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ABSTRACT

Increased penetration of photovoltaics and electrification of traditionally gas appliances are exacerbating existing challenges in cost-effectively balancing electricity grid supply and demand. Decarbonization without incurring expensive transmission and distribution system capacity increases requires shifting building loads from peak demand times to peak renewable production times. Grid operators are evaluating new ways of encouraging load shifting, including using time-varying price structures to provide a financial incentive. If devices incorporate price-responsive controls, a price profile could be designed to yield a wide variety of load curves as needed to optimize grid functionality. Heat pump water heaters (HPWHs) are an ideal device for price-responsive controls because the storage tank enables them to optimize the timing of electricity consumption without impacting hot water delivery service. This paper presents work demonstrating how price-responsive controls for HPWHs can provide different load profiles, as needed to stabilize the grid, in response to different price profiles.

HPWH manufacturers now include web API and CTA-2045 communication capabilities which enable sending load shaping control signals. Pilot studies and preliminary programs have utilized these capabilities with uniform control strategies to reduce 4-9 PM electricity consumption. However, no studies have developed flexible controls capable of both a) responding to constantly varying price profiles and b) customizing logic to match the needs of each HPWH. Berkeley Lab's CalFlexHub project is pioneering price-driven load flexibility by developing and deploying cost-minimizing controls utilizing setpoint setting signals for fleets of HPWHs in response to varying price profiles. Control development is based on simulations using the Flexible Heat Pump Water Heater Performance Predictor which captures the control decisions of a residential, integrated HPWH manufacturer's on-board controller. The proposed cost-reducing controls respond to constantly changing price profiles, providing the ability to change the price profile to generate load curves as needed to maintain grid stability. Preliminary simulations studying the load shaping capabilities of price-responsive controls on a fleet of 60 HPWHs have demonstrated an average of a) 135.4% increases in load during low-price periods, b) >36.8% reductions in electricity peak-price period, and c) 6.2% electricity cost savings.

INTRODUCTION

Dynamic pricing has been investigated to answer the question of how load shifting and load shedding can help with increasing the utilization of renewable energy sources. In this paper, we focus the attention on starting a catalog of types of responses that be caused and trying to determine the type of price curve that is necessary to cause exactly these responses. Dynamic pricing can have a variety of functions, influenced by the factors used to determine them. Possible factors extend across: the current wholesale price, observed load ramps and peaks; the marginal greenhouse gas emissions caused by electricity generation; additional information about expected consumption patterns based on the day of the week; season, or weather forecast; and might also include the transmission grid and distribution grid conditions like transmission capacity limits or known local generation and consumption capacities. Also, prioritizing

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end uses, locations or communities as a measure of political steering can be a differentiating component of dynamic pricing.

Figure 1 indicates how these price components can be categorized. The top left quadrant shows price components that are based on operational needs and actual physical grid limitations, such as grid congestion of distribution or transmission grid level. The bottom left quadrant names economic implications of the operational side: This quadrant includes the wholesale price and peak-day pricing components. The top right quadrant considers politically chosen price components that are rooted in grid limitations. An example of this category is the redistribution of costs for equity measures such as connecting remote areas or providing equitable tariffs for disadvantaged communities. The bottom right quadrant includes politically chosen economic incentives, such as price components representing the marginal greenhouse gas emissions of the current hour's electricity generation as well as special rates for households with low income. However, the assumption is that consumers will respond to high prices and low prices by shifting loads towards those times, not considering the factors that play into price construction.

