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Stabilizing the Grid and Reducing Utility Bills Through Price-Responsive Controls for Heat Pump Water Heaters

Peter Grant **Marius Stübs, PhD** **Bruce Nordman** **Christoph Gehbauer**

ABSTRACT HEADING

The electricity grid is facing increasing challenges in cost-effectively balancing supply and demand. These challenges are exacerbated by increased penetration of photovoltaics, which causes mid-day overproduction, and electrification of gas appliances, which increases peak-period electricity demand. Decarbonization requires shifting building loads from fossil-intensive high-cost times to renewable-intensive low-cost times while maintaining quality of service to occupants. Utilities and ISO's are investigating new ways of incentivizing this load shifting. One promising method is the use of Highly Dynamic Prices (HDPs). HDPs feature continuously changing prices that reflect real-time grid generation and distribution costs and capacity constraints, and thus incentivize consumers to shift their loads. California's CPUC CalFUSE proposal and Hawaii's recent changes demonstrate that electricity tariffs are moving towards this model. For this to work however, loads must have the capability to respond to these prices. Heat pump water heaters (HPWHs) are an ideal device for this purpose because their storage tanks decouple delivery of domestic hot water from electricity consumption. The storage enables control strategies that consume midday solar power to increase the energy stored in the tank, then provide evening peak domestic hot water services using the stored energy.

Berkeley Lab's CalFlexHub project is pioneering price-driven load flexibility by developing and deploying cost-minimizing controls for many flexible loads - including HPWHs - in response to HDP. Control development is based on simulations using the Flexible Heat Pump Water Heater Performance Predictor which captures the control decisions of the on-board controller in a residential, integrated HPWH . The price-responsive controls a) shift load in ways that consume additional midday solar power to help stabilize the grid and reduce overall emissions, b) ensure that occupants receive equal or better hot water delivery service, and c) minimize the operating cost for each home in the fleet. On the grid level, the resulting shift will reduce utility operating costs and emissions, and can avoid expensive system capacity expansions. The control approach is customized to each home based on typical hot water consumption patterns. HPWH controllers, whether on the device or remotely, will receive a schedule of CTA-2045-B signals or set temperature adjustments customized to the current HDP price schedule and home. Simulation results for a fleet of 148 HPWHs on a summer day in Berkeley, California show cost savings of 29% and high price electricity consumption reductions of 80%, while maintaining full quality of service.

INTRODUCTION

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To mitigate the impacts of climate change, the United States has set an ambitious goal of net-zero CO_2 emissions by 2050 and 50-52% reductions compared to 2005 by 2030 (White House, 2021). Achieving this ambitious goal requires rapid electrification, at a time when increased solar power production and evening peak electricity consumption are causing grid stability challenges and driving up system costs in California (California ISO, 2013). The electrification required to meet the carbon emission reduction goals will increase both solar power production and electricity consumption peaks, exacerbating these challenges. New flexible load technologies, including advanced controls leveraging available storage and communication capabilities, are necessary to maintain grid stability and reduce costs (California ISO, 2013). Further, the flexible load technologies must be adaptable, and able to respond to new conditions as the electric grid continues to evolve.

There are many ways to coordinate loads in buildings with grid concerns. Traditional approaches have focused on event-based demand response and grig aggregator models. Recent research projects have focused on retail pricing structures, specifically highly dynamic prices (HDP), to provide economic incentives driving customers to shift their electricity consumption (Freier, Arnold, & Hesselbach, 2019). Uitilies in California now offer dynamic rates as pilot projects (Southern California Edison, 2023). Devices with controls that respond to HDP would reduce operating costs while supporting grid stability and reducing carbon emissions.

Heat pump water heaters (HPWHs) are capable of simultaneously supporting both decarbonization and load flexibility goals. They utilize a 50-80 gal/189-303 liter water storage tank, a heat pump as a primary heating source, and electric resistance elements as backup heating (Hoeschele, Haile, & Grant, 2022). Replacing a natural gas water heater with a HPWH reduces carbon emissions by 50-70% in California and 58% percent nationwide (Brockway & Delforge, 2018). The hot water storage tank enables storing energy and providing demand flexibility to utilities via existing communication protocols (Hoeschele, Haile, & Grant, 2022) (Amasyali et al., 2021). HPWHs are currently the most energy efficient form of water heating, driving demand and increasing their market share (Nevius, Powell, & Meek, 2022) (Wang, Kusnandar, Lin, & Tsai, 2021).

