Can Heat Pump Water Heaters Teach the California Duck to Fly?

Pierre Delforge and Joseph Vukovich, Natural Resources Defense Council

ABSTRACT

California has set ambitious goals for renewable electricity, energy efficiency and greenhouse gas emissions reductions. The pursuit of its renewable electricity goals is already causing grid balancing challenges known as the "duck curve". Can heat pump water heaters contribute to the state's energy efficiency and emissions goals, while also helping mitigate the duck curve and integrate deep renewables?

Heat pump water heaters are known for their high efficiency, but there is little experience with using their thermal storage capability to provide flexible demand resources to the grid and help balance renewable energy resources. Flexible water heating has largely focused on electric resistance technology so far.

This study analyzes the potential for demand flexibility with heat pump water heaters, using both software simulation and lab testing to assess the technical potential for shifting operation from high-price to low-price hours by leveraging their thermal storage capability. Lab testing was performed on four models representing both hybrid technologies using the R134a refrigerant and heat pump-only technologies using CO_2 as a refrigerant. These products were used to map compressor performance at high temperatures, calibrate the simulation model, and validate simulation results. The simulation software was then used to model the operation of several heat pump water heaters of various capacities, under a range of conditions and control strategies.

Results indicate that heat pump water heaters can deliver both efficiency and flexibility benefits, but they require more sophisticated control strategies that balance thermal storage with efficiency losses from higher temperatures.

I. Introduction

A. Water Heater Background

Water heating is a significant energy expenditure in US homes, totaling approximately 18% of the average home's energy consumption according to the Energy Information Administration (EIA 2013). Approximately 90% of homes in California use natural gas-powered water heaters (CEC 2014). At one time, this would have been the environmentally-preferred option—burning natural gas is less polluting than using electricity from a grid powered primarily by coal plants. However, as California's grid has become cleaner, the situation has reversed. Drawing from a grid with a significant, continually growing amount of renewable energy presents a compelling alternative to natural gas water heaters (NGWHs).

There are two primary types of electric water heaters: electric resistance and heat pumps. Electric resistance water heaters (ERWHs) create heat by passing an electric current through a resistive element. Heat pump water heaters (HPWHs), in contrast, operate like refrigerators in reverse. They use energy to absorb heat from a cooler part of the environment and deliver it to a warmer portion. This process is fundamentally more efficient than generating heat through electric resistance, and consequently HPWHs are usually two to three times as efficient as the most efficient ERWHs (DOE 2018).

Utilities have used ERWHs as part of large, widespread grid flexibility programs for many years (Hledik, Chang, and Lueken 2016). More recently, there has been expanded interest in this subject in the United States due the Energy Efficiency Improvement Act of 2015, which, among other things, granted an exemption from energy efficiency standards for certain ERWHs so that they could be used for demand response programs (FERC 2016).

At the same time, the water heater market continues to evolve. Although currently a small share of the market at 1% of electric water heaters (EPA 2017), HPWHs offer substantial environmental benefits due to their greatly increased efficiency compared to ERWHs. Further improvements are being developed and shipped, such as HPWHs that use CO_2 as a refrigerant. These have a small market share currently but offer even higher levels of efficiency and may be poised for further growth (Zhang, Chin, and Wang 2015). The already high efficiency of HPWHs make them an attractive option in regions that have set ambitious climate goals, such as California. However, whether the high efficiency of HPWHs can be paired with the benefits of grid flexibility has not been explored at significant scale. HPWH grid flexibility pilots have been comparatively much smaller scale, such as a 20-site study by Duke Energy (Gurlaskie 2016).

This study investigates the potential benefits of HPWH thermal storage using simulations of HPWH performance. This paper proceeds as follows. First, the storage potential of HPWHs is explored in greater detail. Next, the HPWH simulation, including the laboratory data used to verify it, is discussed. Finally, the simulation results for different models of heat pump water heaters under a variety of conditions and control strategies are examined, followed by a discussion of the results and potential greenhouse gas (GHG) benefits.