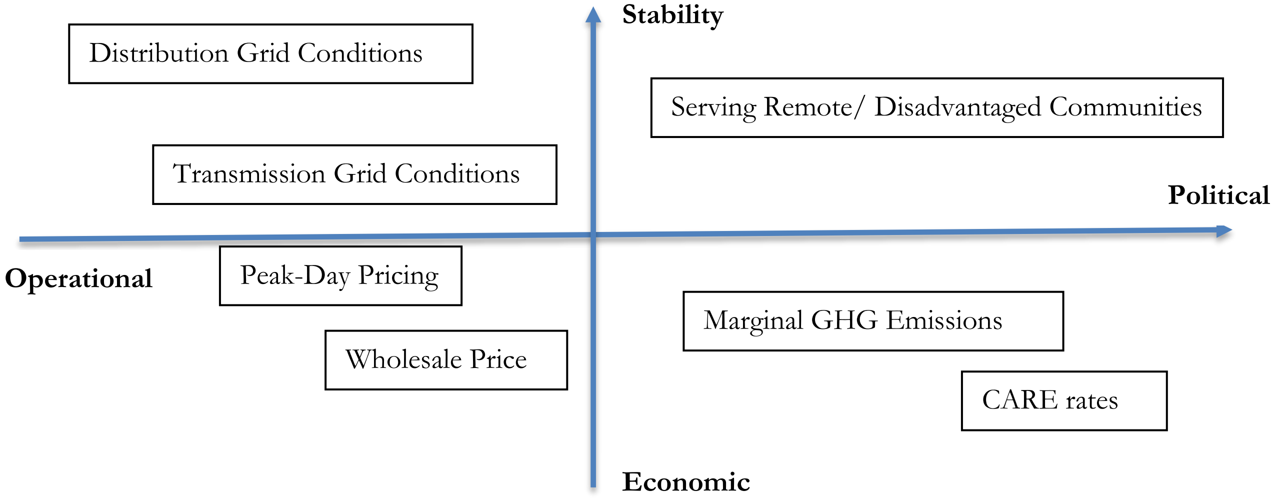

Figure 1: Categorizing components of a dynamic electricity price in two dimensions. The y-axis indicates for each price component whether it is based on the grid capacity in a specific moment or rather on the cost that is needed to provide the required service. The x-axis indicates whether it is quantified rather by operational or by political reasoning.

According to Hoeschele, Haile, & Grant (2022), heat pump water heaters (HPWHs) can simultaneously achieve decarbonization and load flexibility goals by using a 50-80 gal/189-303 liter water storage tank, a heat pump as the primary heating source, and electric resistance elements as backup heating. Replacing a natural gas water heater with a HPWH can reduce carbon emissions by 50-70% in California and 58% nationwide (Brockway & Delforge, 2018). HPWHs are the most energy-efficient form of water heating, leading to an increase in market share (Nevius, Powell, & Meek, 2022) (Wang, Kusnandar, Lin, & Tsai, 2021). Recent studies have developed load shifting controls using cloud-based signals to maximize electricity consumption during high renewable energy production, minimize consumption during weak evening periods, and ensure adequate hot water supply (Carew, Larson, Piepmeier, & Logsdon, 2018). The controls shift load from high-price, evening peak periods to low-price mid-day periods by modulating the set temperature of the water heater (Hoeschele, Haile, & Grant, 2022) or sending CTA-2045 signals during mid-day. However, prior studies have shown weaknesses in the existing control strategies, and experimentation with different solutions has been conducted.

Grant et al. found that load shifting controls using California's Time Dependent Valuation metric could decrease operation costs by up to 84% on days with high variation in hourly TDV multipliers, but increased operation costs on days with low variation (Grant & Huestis, 2018). Carew et al. developed a methodology to translate a price profile into different set temperatures but found that the algorithm did not perform well when applied to a broader array of draw profiles (Carew, Larson, Piepmeier, & Logsdon, 2018). Hoeschele et al. reduced peak period electricity consumption by up to 73% by performing load shifting on HPWHs serving four apartments but noted that increasing the set temperature of a HPWH could cause the use of electric resistance elements instead of the heat pump, increasing electricity costs.

METHODOLOGY

The following subsections provide information on 1) the utilized HPWH modeling tool, 2) the price-responsive control algorithm, 3) the draw profiles, and 4) the metrics to differentiate the resulting load and price profiles.

Heat Pump Water Heater Modeling

The simulation in this paper models a fleet of HPWHs with controls emulating a manufacturer's products dependent on 60 dedicated draw profiles and varying price profiles. The used model is the Flexible Heat Pump Water Heater Performance Predictor, which has the heat pump, resistance elements, and control logic all closely match the designs and behavior observed in field monitoring studies (Hoeschele, Haile, & Grant, 2022).