Modern HPWHs communicate through the CTA-2045-B protocol, providing communication capabilities that enable load shifting. CTA-2045-B's control capabilities include 1) increasing energy stored in the tank with a "Load-Up" command which brings the water to the set temperature, 2) an "Advanced Load-Up" command, which heats the water to an elevated set temperature (Consumer Technology Association, 2021), and 3) the "Shed" command which informs HPWHs to delay heating cycles by letting the water in the bottom of the tank be colder than usual. The standard also facilitates reporting the HPWH's electricity consumption and a state of charge estimate.

Recent research projects have developed state-of-the-art load shifting controls that utilize cloud-based signals to a) maximize electricity consumption during times of high renewables production, and 2) minimize electricity consumption during evening peak periods, and c) ensure occupants receive satisfactory supplies of hot water (Carew et al. 2018) (Hoeschele, Haile, & Grant, 2022) (Grant & Huestis, 2018) (Manasseh et al. 2021). Load is typically shifted from high-price, evening peak periods to low-price mid-day periods by either increasing the set temperature of the HPWH or sending CTA-2045-B signals during mid-day. Reduced set temperatures or CTA-2045-B Shed signals then drive the HPWH to rely on the increased energy stored in the tank, reducing the electricity consumed during the peak period. These controls are typically based on engineering judgment without adjusting to local usage patterns.

Prior studies have either identified weaknesses in the existing control strategies, or experimented with different solutions. Grant et al. analyzed the performance of load shifting controls using California's Time Dependent Valuation (TDV) metric (which are analogous to HDP) and found that a) load shifting could decrease operation costs by up to 84% on days with high variation in hourly TDV multipliers, and b) load shifting on days with low variation in hourly TDV multipliers increased operation costs (Grant & Huestis, 2018). Cost increases arose from decreased efficiency, and increased consumption on days when there was no price variation to provide savings. The result indicated that load shifting should only be performed on days with a considerable price differential. Carew et al. developed a methodology to translate a price profile into different set temperatures based on average hot water draw profiles, but found that the algorithm did not perform when applied to a broader array of draw profiles (Carew, Larson, Piepmeier, & Logsdon, 2018). Hoeschele et al. performed load shifting on HPWHs serving four apartments, and reduced peak period electricity consumption by up to 73% (Hoeschele, Haile, & Grant, 2022). That project also showed that load shifting by increasing the set temperature of a HPWH can cause use of the electric resistance elements instead of the heat pump, increasing electricity costs by up to 49-63%. Manasseh et al. tested a method of customizing controls to different homes based on average electricity consumption during both morning and evening peaks, and found results that customizing the control increased shed load during the evening peak period by 16% (from 622 Wh to 740 Wh) per HPWH.

These challenges and proposed solutions lead to the following opportunities to improve load shifting controls for HPWHs: 1) Develop controls that shift load without accidentally activating the resistance elements, 2) Create a control algorithm capable of optimizing for the needs of the grid as they vary day to day, 3) Implement controls that are optimized for local occupant behavior, and 4) Combine the above items in a manner that reduces occupant utility bills.

The third point is particularly challenging due to the limited data available. HPWHs do not include flow meters, and including flow meters would increase the installed cost. Further, hot water draw patterns vary significantly enough day-to-day that predicting occupant behavior is quite challenging (Starke, et al., 2020). Control algorithms that optimize for local occupant behavior must use only using data communicated via manufacturer APIs or CTA-2045-B, such as electricity consumption or tank state of charge estimates. Advanced control techniques such as Model Predictive Control (MPC), in conjunction with data-driven models, may be equipped to take on this challenge. With MPC, a given system model, the HPWH storage tank and heat pump in this case, and data inputs, such as weather forecast and prediction of hot water demand, are numerically optimized to find the best control solution given the current HDP profile. MPC has been successfully used for shifting cooling demand in buildings (Gehbauer et al., 2020) and HPWHs (Jin et al., 2014) given static time-of-use electricity tariffs.

This paper introduces a control algorithm that addresses all four development points. The control algorithm leverages existing CTA-2045-B communication capabilities to a) avoid excessive use of electric resistance elements, and b) ensure that the developed controls are deployment-ready. Simulations using Flexi-HPWH (Hoeschele, Haile, & Grant, 2022), which closely matches the specifications and control of one manufacturer's HPWHs, develop a command schedule that reduces the operating cost of HPWHs over any supplied price schedule. The simulations use 148 monitored, daily hot water draw profiles in Berkeley, CA, enabling development of different control schedules for HPWHs with different use patterns. The resulting control strategy is designed to reduce operating cost, support grid stability, customize to different hot water use patterns and price schedules, and be deployed using current industry-adopted technologies.

