the adjusted temperature set point to go below the desired temperature set point as well when the price goes below the average (i.e., precooling is allowed). There are two slopes for this controller: k1 and k2. The benefit of this strategy is to allow the house to be pre-cooled during the low price period, which will help alleviate the homeowner discomfort if the AC is turned off during the high-price period that follows. In this case, the controller will not adjust the HVAC set points above T_{max} and below T_{min}.

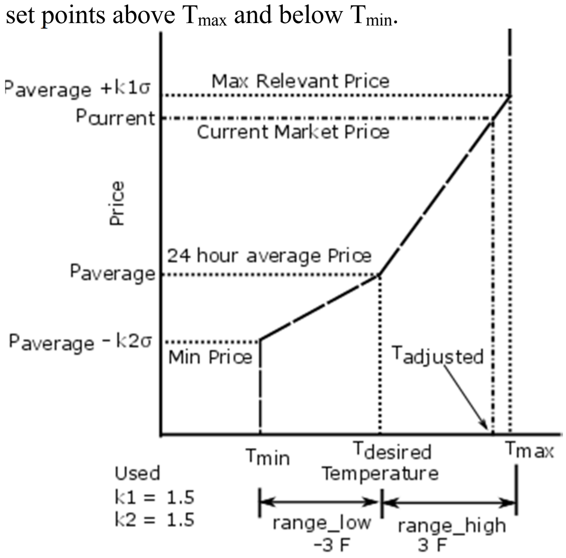

Fig. 2. Transactive control strategy 2 (with pre-cooling).

For this study, k1 and k2 are chosen at 1.5. $Range_{high}$ and $Range_{low}$ are chosen at 3°F and -3°F, respectively. The rest of the paper discusses results of applying these two transactive control strategies on a single house, and 100 houses.

III. Simulation Study

GridLAB-D (a distribution system simulation and analysis tool) has been chosen to perform the simulation study with the house_e module that uses the Equivalent Thermal Parameter (ETP) model. Also, a real-world price signal from the ComEd's residential real time pricing program is used to simulate the market price for the case study[13]. ComEd is the largest electric utility in Illinois which serves Chicago area. The price signal varies between -2.7 cents/kWh to 19.3 cents/kWh with mean of 2.8 cents/KWh during the chosen month (in June 2015). The location for simulation has been set to one of the service areas of ComEd.

A. *Base case scenario*

Fig. 3 shows the base HVAC operation of a simulated house on a hot summer day (i.e., June 14, 2015), along with the indoor/outdoor temperature, cooling set points and the COMED price signal that varies every hour.

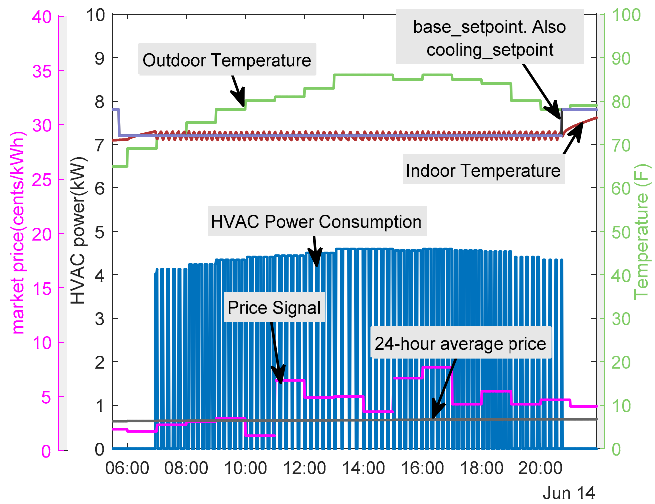

Fig. 3. Base case HVAC operation from 06:00 to 20:00 on a summer day.

The simulated house has a floor area of around 2200 square feet, with one HVAC unit and a decent thermal integrity (Integrity level of 4 in GridLAB-D). The thermostat schedule is made to follow a typical wake-leave-return-sleep pattern switching between 78°F and 73°F. Weather data used for the simulation is the typical meteorological year (TMY) data for Chicago. Based on the time series outdoor temperature data the month of June is calculated to have 211 cooling degree days (i.e., the number of degrees that a day's average temperature is above 65° F). And hence the AC runs for most of the time due to high temperature.