The storage tank model features 20 segments at different depths in the tank. The storage tank size assumed for our simulations is 80 gallons. Heat transfer calculations track the standby losses, water flows, and heat additions to each segment of the tank for each timestep. 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 1.23 kW-thermal, with a COP curve matching the observed field performance.

Price-Responsive Supervisory Control

The price-responsive control algorithm utilized in this paper increases or decreases the set temperature of the HPWH in response to changes in the price profile. The goal is to 1) increase electricity consumption when prices are low, and store extra energy in the HPWH storage tank, and 2) avoid electricity consumption by relying on storage when prices are high. For any given price profile the algorithm 1) identifies the mean and standard deviation of the profile, 2) compares the current price to the mean price ± one standard deviation, and 3) changes the set temperature. The controller uses a base set temperature of 125 °F / 52 °C. If the price is above the mean plus one standard deviation, the controller reduces the set temperature to 120 °F / 49 °C. If the price is below the mean minus one standard deviation, the controller increases the set temperature to a value between 125 °F / 52 °C and 140 °F / 60 °C depending on the typical daily electricity consumption of the HPWH. The variation in set temperature during low price times provides an ability to adjust load shifting control in response to different occupant behavior patterns.

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.

Metrics

This paper's goal is to evaluate how exactly the electric demand profile differs with different price profiles. In order to avoid to many parameters, we look at a price signal that is shifted. We characterize the load curves of HPWHs using specific metrics. Firstly, we examine the distribution of charging activities throughout the day. Secondly, we compare the operating costs of unsupervised HPWH operation, that is operation as implemented by the manufacturer, to the supervised operation, that is responding to the different shifted price profiles using the described price-responsive supervisory control. Finally, we analyze the distribution of price fluctuations, both increases and decreases, over the course of the day.

For the purposes of this paper, we present a universal dynamic tariff that is dependent on the observed grid state in historical data from California in 2019. We use the methodology to derive a dynamic tariff as described by Gerke et. al. (Gerke et al. 2022) where the price is mostly influenced by a specific hour's system-level peak load and by the observed three-hour load ramp towards that specific point in time. Figure 2 shows the composition of the price signal.

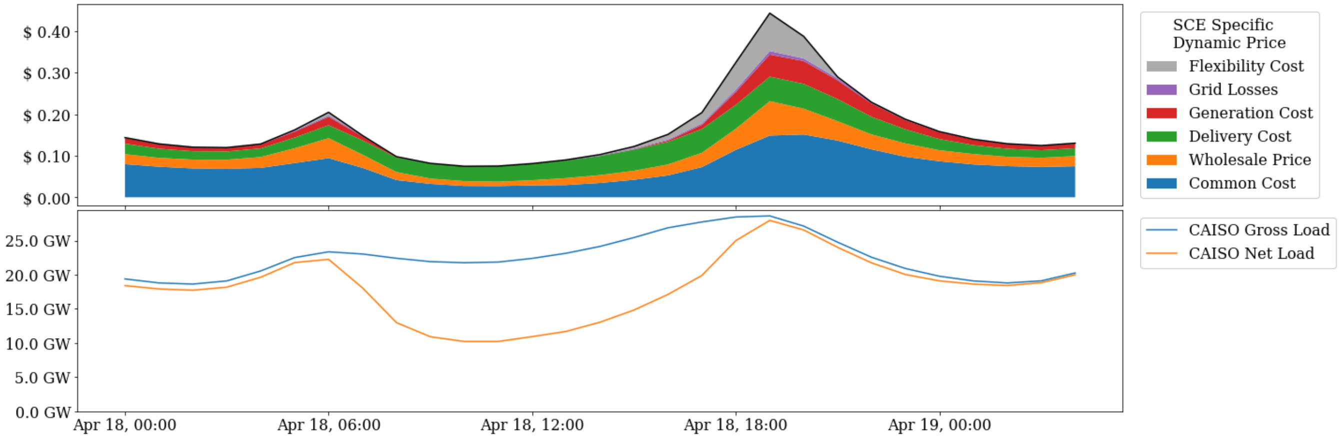

Figure 2: The composition of the price signals takes several factors into account. The main driver of the price curve is the net load in the California power system (CAISO), which is the total power subtracted by utility-scale renewables.