METHODOLOGY

The following subsections provide information on 1) the utilized heat pump water heater modeling tool, 2) the draw and 3) price profiles studied, 4) CTA-2045-B schedule development, and 5) the HPWH grouping approach.

Heat Pump Water Heater Modeling

The simulation study utilized the Flexible Heat Pump Water Heater Performance Predictor, which closely matches field monitoring electricity consumption and thermostat temperature data of one manufacturer's products (Hoeschele, Haile, & Grant, 2022). The model includes 1) A water storage tank, 2) One heat pump which provides heat to the bottom of the tank, 3) Two backup electric resistance elements (one close to the top and one close to the bottom of the tank), 4) Control logic emulating field monitoring observations of a manufacturer's products, and 5) Responses to CTA-2045-B control signals.

The storage tank model features 20 equally sized segments at different depths in the tank. The simulations for this paper assumed an 80 gallon storage tank. Heat transfer calculations track the standby losses, water flows, and heat additions to each segment of the tank for each timestep. The heat pump, resistance elements, and control logic all closely match the designs and behavior observed in field monitoring studies (Hoeschele, Haile, & Grant, 2022). Two thermostats, one close to the top of the tank and the other close to the bottom, activate/deactivate the heating sources. The heat pump has a nominal heating capacity of 4,197 Btu/hr-thermal / 1.23 kW-thermal, with a coefficient of performance (COP) curve matching observed field performance. The model assumes a wrap around condenser coil and buoyancy flows by adding heat to all nodes below the stratification layer. There are two 3.8 kW backup resistance elements, one connected to the upper thermostat and one connected to the lower thermostat. If the lower thermostat detects that the water temperature is below the set temperature by more than a specified deadband, the heat pump activates to heat the water in the tank. If the upper resistance element identifies that the water temperature is below the set temperature by a second deadband, the resistance elements activate. The modeled system includes 125 °F /

51.7 °C default set temperature with a mixing valve set at 120 °F / 48.9 °C, in accordance with regulations (AHRI, 2022).

Responses to CTA-2045-B control signals were added for this project matching the Light Shed, Load-Up, and Advanced Load-Up commands from AHRI Standard 1430-2022 (AHRI, 2022), using reasonable assumptions and input from industry partners. Each response corresponds to an operating mode with a set of actions, as shown in Table 2. Since each manufacturer responds to the control signals in different ways the responses to CTA-2045-B signals will need to be updated for simulations studying specific products. After receiving a CTA-2045-B signal the HPWH remains in that operating mode for four hours. The operating mode will be overwritten when receiving a different control signal. If the HPWH receives a signal which does not change the operating mode (e.g. a shed signal while in shed mode) the four-hour timer restarts without changing the current operation of the heat pump.

Table 1: Modeled HPWH Responses to CTA-2045-B Control Signals

Signal Command	Action
Load-Up	Activate heat pump until water reaches set temperature Reduce heat pump deadband to 2 °F/1.1 °C
Advanced Load-Up	Increase set temperature by 15°F/8.3 °C Resistance elements do not respond to elevated set temperature Activate heat pump until water reaches set temperature Reduce heat pump deadband to 2°F/1.1 °C
Shed	Deactivate heat pump Increase heat pump deadband by 50%

The operating modes do not change the operation of the electric resistance elements. Any use of CTA-2045-B control signals that increases the risk of occupants receiving cold water will yield electric resistance heating, simultaneously reducing the chances of delivering cold water and increasing the HPWH's operating costs.

Draw Profiles

The hot water consumption behavior of the occupants was simulated using California's Title 24 daily hot water draw profiles (Kruis, Wilcox, Lutz, & Barnaby, 2017). Each daily draw profile is monitored data from a home in Southern California (DeOreo, et al., 2011). Different draw profiles represent different numbers of occupants (1-5) and day types (weekday (D), weekend (E), and holiday (H)). There are 10 variants for each combination of occupant number and day type. The daily draw profiles are each given names depicting the detail of the draw profile. For instance, the 4th draw profile with two occupants on a weekend is named 2E4. This study utilized all draw profiles for 1-5 occupants, totalling 148 different monitored hot water use cases.