The following equation derived in [8] is used by the controller to change the HVAC set point according to the market price.

$$T_{adjusted} = T_{desired} + \left(P_{clear} - P_{avg}\right) * \frac{(|range_{high} - range_{low}|)}{\mathrm{ki}*\sigma} \quad (1)$$

In this paper, two different control strategies described in Section II are studied. Results of these strategies are shown in Fig. 4 and Fig. 5, respectively.

In Fig. 4, it can be seen that near the beginning of the high-price signal around 11:30, there is a price dip. However, the set point remains fixed at the base set point of 73°F. At the time of peak pricing starting from 11:30, the set point is increased with the increase in electricity price. This results in the AC operation being deferred for some time, after which it again starts cycling, albeit with lower cycling period due to the increased set point.

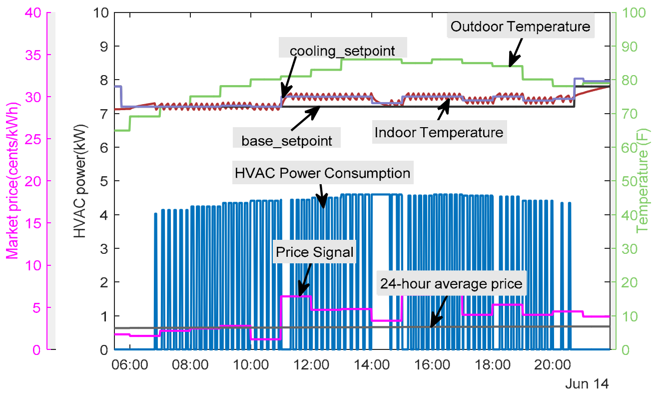

Fig. 4. HVAC operation with the transactive controller - strategy 1 implemented (no pre-cooling).

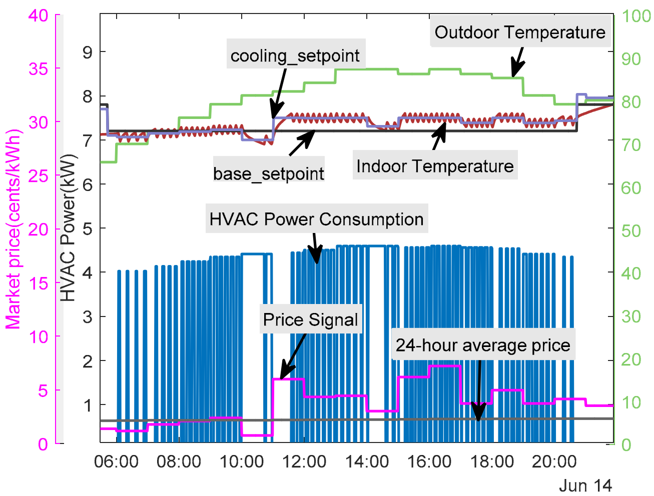

Fig. 5. HVAC operation with the transactive controller - strategy 2 implemented (pre-cooling).

In Fig. 5, the price dip at round 10:00 results in lowering the HVAC set point below the base set point, which turns on the AC and thus lowering the indoor temperature. In the subsequent price rise period, the pre-cooled temperature helps defer the AC operation for the longer period of time, and reduces the energy consumption during the high price period.

B. Behaviour with multiple houses

The next step is to study the aggregated HVAC response of a group of 100 houses. For this, floor area, thermal integrity and heating and cooling set points are randomized around those of the single house.

- Floor area is randomized with the normal distribution of the mean area of 2186 square feet and the standard deviation of 200 square feet.
- Thermal integrity level for 25 houses are set to 'Above Normal', 36 houses set to 'Normal', 18 houses set to 'Very Good' and 21 houses set to 'Good'.
- Thermostat cooling schedules follow the mean weekdays wake-leave-return-sleep schedule of 05:00-08:00-15:00-20:00 with set points of 73°F-78°F-73°F-78°F. The mean weekend wake-sleep times are 05:45-20:00 and the set points are 73°F-78°F. This schedule is randomized using a normal distribution with the mean of the existing set point and temperature standard deviation of 2°F, and time standard deviation of 1 hour.