RESULTS

We simulated 24 price profiles, ranging from a price shift of -11 to a price shift of +12 hours. Figure 3 displays an example of an ensemble of four price profiles that are shifted by different time intervals (-6 hours, 0 hours, +6 hours, and +12 hours) and the resulting load shapes.

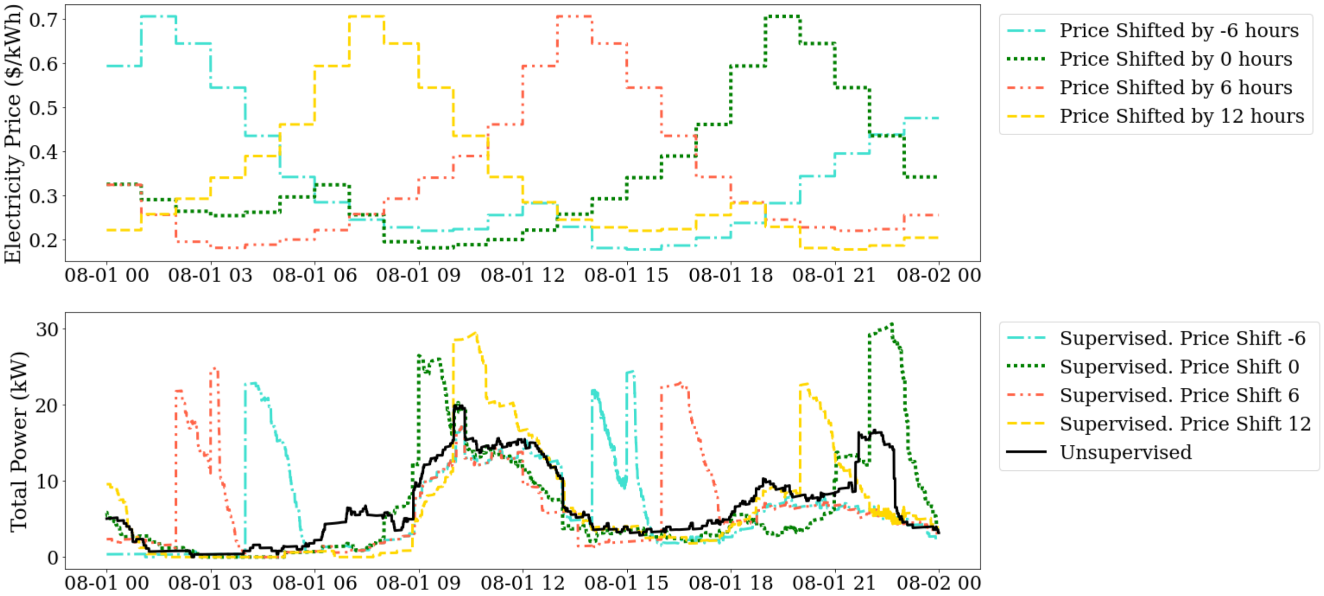

Figure 3: Response of a fleet of 60 HPWHs to shifted electricity price curves. The upper plot shows the electricity price and the lower plot shows the response in the resulting load.

Looking at times of high and low price, we can validate that during the low-price periods, that is average price minus one standard deviation, the fleet responds almost uniformly by increasing loads. This is shown in Figure 4. In high-price periods, where the price exceeds the daily average plus one standard deviation, the fleets reduce load except for a few outliers. A fractional change in load of one means that demand has increased by 100%. This value is also used in the case where the unsupervised operation leads to zero demand and demand is triggered by the supervised operation: A good example for this behavior are the price profiles shift +4 to +7. These have low-price periods between 2am and 5am, where no water heating happens under unsupervised operation in most of the simulations. The increase in these low-price periods is therefore infinity, which we interpret as 100% in the context of this study. Another interesting example are price profiles shift 8 and 9 with an average increase of 0% during the low-price period. The low prices coincide with the morning demand, therefore in the unsupervised operation, most of the HPWHs are already running, leaving no room to further increase the power consumption. With respect to load reduction during the high-price period, it is worth having a look at price profile shifts -7 and -8. Apart from outliers, there is no reduction of load during the high-price period, because it falls in the night time where no loads were to be expected anyway. On average, the power consumption across all HPWHs and price profiles is increased during low-price periods by 135.4% and is reduced during high-price periods by 36.8 %.