Price Profiles

The simulations utilized hourly dynamic price schedules representing the state of California's electricity grid (Gerke et al., 2022). The price schedule reflects electricity supply costs such as wholesale, generation capacity, flexibility capacity, delivery capacity, wildfire mitigation, administration, grid metering, and public purpose programs. The price schedules were designed to be revenue neutral for California's utilities while distributing the revenue according to the times of highest grid utilization. Prices typically peak in the evening, with summer peaks reaching as high as $0.90/kWh. Mid-day prices, during times of high solar production, are commonly below $0.20/kWh.

Heat Pump Water Heater Grouping

The simulation study utilized all 148 daily draw profiles with between one and five occupants from the Title 24 data set. The hot water consumption in the draw profiles ranged from 0.03 to -146 gal (/0.1- to 553 L) per day, causing a range of 0.7 to 10.2 kWh/day of electricity consumption. Depending on the timing of the hot water consumption, the variations in hot water consumption also changed the timing of electricity consumption. Figure 1 presents sample hot water and electricity consumption profiles for draw profiles 5E1 (solid line), 5H8 (dashed line), and 3H0 (dotted line). The 5E1 and 5H8 profiles were both high use days, with 5E1 consuming 146 gal/553 L and 9.8 kWh while 5H8 consumed 133.9 gal/507 L and 10.2 kWh. 3H0 consumed very little water, 0.03 gal/0.1 L, and required only 0.7 kWh to overcome the jacket losses. The high use draw profiles both forced resistance element operation, and would probably benefit from a CTA-2045-B signal schedule that uses the Advanced Load-Up command to increase energy stored in the tank prior to periods of high hot water consumption. The increase in stored energy would avoid resistance element operation. In the case of 5H8, Advanced Load-Up could also shift electricity consumption from the high-price evening peak to the low-price mid-day solar peak. 3H0 caused very little electricity consumption, and likely would not benefit from any CTA-2045-B signal schedule. The differences in the load curves indicate that each draw profile has different load shifting potential and optimal CTA-2045-B control schedules.

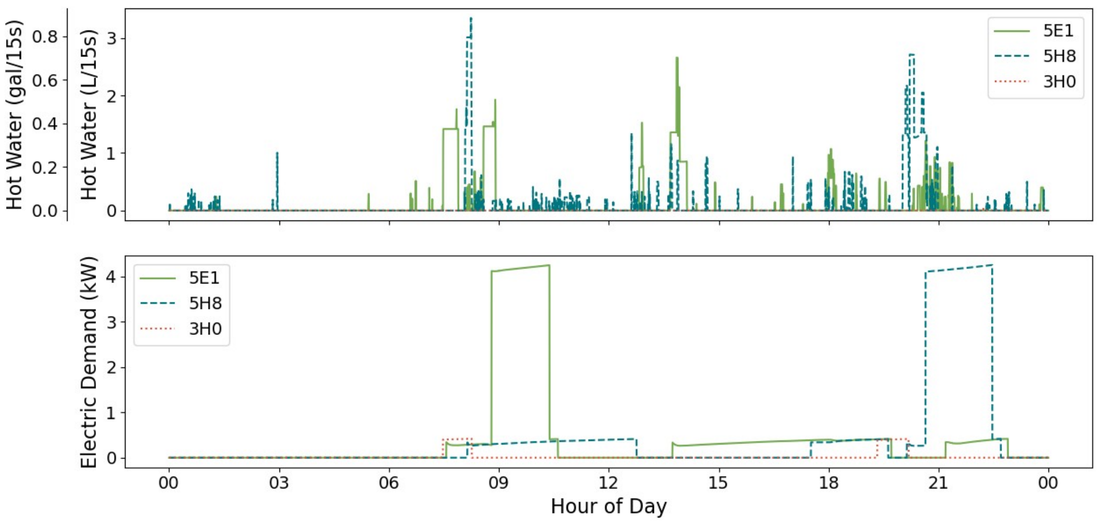

Figure 1: Sample hot water (top) and electricity (bottom) consumption profiles

The baseline load curves presented in Figure 1 were generated via simulation using perfect knowledge of hot water consumption patterns. Since HPWHs currently do not measure or report hot water consumption, forecasting the upcoming hot water load and creating a customized CTA-2045-B signal schedule is not feasible. Instead, the CTA-2045-B signal schedule for field HPWHs must be identified by 1) obtaining the baseline electricity consumption profile, 2) identifying a HPWH with a similar baseline electricity consumption profile, and 3) assigning the CTA-2045-B schedule optimized for the similar profile to the field HPWH. Further, since hot water consumption in real buildings is not identical from day to day, the deployment approach must identify a CTA-2045-B schedule that performs well for a group of similar baseline electricity consumption profiles.