Based on the distribution, the simulation outcome during a peak pricing event is shown in Fig. 6, illustrating the average HVAC power consumption of 100 houses, along with indoor/outdoor temperature, average cooling set points and electricity price signal. Since, no controller is implemented in this base case, the operation of the HVAC is indifferent to the changing price signal.

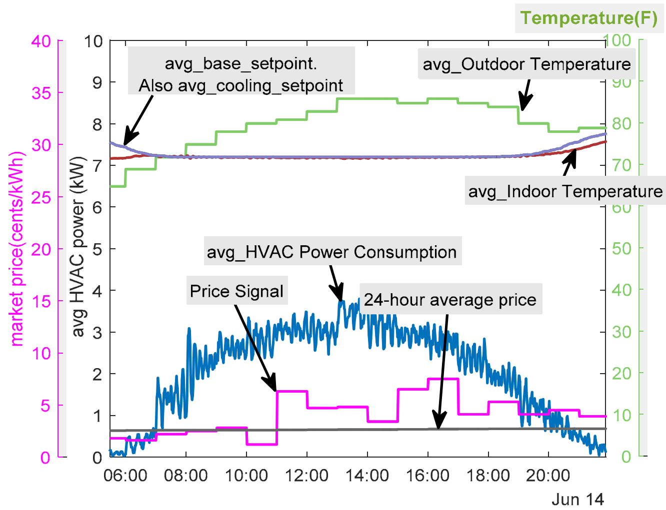

Fig. 6. Average HVAC power consumption of 100 houses (base case).

The HVAC power consumption of 100 houses when the transactive controller based on strategy 1 is implemented is shown in Fig. 7. At the onset of the high-price signal at around 11:00, we can see that suddenly all AC loads go to zero, and come back after some time. A sudden increase in HVAC load at around 14:00 is also experienced owing to the price dip.

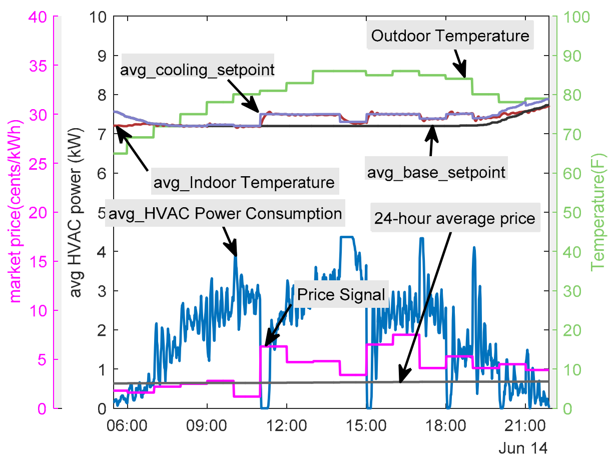

Fig. 7. Average HVAC power consumption of 100 houses with the transactive controller – strategy 1 implemented (no pre-cooling).

Fig. 8 illustrates the average HVAC power consumption of 100 houses when strategy 2 is implemented. Around 10:30 when the price dips below the average, a large pre-cooling load appears. This pre-cooling action does significantly decreases the average indoor temperature and hence in the high-price period that follows, AC operation could be deferred for a longer period of time than that without pre-cooling.