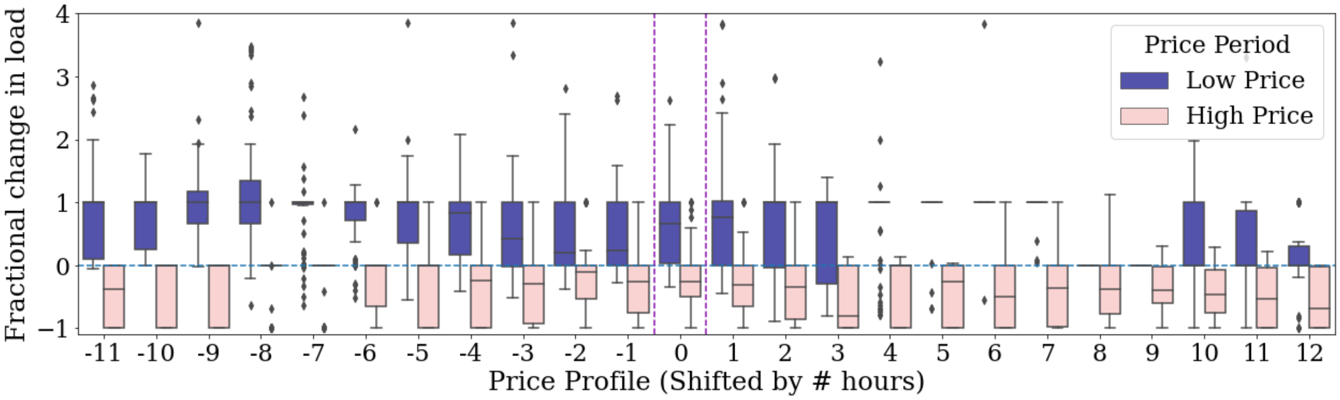

Figure 4: Low-price and high-price periods and the fleet's response in electricity consumption. The x-axis shows which price profile was used in the respective simulation.

Figure 5 depicts a heatmap comparing shifted price signals, where each column represents a Price Shift from -11 to 12 hours. The first column shows the "No supervisory control" scenario, while the zero-hour shift is the unmodified price shape. Under supervisory control, it is clearly visible that two main heating events happen and that these events are directly related to the shifting. The first main event happens around 9am for the unmodified price shape and coincides with ramping up of renewable electricity generation due to sunrise and California's strong dissemination of PV panels, both behind-the-meter and utility scale. The second main event happens around midnight and coincides with the end of the daily evening consumption peak. Both main events are therefore driven by excess supply of electricity. Further, two additional notable events are visible across all load shifts and the unsupervised operation of the HPWHs. The stronger of these two happens from 9am until 1pm, while the weaker event happens from 6pm until 10pm. The consistency of the events across price shifts indicates that these are demand driven, that is due to consistent water consumption patterns of the HPWH users. The only price shifts where the main "demand" event changes are the price shifts of two and three hours, where the low price coincides with or precedes the main water demand. Here the price is particularly low around 5am and 6am, which coincides or even precedes the main water demand and therefore reduces the amount of water that needs to be recovered later.