To prepare for the realities of field deployments, the 148 HPWHs were separated into 10 groups based on their simulated daily electricity consumption (kWh/day). The daily consumption of each HPWH provides insight into how much load can be shifted to low cost times of day. Each group of HPWHs spans a range of average daily electricity consumption of the same size. With this approach, the groups contain different numbers of HPWHs.

CTA-2045-B Schedule Development

The control algorithm generates a schedule of CTA-2045-B commands that reduce the cost of operating a group of HPWHs. It generates the CTA-2045-B command schedule by 1) identifying the increase/decrease in electricity price over a specified look ahead window, and 2) comparing that price change to threshold values. Parameters specifying the number of hours to look ahead and threshold values for Load-Up, Advanced Load-Up, and Shed define the controller's structure. For instance, if the controller is programmed to send a Shed command if the price decreases by 0.10 $/kWh within the next four hours and the price decreases by 0.15 $/kWh after two hours, the controller will send a Shed signal. If the price change exceeds the price threshold for multiple parameters, the controller prioritizes Advanced Load-Up first.

A parametric study of the different hours and threshold parameter values enables identifying the lowest cost strategy for a given group of HPWHs. Table 2 shows the number of hours to look ahead and thresholds used in the parametric study. Advanced Load-Up includes a threshold parameter of 10 $/kWh to ensure there was an option that never utilized the Advanced Load-Up command. The same objective was accomplished with the one hour, 0.15 $/kWh combination for both Load-Up and Shed.

Table 2: Parameter Values Used in the Parametric Study

CTA-2045-B Command	Hours to Look Ahead (hr)	Price Threshold ($/kWh)
Load-Up	1, 2, 3, 4	0.05, 0.1, 0.15
Advanced Load-Up	3, 4, 5, 6, 7, 8, 9, 10	0.25, 0.3, 0.35, 10
Shed	1, 2, 3, 4	0.05, 0.1, 0.15

Upon completion of the parametric study, the algorithm was set to use the CTA-2045-B control schedule that yields the lowest average cost of operation for a specific group and price schedule combination. This control schedule can be applied to that group on days with that price schedule. Pre-computing the parametric study enables widespread field deployments, as fleet operators can obtain the control strategy from a lookup table instead of performing a parametric study daily.

Sending a CTA-2045-B control signal to all HPWHs in a fleet could activate every heat pump simultaneously, causing a sudden change in the electric demand which the grid must provide. To avoid this occurrence, the control algorithm utilizes a state of charge (SOC) algorithm to send signals to the HPWHs in the fleet sequentially. The SOC for a given HPWH is defined as the average temperature of water in the tank divided by the base set temperature (not the elevated set temperature when in Advanced Load-Up mode). Initially, all HPWHs with a state of charge below 75% are sent Load-Up and Advanced Load-Up signals. Every five minutes the threshold is increased by 2% (e.g. after five minutes the threshold becomes 77%) and the signals are sent to all HPWHs below the new threshold. This process continues until the threshold is 100%, and all HPWHs with water below the user specified set temperature have received the signal.

Control Performance Evaluation

The performance of the price-responsive CTA-2045-B signal schedules was compared to the performance of the manufacturer's control logic with no price-responsive controls. Evaluations included: 1) Cost: The cost of operating the fleet of HPWHs for one day, 2) Shifted Load: Reduction in the electricity consumed during times of day when the price was above average, using high prices as a proxy for times when the grid needs to reduce load, and 3) Avoided Curtailment: The electricity consumed between 9 AM and 5 PM, representing times when ample solar power is available.

RESULTS

The following subsections present the control approach's performance for each group and the entire fleet.

Control Performance by Group

Table 3 presents the impacts of the load shifting control on each group of HPWHs in the fleet. Some groups featured a kWh/day range which did not include any HPWHs, so not all groups are presented. The first three parameters listed in control strategy are the hours to look ahead in order of Load-Up (LU), Advanced Load-Up (ALU), and Shed (S). The remaining three parameters are the price threshold values in the same order.