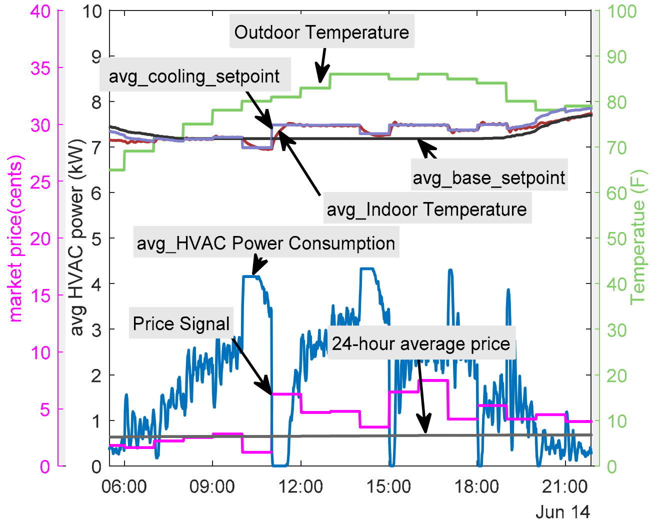

Fig. 8. Average HVAC power consumption of 100 houses with the transactive controller – strategy 2 implemented (pre-cooling).

IV. Results and Discussions

In order to properly weigh out the pros and cons of different control strategies, two indices are defined to quantify the discomfort experienced by homeowners.

- *High_temp_discomfort_index (HTDI)* is defined as the average temperature difference of the indoor temperature (T_{indoor}) from the original set point ($T_{desired}$), when $T_{indoor} > T_{desired}$, during a specified period.
- *Low_temp_discomfort_index (LTDI)* is defined as the average temperature difference of the indoor temperature (T_{indoor}) from the original set point ($T_{desired}$), when $T_{desired} > T_{indoor}$, during a specified period.

These indices are calculated as shown in (2) and (3), where N denotes the total number of time intervals during a specified period. Since the time interval defined for this study is one minute and the study period is the month of June, N is 43,200 (30 days x 24 hours/day x 1440 minutes/hour). Note that during a summer month, a lower HTDI is preferred, while a decent LTDI (close to base case) is acceptable. The LTDI should not be too negative so as to make the house uncomfortably cold.

$$HTDI = \frac{1}{N}\sum_{i=1}^{N} max(T_{indoor_i} - T_{desired_i}, 0) \quad (2)$$

$$LTDI = \frac{1}{N}\sum_{i=1}^{N} max(T_{desired_i} - T_{indoor_i}, 0) \quad (3)$$

Table I shows how the HTDI and LTDI, as well as the one-month electricity consumption and one-month electricity cost (for the month of June) are affected by the application of the two different control strategies for a single house.

Results are quite interesting: the scheme with pre-cooling shows higher electricity consumption than the one without pre-cooling (though both cases have lower electricity consumption than the case with no control). However, the electricity supply cost is actually slightly less. This is because, in the pre-cooling scheme, the AC is in operation to bring the temperature below the set point during lower-price periods, which obviously consumes extra electricity. However, this extra-consumption is offset in terms of cost as electricity price is lower during the pre-cooling period and this scheme defers the AC operation for a longer period of time during the price-hike period. In terms of HTDI, pre-cooling is clearly better than no pre-cooling, so it might be tempting to use the pre-cooling scheme because even though it has higher electricity usage, it comes with slightly less supply costs. However, this tiny supply cost advantage is offset due to the fixed (about 4.3 cents/kWh) transmission, distribution and other miscellaneous charges on the COMED pricing scheme. The total electricity cost is shown in the last column of Table I. Hence, the scheme without pre-cooling gives the highest savings.

A similar comparison is shown in Table II for the case of 100 houses. The result for 100 houses is in line with that for a single house, with the average savings of around $2.66/month per household (5.23%) with strategy 1. The actual savings for each house (not shown in Table) varied from $1.77/month to $3.57/month. In terms of energy consumption, the savings vary from 11.05 kWh/month to 27.65 kWh/month with the mean savings of 18.6 kWh (2.7%) per month. It is noteworthy that 2.7% energy savings resulted in 5.23% cost savings because the energy savings mostly occurred during high price periods.