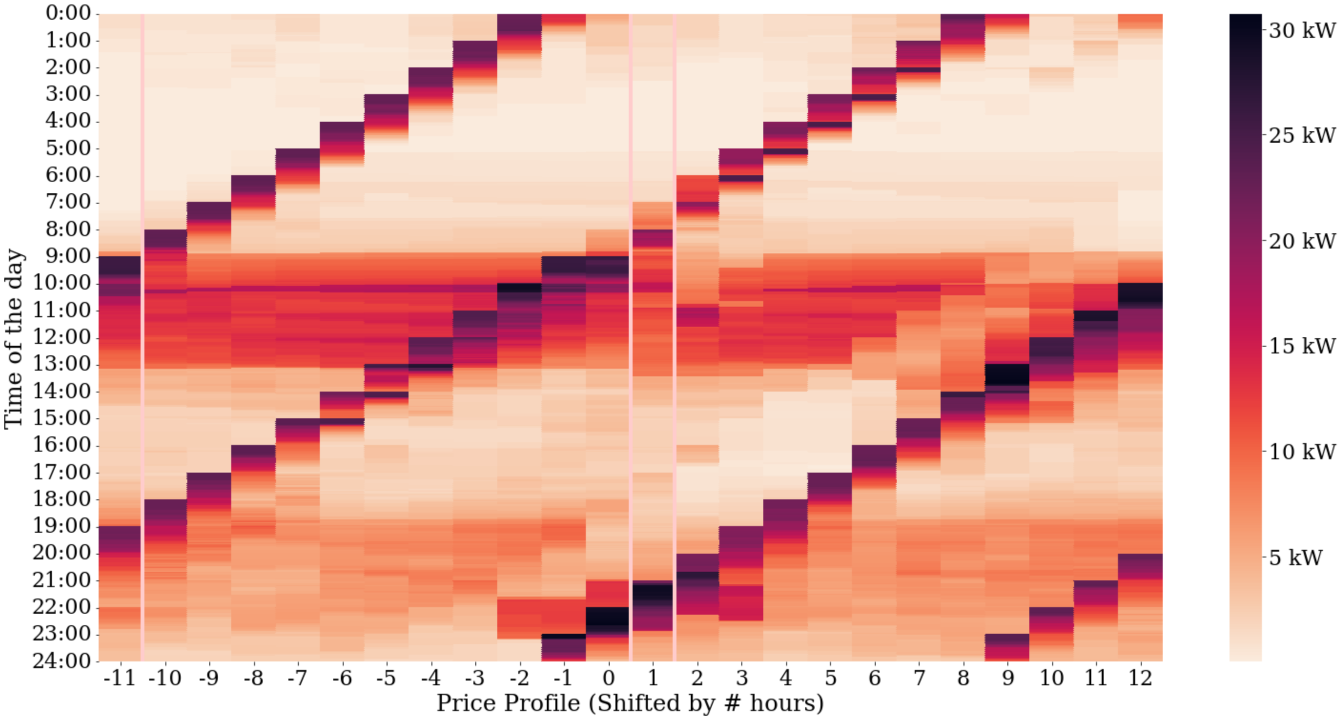

Figure 5: The power consumption of the fleet of HPWHs is visualized. The y-Axis shows the hour of the day. The x-axis indicates which price shift has been applied. The first column on the x-axis represents the unsupervised operation of the fleet, while all other columns represent a specific price shift from -11 hours up to 12 hours. The color scale goes from white, which means no consumption in a specific hour, up to black with 30 kW when the whole fleet is charging.

The capability of the investigated algorithm to have the HPWHs operate optimally under the given price profile also depends on the relation to the draw pattern as required by the individual households. Figure 6 shows the daily operation cost of the fleet of HPWHs under the price profiles -11 to 12. On average, 14 out of the 24 price profiles of the load profiles cause the HPWH operation to save money with respect to the applied price profile. The other seven price profiles can be grouped into three price shifts groups -7 until -5, -3 until -2 and 5. The interpretation of this finding is that in these cases, the low-price periods are not well aligned with the observed user behavior. As can be seen in the previous plot, the pre-heating phases shift across each hour, whether there is demand for hot water or not.