B. Thermal Storage and Grid Flexibility

Conventionally, a water heater's operation is driven by the demand for hot water in a building, regardless of the time of day at which it occurs. However, electric water heaters can be controlled to prioritize heating at times when power is abundant, low-price and low-carbon, and avoid heating at times when power is in high demand, higher-price and higher-carbon. In other words, they can pre-heat water, and store thermal energy until it is needed later. This thermal storage is a form of grid flexibility.

There are several types of grid flexibility services (Pierpont et al. 2017), including emergency and short-term reserve, ramping, intraday balancing, and seasonal balancing. This study focuses on intraday balancing, i.e. shifting electricity consumption from hours of peak demand to hours of low demand, which is where the contribution of HPWH is most promising. This reduces the need for construction of peaking generation capacity. It also means that fewer inflexible fossil power plants need to be idled during the day in order to ramp up to meet peak demand in the evening. Finally, shifting demand to off-peak hours when solar power is plentiful helps integrate additional solar power to meet the shifted demand. These changes lead to increased use of clean energy, reduced use of fossil energy, and reduced GHG emissions.

These attributes of grid flexibility are of particular interest to California because of its so-called "duck curve." Named after its visual resemblance to a duck in profile, the duck curve is a graph of net electricity demand after subtracting renewable power generation. In effect, it shows how the demand for non-renewable energy resources varies over the course of each day. On a typical spring day (and to a lesser extent in other seasons), the duck curve shows a slight peak of moderate demand in the morning, followed by a steep decline in the afternoon as solar reaches peak generation hours, and finally a still steeper upward ramp in the evening as solar generation wanes and demand increases. The steep afternoon ramp and high evening peak mean that some dirty, inflexible fossil fuel plants must be kept idling during the day because they are not flexible enough to otherwise be able to meet the steep increase in demand. This forces curtailment of some renewable generation, hurting the economics of these resources and making it more difficult to integrate additional solar into the grid.

Grid flexibility offers the ability to shift some demand from the evening peak to earlier in the day when solar power is readily available. This means that less inflexible fossil generation capacity needs to be kept idling in order to meet the evening peak. It also means that additional solar capacity can be installed in the afternoon to meet the shifted demand.

There are multiple strategies for implementing grid flexibility that alter the operation of HPWHs in slightly different ways. It is important to consider the risk that a given control strategy might result in a consumer running out of hot water, a so-called "runout event." Runout events are disruptive and make it much less likely that a consumer would be willing to participate in a flexibility program. Runout events can occur with all types of water heaters and can be minimized by sizing the water heater accordingly to the expected draw volume. Sizing guidelines specify a maximum of 12 runout events per year (Hiller 1998). While technology and usage (e.g. low-flow fixtures) have changed substantially since this work, we do not believe that this would directly impact consumer tolerance of runouts and thus we used this guideline to determine the success of each simulation run.

Thermal storage, like battery storage, does however, come with the cost of reduced efficiency. Heating water in advance instead of as it is needed means that some thermal energy will be lost as the hot water sits in the tank. Grid flexibility also requires HPWHs to operate at higher temperatures part of the time, to increase the HPWH thermal storage and minimize energy use over peak, which also imposes an operational efficiency penalty. This study investigated whether grid flexibility could be implemented to minimize efficiency losses while maximizing customer costs and GHG emissions reductions.

II. Methodology

In order to analyze the potential benefits of grid flexibility, this study simulated the operation of HPWHs, under different conditions and control strategies. Simulation runs covered all combinations of 4 HPWH brands, 3 tank sizes (50, 65, 80 gallons), 16 California climate zones, in homes ranging from 1 to 5 bedrooms, with 3 price signals and 3 control strategies. Lab testing was also performed to 1) calibrate the simulation model at higher setpoint temperatures; 2) validate simulation results.