Each group of HPWHs attained the lowest operating cost using a different set of parameters. In some cases the change was minor (e.g. the only difference between group 1 and 2 is that the Load-Up price threshold changed from $0.05 to $0.10), and in other cases it was major (e.g. groups 1 and 3 only have 1 shared parameter value). The cost savings for each group ranged from 21% to 62%. Generally, the groups with more HPWHs and lower kWh/day values achieved lower cost savings than the groups with fewer HPWHs and higher kWh/day values. Peak load consumption reductions ranged from 59% to 96%, and showed the opposite trend. Groups with more HPWHs and lower kWh/day values achieved the highest load shifting performance. Some HPWHs did show higher operating cost, ranging from 0-19% of HPWHs depending on the group.

Table 3: Results for Each Group of HPWHs

Group	Consumption Range (kWh)	Number of HPWHs	Control Strategy						Cost Savings (%)	Peak kWh Reduction (%)	HPWHs with Increased Cost (%)
			Hours to Look Ahead (hr)			Price Threshold ($/kWh)					
			LU	ALU	S	LU	ALU	S			
1	062 - 1.58	47	2	10	3	0.05	0.30	0.05	31	96	19
2	1.58 - 2.54	51	2	10	3	0.10	0.30	0.05	27	94	17
3	2.54 - 3.5	33	4	7	1	0.10	0.35	0.05	25	70	18
4	3.50 - 4.60	12	4	7	2	0.10	0.35	0.10	21	58	16
6	5.42 – 6.39	1	1	3	3	0.15	0.35	0.05	61	82	0
8	7.35 - 8.31	1	2	3	3	0.05	0.35	0.05	48	62	0
10	9.27 - 10.23	3	3	2	2	0.05	0.30	0.05	40	70	0

Fleet Performance

Figure 2 presents the results of the entire fleet. The top subplot shows the price of electricity throughout the day. The middle subplot shows the electric demand of the fleet with (Supervised, solid line) and without (Unsupervised, dashed line) the CTA-2045-B control signals. The bottom plot presents the operating cost per 15s timestep. The regions with shaded background show times when the electricity price was above average. Figure 2 shows that the CTA-2045-B signal schedules reduced load during the high price periods and increased load during the low-price period. As shown in the lower plot, this load shifting strategy reduces the operating cost of the fleet of HPWHs. The supervisory control reduced the operating cost of the fleet by 29%, reduced the high price electricity consumed by 80%, and increased electricity consumption during the mid-day solar peak by 100%.

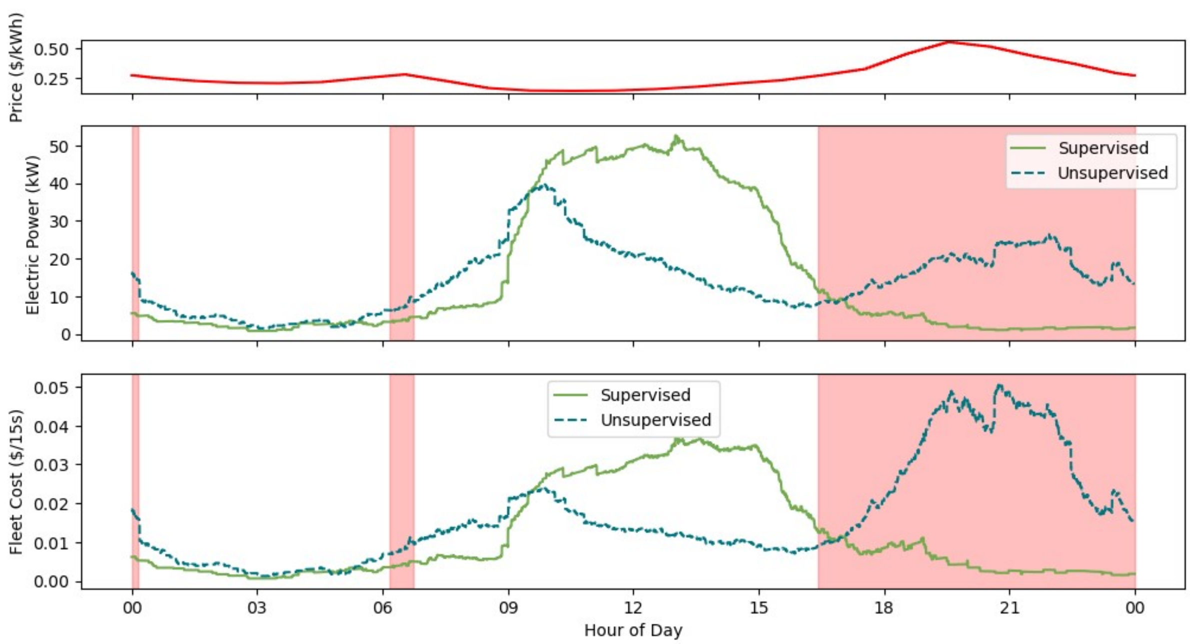

Figure 2: Electricity price (top), fleet electric demand (middle), and operating cost (bottom) comparing the fleet performance with CTA-2045-B (Supervised) and without (Unsupervised) control schedules