TABLE I. Electricity, Cost and Discomfort comparison for a Single House

Control Type	HTDI	LTDI	Electricity consumption (kWh/ month)	Electricity supply cost ($/month)	Total electricity cost ($/month)
Base case: no control	0.109	-1.162	647	23.01	50.83
Strategy 1: no pre-cooling	0.247	- 1.103	626	21.24	**48.15**
Strategy 2: pre-cooling	0.210	-1.197	639	21.12	48.59

TABLE II. Average Electricity Consumption, Cost and Discomfort comparison for 100 Houses

Control Type	HTDI	LTDI	Average Electricity consumption (KWh/ month)	Average Electricity supply cost ($/month)	Average total electricity cost ($/month)
Base case: no control	0.03	-1.00	668.0	23.41	52.14
Strategy 1: no pre-cooling	0.18	-0.93	649.4	21.56	**49.48**
Strategy 2: pre-cooling	0.16	-1.07	661.7	21.39	49.84

Fig. 9 shows the effect of aggregation and transactive control on the load distribution over a one-month period. The x-axis denotes the HVAC load for a single house case and the average HVAC load for the 100-house case; y-axis denotes the percentage of time indicated values was equaled or exceeded. This figure implies: For a single house, the HVAC unit was in operation for about 20% of the time, or in other words the HVAC unit remains idle for 80% of the time. For the 100-house case, the average power is close to 0 for about 20% of the time. This indicates that all 100 HVAC units are not in operation at the same time for about 20% of the time. For the rest of the time, some HVAC units are in operation.

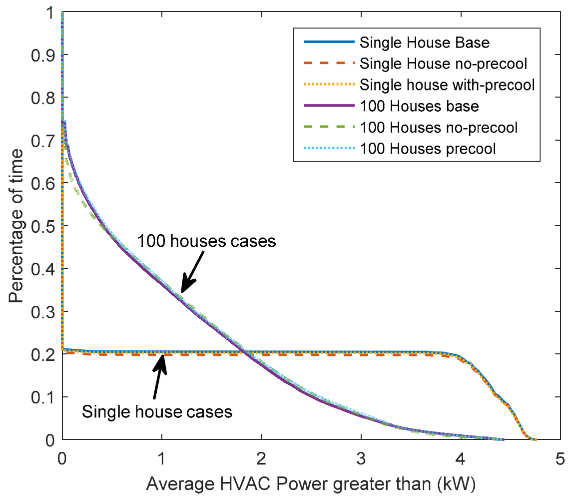

Fig. 9. Inverse HVAC load duration curves for a single house and 100 houses.

It is worth noting that while the controllers can reduce the peak during the peak period, it does not actually remove the peaks. They just shift the peaks, sometimes even creating peaks during market price dip. Nonetheless the no pre-cooling strategy slightly improves the peak distribution, compared to the base case and the pre-cooling case. The slight improvement in peak reduction by different control strategies is shown in Table III. It should be noted that the negligible peak load reduction does not mean the control has no benefit, the control resulted in shifting of the peaks from high-price to low-price regions and hence resulted in cost savings.

TABLE III. PEAK LOAD REDUCTION

Case	Load greater than	Percentage of Time		
		Base Case	Without pre-cooling (strategy 1)	With pre-cooling (Strategy 2)
Single House	4 kW	18.73%	18.18%	18.50%
100-House	3.5 kW	2.3%	2.0%	2.3%

V. CONCLUSION

Through a simulation study this paper quantifies the cost savings that can be achieved by using different transactive control algorithms using the thermostat set point adjustments in realistic scenarios. Real market price signals, a physical model of residential houses and real weather data were used to bring the simulation close to the real world. Two variations of a popular transactive control algorithm were studied, and a simple strategy without any pre-cooling was found to be the best choice for cost savings.

Monthly electricity bill savings of a typical house with real-time price signals seems to be modest ($1.77 to $3.57 per month) with corresponding energy reduction of 11.05 kWh to 27.65 kWh. Most of these savings comes from the lowered cycling of the HVAC, due to the increase in temperature set points by the controllers. The modest savings, though unattractive, is explainable due to the fact that the real time price becomes very high often at the same time when the outdoor temperature is also high, and during such periods HVAC operation can only be deferred for a brief amount of time (few minutes) before the temperature drifts above the increased set points. This suggests that research on HVAC energy consumption reduction and cost savings should look beyond simple set-point changes during peak demand. Further research can be conducted to explore possible savings resulting from incorporating the control of other household appliances, such as water heaters and clothes dryers.

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