A. Simulation Model

The study uses a simulation model, HPWHSim, first developed by Ecotope in 2012 (NEEA 2015). The simulation is designed to model HPWH operation in a variety of configurations. It takes annual hourly profiles for hot water draws, inlet water temperature, and surrounding air temperature as inputs. It then performs a minute-by-minute simulation of the water temperature in the tank, activating the compressor and resistive elements of the HPWH as necessary. The simulation has previously been validated using real-world performance data (NEEA 2015) and is currently used as a component of the California Building Energy Compliance Calculator (CBECC-Res), the California Energy Commission's open-source software used to determine compliance with building codes for low-rise residential buildings (CEC 2016).

The model is configurable to closely represent the most common HPWH models on the market, by adjusting the quantity and arrangement of resistive heating elements, condensing coil arrangement, compressor performance, and built-in manufacturer controls. The location of the HPWH in the home and the climate zone are modeled through representative inlet and air temperature hourly profiles. The size of the homes is modeled by different draw patterns for each home size from 1 to 5 bedrooms.

To calibrate and validate the performance and accuracy of the simulations, laboratory testing data was used. While a significant amount of research has been conducted regarding the performance of HPWHs, grid flexibility may require HPWHs to operate outside the performance ranges that have been previously studied. For instance, many HPWHs typically operate at temperatures between 120°F and 130°F. However, storing sufficient thermal energy to enable grid flexibility could require operating at higher temperatures, such as 140°F or potentially up to 160°F. As a result, additional testing was performed to measure the performance of HPWH compressors at these higher temperatures. These results are displayed below in Figure 1.

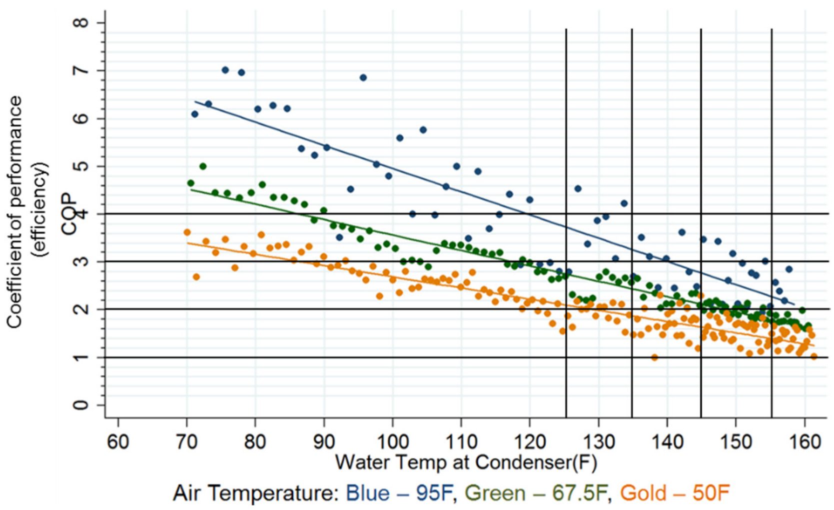

Figure 1. Relationship between water temperature and compressor efficiency. *Source*: Author Calculations.

Figure 1 indicates that compressor performance degrades as water temperature increases. A significant factor in this effect is the thermodynamic cycle of the refrigerant used in many HPWHs—R134a. HPWHs using R134a can be very efficient, between 200% and 400%

efficient, when heating water up to temperatures of 120°F. However, this efficiency is almost halved when heating water to 160°F.

It is important to recognize that not every HPWH uses R134a, and in fact one of the HPWHs examined in this study uses CO_2 as a refrigerant. This model was able to provide thermal storage at higher temperatures without the compressor efficiency loss of the models using R134a. While CO_2 is currently a premium technology in HPWHs, this could change in the future.