The performance of the control approach is highly sensitive to the grouping of the HPWHs. Customizing the CTA-2045-B signal schedule to each HPWH individually reduced operating costs by 44%. Creating one CTA-2045-B signal schedule for the entire fleet of HPWHs reduced operating costs by 13%. This divergence demonstrates that customizing the control strategy to different occupant behaviors is critical. The grouping method used in this study, creating 10 groups based on average kWh/day, yielded operating cost reductions of 29%, capturing 66% of the possible savings.

DISCUSSION

This study developed and evaluated the performance of a deployment-ready algorithm to develop cost-minimizing price- and behavior-responsive CTA-2045-B signal schedules. While prior studies have tested predetermined schedules with manual customization, this is the first study to develop an automated tool-chain that can be easily implemented by load shifting program operators. Further research efforts will focus on a) developing an improved grouping strategy, b) evaluating the control solution with other price schedules, c) evaluating the impacts in terms of carbon emissions, d) deploying the controls in the laboratory and field environments, and e) exploring other control strategies such as MPC.

This study showed that an algorithm customizing CTA-2045-B signal schedules in response to both price schedules and occupant behavior patterns can simultaneously reduce operating costs, support grid stability, and increase absorption of mid-day renewable energy. The approach described in this paper reduced operating costs by 28.5%, reduced peak load by 79.6%, and increased mid-day solar energy consumption by 99.6%. Customizing the CTA-2045-B signal schedule to different groups displaying different typical behavior patterns increased the cost savings from 12.9% to 28.5%.

These results agree with prior studies which showed that load shifting controls for HPWHs could effectively reduce their peak period electricity consumption (Hoeschele, Haile, & Grant, 2022) (Manasseh, Metzger, Ebony, Ashley, & Hunt, 2021). The conclusion that creating different control schedules for different occupant behavior patterns can improve performance agrees with related prior research (Manasseh, Metzger, Ebony, Ashley, & Hunt, 2021). These results improve upon the prior work by Hoeschele et al., where using a web API to directly change set temperatures sometimes caused resistance element operation and increased electricity costs (Hoeschele, Haile, & Grant, 2022) by avoiding use of the resistance elements to perform load shifting.

The potential cost savings of 44% if each HPWH received a customized CTA-2045-B control schedule compared to the 29% with the proposed solution shows potential to improve the grouping of HPWHs. Achieving the 44% savings of individually controlled HPWHs would require perfect knowledge and repeatability of hot water use, and the individual control case represents the potential more than an achievable target. Improved methods of identifying similarity in typical electricity consumption behaviors for each HPWH could approach the 44% limit represented by individual control of each HPWH while accepting the uncertainty inherent in field deployments. Improved grouping mechanisms would require an accurate understanding of how load patterns change day to day within a specific house, and could enable deployment of MPC in future projects. Improved grouping mechanisms would require an accurate understanding of how load patterns change day to day within a specific house. Alternatively, data-driven models paired with MPC algorithms may be able to leverage the limited data available to find optimal control setpoints in real time.

Future work will transition this approach from simulation to the laboratory environment. Further research studies will enable customizing the assumptions and controls to different manufacturer's products, updating the controls to respond to day-to-day variability in hot water consumption, and determining the impact that load shifting controls have on the long-term reliability of HPWHs.

CONCLUSION

Meeting the United States' rapid decarbonization goals while maintaining grid stability requires wide-spread deployment of load shifting controls. Heat pump water heaters provide both decarbonization benefits, and possess the requirements for load flexible controls. This paper presents a novel toolchain for developing load shifting controls that are customized to both price and occupant behavior schedules, utilizing only currently available heat pump water heater capabilities and are therefore easy to deploy. Simulations on a fleet of heat pump water heaters using 148 different monitored hot water draw profiles showed 28.5% electricity cost savings, 79.6% peak load reductions, and 99.6% increased mid-day solar energy consumption for a sunny day in Berkeley, California.