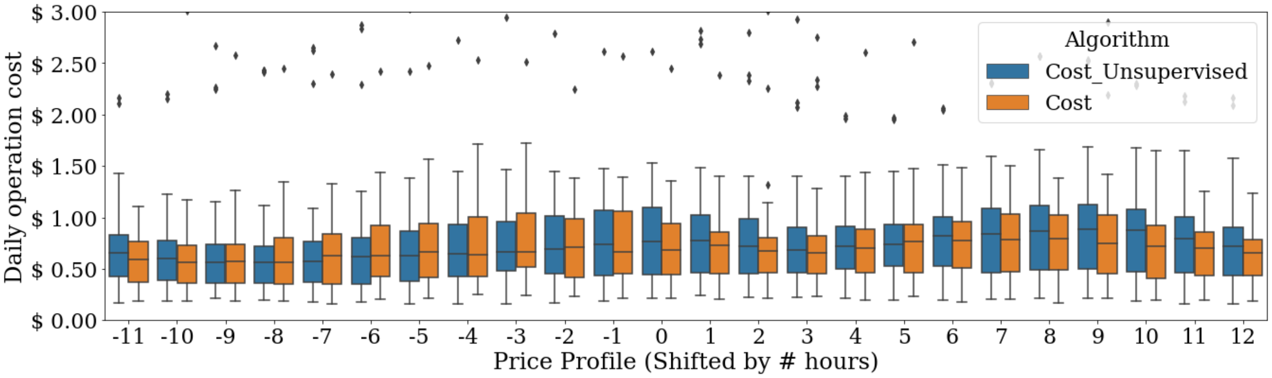

Figure 6: The daily operation cost of the fleet is scaled on the y-axis. The individual price profiles are on the x-axis. Blue (darker) boxes are unsupervised operation and orange (brighter) boxes represent supervised operation.

While individual HPWHs can achieve savings of 58.6 %, those cases have to be discarded as outliers. When summing up the cost differences of all 60 HPWHs of the fleet separately for each of the 24 investigated price profiles, we can state that the investigated supervisory control algorithm is able to reduce the fleet's operation cost for 22 of 24 price profiles, with average savings of 6.2 %. In order to get a better understanding of how the customers' savings are realized Figure 7 shows the total cost difference. That is, the red color shows where the algorithm is causing additional cost with respect to the unsupervised operation, and the blue color indicates that customers are saving money during that time. In contrast to Figure 5, we identify a time period before the evening peak, where in case of the zero-shift between 6pm and 9pm the supervisory control is saving money for the customers. Comparing this back to Figure 5 completes the picture that the high price period is successfully avoided.