B. Hot Water Draw Patterns

Special care was taken to ensure a significant diversity in water draw patterns. Simulating the same daily draw profile for an entire year would have made simulation results very sensitive to different draw patterns and potentially non-representative. Instead, unique draw patterns were extracted from CBECC-Res. These patterns are the result of mixing and matching 48 real, observed draw days to create annual draw patterns for each occupancy level. They take into account the day of week (weekdays and weekends have different typical draw patterns), holidays, and seasonal effects (winter draws are significantly larger due to colder inlet temperatures, higher user temperature requirements, and higher thermal losses). The result is a representative, unique draw pattern for every day of the year.

C. Price Signals

The study uses price signals to indicate to the HPWH when to charge (load up) and when to avoid running (shed). Control strategies are the algorithms that determine HPWH operation to minimize operational cost for each price signal. The price signal can be either a retail price of electricity, or the marginal cost of electricity from a utility's perspective, or a building code energy metric like California building code's time dependent valuation (TDV).

Utility Marginal Costs. This price signal represents grid energy costs from the utility's perspective. This also represents a societal cost in the sense that utility marginal costs are passed on to all customers as part of electricity rates. For this study, we used publicly available data from the California Public Utilities Commission's (CPUC) General Rate Case phase 2 to compile Pacific Gas and Electric's projected hourly marginal costs for 2024. We chose 2024 because it represents a mid-term horizon that allows policy planning and implementation, and was the latest year available. These prices include the cost of energy generation (hourly wholesale market prices), GHG emissions costs under California's Cap and Trade policy, capacity costs (the cost of maintaining reserve capacity to serve demand at all times), and power transmission and distribution costs. PG&E's marginal costs are shown below in Figure 2.

This utility perspective does not include fixed utility costs paid by utility customers for non-energy costs such as utility administrative costs, cost of capital, and shareholder profits, and is therefore significantly lower than retail rates. Negative prices in the middle of the day represent times when demand is low and solar power abundant, and the utility needs to curtail solar and wind generation to keep inflexible fossil plants running ready for the afternoon ramp.

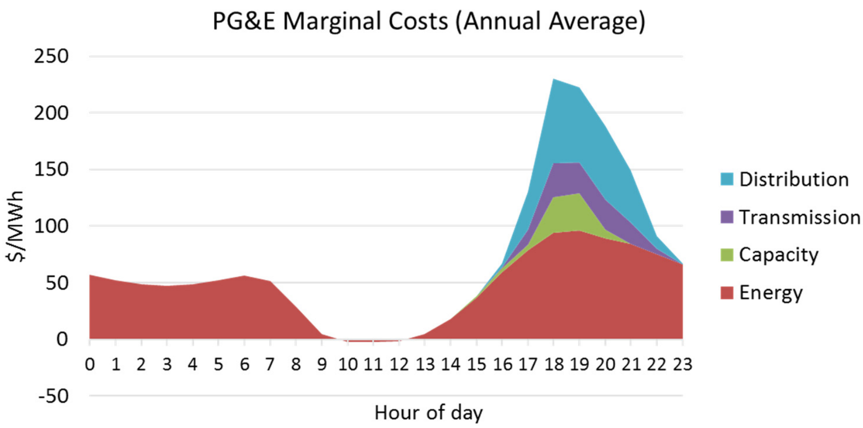

Figure 2. Pacific Gas & Electric hourly marginal electricity costs, annual average. *Source*: CPUC 2016a.

Residential Time-of-Use Rates. Under a time-of-use (TOU), or time-varying rate plan, customers pay more than average for electricity at peak hours (e.g., from 5:00-9:00 pm) and less than average at times of low demand. TOU rates incentivize customers to adjust their behavior to save on energy costs, and perhaps more importantly to use flexible equipment that can automatically shift load from high-price to low-price time periods.

Under CPUC policy (CPUC 2016b), California investor-owned utilities (IOUs) will transition their customers to a default TOU schedule in 2019. These 2019 default TOU schedules are transition schedules designed with minimal peak/off-peak price differentiation to avoid negatively impacting customers, and as such provide low financial incentives for load shifting. More highly differentiated TOU are also available for customers to voluntarily opt-in, for example for customers with electric vehicles who want to charge at night on low off-peak electricity.