REFERENCES

AHRI. (2022). *2022 Standard for Demand Flexible Electric Storage Water Heaters.* Air-Conditioning, Heating, and Refrigeration Institute.

Amasyali, K., Munk, J., Kurte, K., Kuruganti, T., & Zandi, H. (2021). Deep Reinforcement Learning for Autonomous Water Heater Control. *Buildings, 11*. doi:10.3390/buildings11110548

Brockway, A., & Delforge, P. (2018). Emissions reduction potential from electric heat pumps in California homes. *The Electricity Journal*, 44-53. doi:https://doi.org/10.1016/j.tej.2018.10.012

California ISO. (2013). *What the duck curve tells us about managing a green grid.* Folsom, CA: California Independent System Operator.

Carew, N., Larson, B., Piepmeier, L., & Logsdon, M. (2018). *Heat Pump Water Heater Electric Load Shifting: A Modeling Study.* Ecotope, Inc. Retrieved from https://ecotope.com/ecotope-publications-database/

Consumer Technology Association. (2021). *ANSI/CTA Standard Modular Communications Interface for Energy Management ANSI/CTA-2045-B.* ANSI.

DeOreo, P., Mayer, P., Martien, L., Hayden, M., Funk, A., Kramer-Duffield, M., . . . Herberger, M. (2011). *California Single-Family Water Use Efficiency Study.* California Department of Water Resources. Aquacraft, Inc.

Freier, J., Arnold, M., & Hesselbach, J. (2019). Introduction of an approach to develop dynamic electricity prices for residential customers. *16th International conference on the European Energy Market (EEM)*, (pp. 1-6). Ljubjana.

Gehbauer, C., Blum, D. H., Wang, T., & Lee, E. S. (2020). An assessment of the load modifying potential of model predictive controlled dynamic facades within the California context. Energy and Buildings, 210, 109762.

Grant, P., & Huestis, E. (2018). *Lab Testing Heat Pump Water Heaters to Support Modeling Load Shifting.* Frontier Energy, Inc. Pacific Gas and Electric Company. Retrieved from https://etcc-ca.com/reports/lab-testing-heat-pump-water-heaters-support-modeling-load-shifting

Hoeschele, M., Haile, J., & Grant, P. (2022). *Evaluation of unitary heat pump water heaters with load-shifting controls in a shared multi-family configuration.* Pacific Gas and Electric Company.

Jin, X., Maguire, J., & Christensen, D. (2014). Model predictive control of heat pump water heaters for energy efficiency. Proceedings of the 18th ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, USA, 21-26.

Kruis, N., Wilcox, B., Lutz, J., & Barnaby, C. (2017). Development of Realistic Water Draw Profiles for California Residential Water Heating Energy Estimation. *Proceedings of Building Simulation 2017: 15th Conference of IBPSA. 15*, pp. 876-884. San Francisco, USA: IBPSA.

Manasseh, O., Metzger, C., Ebony, M., Ashley, T., & Hunt, W. (2021). Nontargeted Vs. Targeted Vs. Smart Load Shifting Using Heat Pump Water Heaters. *Energies, 14*. doi:10.3390/en14227574

Nevius, M., Powell, J., & Meek, M. (2022). *Northwest Heat Pump Water Heater Market Progress Evaluation Report #6.* Northwest Energy Efficiency Alliance.

Perry, C., Khanolkar, A., & Bastian, H. (2021). *Increasing Sustainability of Multifamily Buildings with Heat Pump Water Heaters.* American Council for an Energy-Efficient Economy. Retrieved from aceee.org/research-report/b2101

Southern California Edison. (2023, March 29). *SCE Dynamic Rate Pilot - Emerging Markets & Technologies*. Retrieved from https://www.dret-ca.com/dynamic-rate-pilot/

Starke, M., Munk, J., Zandi, H., Kuruganti, T., Buckberry, H., Hall, J., & Leverette, J. (2020). Real-Time MPC for Residential Building Water Heater Systems to Support the Electric Grid., (pp. 1-5). doi:10.1109/ISGT45199.2020.9087716

Wang, F., Kusnandar, Lin, H., & Tsai, M. (2021). Energy Efficient Approaches by Retrofitting Heat Pumps Water Heating System for a University Dormitory. *Buildings, 11*. doi:10.3390/buildings11080356

White House. (2021). *The Long-Term Strategy of the United States. Pathways to Net-Zero Greenhouse Gas Emissions by 2050.* Washington, D.C.: WhiteHouse.gov.