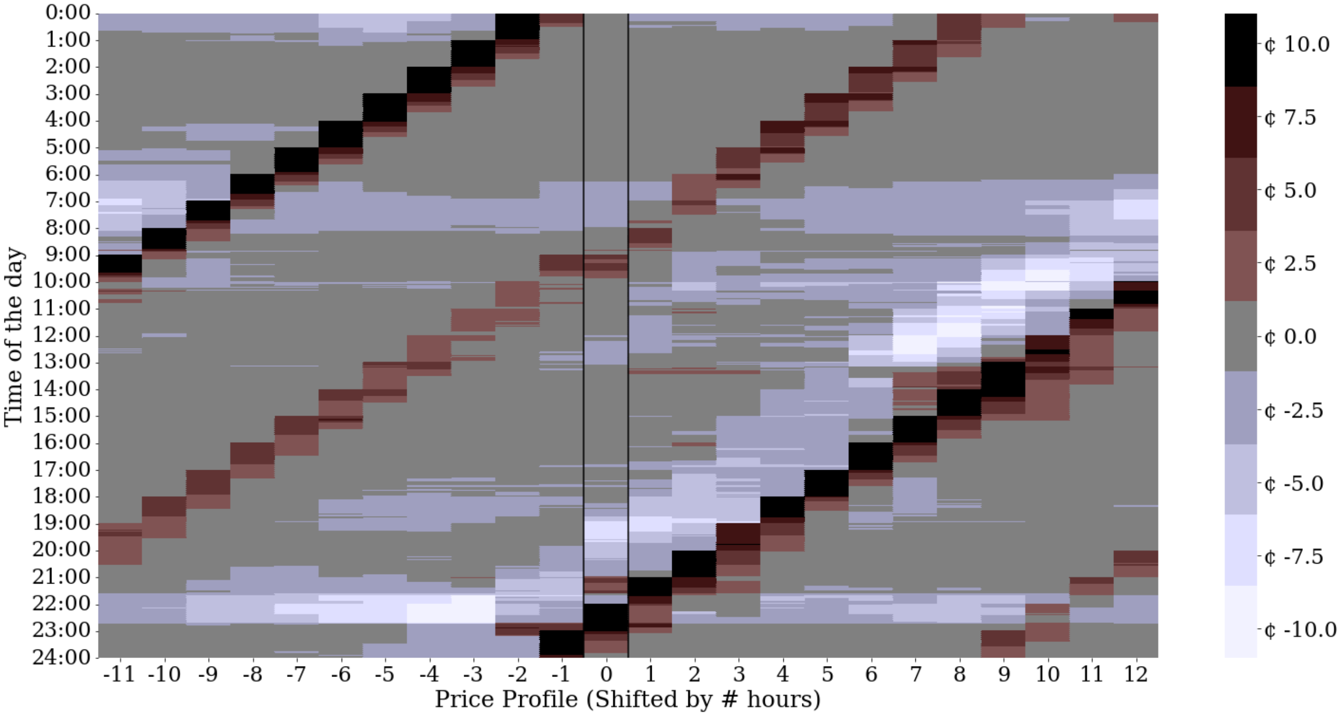

Figure 7: The hourly operation cost difference between supervised and unsupervised operation of the fleet. The additional cost is indicated with colors ranging from white/blue (savings) over light grey (no change) until red/black (increased operation costs) on average per HPWH. The individually shifted price profiles are on the x-axis.

DISCUSSION AND FUTURE WORK

Applying shifted price profiles to the operation of the price-responsive fleet of HPWHs reveals a couple of findings. First, it can be observed that two important factors play into the operation of the simulated operation, which are the price profile and the water draw pattern of the buildings' inhabitants. Both factors contribute significantly to the HPWHs' electricity consumption. The price profile adds to the variability of the power consumption, and can cause significant power increase as well as decrease at any time of the day. The flip side of this finding is that the investigated algorithm is not always optimal with respect to the financial impact on the customers; pre-heating water in the early morning hours such as 2am doesn't provide value to the customers and will therefore probably be ruled out by future versions of the supervisory control algorithm.

Second, it can be observed that the decrease in consumption is limited. Since the quality of service must be provided for the customers, it depends on the size of the water tank and its insulation, how long in advance water heating makes economical sense. The increased hot water consumption in the early morning hours across all households is compensated without regarding the applied price profile. Therefore, increasing the electricity price between 9am and 1pm has only a limited effect. It also can trigger the resistance element, creating additional cost for the customers, when the set point is lowered despite high consumption. It is an interesting research question though if adjusted pricing schedules would be capable of reducing that base consumption, which is a question that we will investigate in future work. In order to avoid this behavior, price profiles would likely need to include low-price periods overnight and high-price periods in the morning.

It remains unclear if the peaking at the start of the low-price period and at the end of the high-price period are really necessary from an operational standpoint. Re-heating could potentially be delayed by part of the fleet, thereby increasing the economic viability of the demand response and reducing the system level ramping at the beginning of a new hour. We will investigate additional supervisory control algorithms in future work.
This study shows that load shedding and load increase are possible with the investigated simple strategy, which confirms our initial hypothesis and strengthens the credibility of our research direction.

In future work, we will validate our approach in a laboratory environment to investigate the long-term reliability of HPWHs with load-shifting controls. A follow-up study will investigate customizing the assumptions and controls to different manufacturers' products and updating the controls to respond to hot water consumption day-to-day variability. This way, we also plan to point out how the paper's findings can contribute to the further development of AHRI Standard 1430-2022 (AHRI, 2022)

CONCLUSION

Due to the "electrify everything" policy of the United States and many places around the globe, flexibly programmable heat pump water heaters (HPWHs) will become widely disseminated during the coming years. Using their flexibilities to support the electricity grid is a valuable contribution to the energy transition. One possible way to direct the flexibility of HPWHs is by sending signals of price shapes, so-called dynamic prices or price profiles. In this paper, we describe that shifting existing price profiles by hour intervals is a possible way to shift the energy consumption associated with heat pumps while still maintaining quality of service and saving money for the customers. We investigate a simple supervisory control algorithm that changes the set temperature of the HPWHs whenever the current price diverges from the average daily price by more than the standard deviation. We find that this algorithm in combination with the investigated 24 price profiles can trigger load increase and load shedding at any hour of the day while maintaining the quality of service level. In our future work, we will investigate a wider range of price profiles and supervisory control algorithms and add additional metrics to allow grid operators to choose the optimal strategy for their operational needs.

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