As none of the available optional rates were designed with heat pumps in mind when this study was initiated in summer 2017, we developed our own hypothetical "NRDC Flexible Water Heating rate," that is reflective of PG&E marginal costs, with a retail rate adder to cover fixed utility costs. We designed the rate with a roughly 3:1 peak/off-peak differential in order to provide a meaningful price signal for load shifting. These hypothetical TOU rates are shown below in Figure 3.

Hypothetical Summer and Winter Time-of-Use Rates

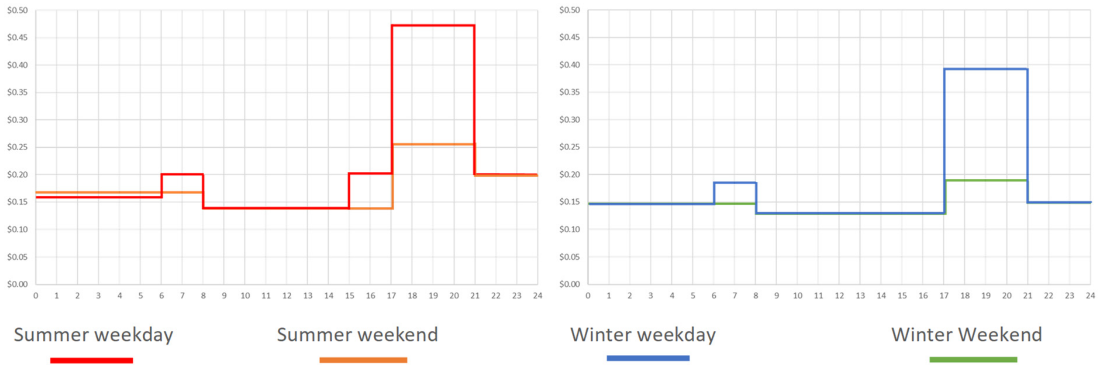

Figure 3. NRDC hypothetical time-of-use rate. *Source*: Author Calculations.

E. Control Strategies

The study simulated 3 control strategies, from the simplest and easiest to implement, to the most sophisticated that requires technology development and isn't readily available today. When investigating the three options, a baseline setpoint of 125°F was used. Simulations tested the performance of each strategy at 135°F, 145°F, and 155°F.

Simplest: On/Off. The simplest strategy simply blocks the HPWH from operating during peak hours (5 pm to 9pm) when power is comparatively expensive. The advantage of this approach is that it requires little investment to implement—a user could install a simple timer system to block heating during peak hours. This simplicity is also its chief limitation. If hot water draws during peak period exceed the tank's storage capacity, it is unable to recharge. This can lead to runout events, causing water to be delivered to the customer at a lower temperature than desired.

Increasing the water storage temperature increases storage capacity but also leads to higher energy losses from operating at a higher temperature where HPWH compressors are less efficient and standby thermal losses higher.

Smarter: Load-up/Shed. A more sophisticated strategy is to load-up (pre-heat) water during off-peak hours but only just in time for peak, in order to minimize the time spent operating at a high temperature; and to "soft shed" during peak hours, meaning delay recharge but still allow charging in cases of exceptionally high draws to prevent runouts. The load-up phase is an essential precursor to the shed phase, in order to increase storage capacity and allow shedding over peak with minimum risk of runout.

The load-up/shed strategy was designed to improve upon the on/off strategy while still remaining relatively simple to implement. It works well with a TOU price schedule, and can be implemented by a local control module, without requiring a remote flexibility program to be offered by the utility or a third-party. However, this also limits it to TOU rate schedules, and it cannot handle dynamic price signals such as from a utility or third-party flexibility aggregator.

Smartest: "Optimal Price" Optimization. The most advanced strategy uses the projected hourly price of energy over the next 24 hours to compute the optimal pattern of pre-heating to minimize cost and runouts for this 24-hour price schedule. The price schedule can be either a 24-hour day-ahead price signal from the utility, or a fixed time-of-use price signal. The algorithm considers the effects of reduced efficiency at higher operating temperatures, and balances price arbitrage with efficiency losses. For example, it only pre-heats minimally if peak prices are low that day, but pre-heats to maximum temperature on days when the differential between on- and off-peak prices is the highest.

III. Findings

To fully examine the results and implications of this study, simulation results for each control strategy are discussed individually, followed by a discussion of the broader policy implications. Specific numbers discussed for each strategy refer to simulation results for a median-size 3-bedroom home. Results differed only slightly for other home sizes and are not discussed separately here for the sake of concision.

A. Control Strategies

On/Off. At 135°F, control scenarios were able to meet customer demand in all except the coldest CA climate zones, but only with larger tank sizes, 66 and 80-gallon. Smaller tank sizes incurred more runouts than the set limit. Customer TOU savings were minimal or negative, varying from 7% savings to 8% extra costs depending on models and climate zones, with a median of 0% savings. This reflects the fact that price gains from load shifting were offset by efficiency losses from operating at a higher temperature. At 145°F and 155°F, 50-gallon tanks successfully implemented on/off controls in more climate zones but with an average cost increase of 9% and 23% respectively. The CO_2-heat pump model offered significant savings of between 11-19% (median of 16%) in all climate zones with no runout events.

In summary, on/off control strategies on hybrid HPWH require large tanks to avoid runouts, and yield little or no savings.

Load-up/Shed. This strategy was significantly more effective than on/off. Using a 135°F load-up setpoint, the hybrid models met customer demand in all climate zones except climate zone 16 (colder climate, mostly the Sierra Nevada), and offered customer savings between 10-19% (median 14%). At 145°F and 155°F, load-up/shed provides reduced savings of 10% and 5% respectively. Figure 4 summarizes load/shed results by set point for hybrid HPWHs.

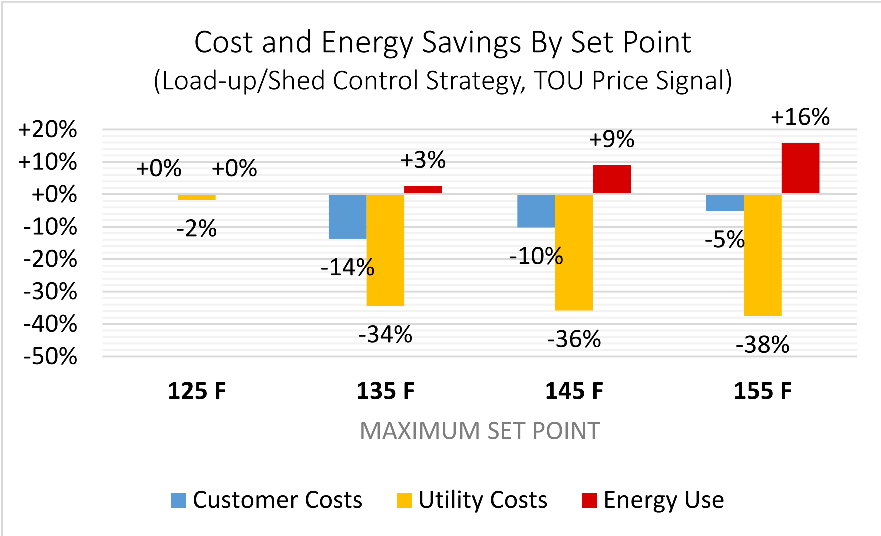

Figure 4: Hybrid HPWH Costs and Energy Savings by Setpoint. *Source*: Author Calculations.

The CO_2 heat pump model was effective at load shifting with savings of 14% to 20% (median 18%) in all climate zones with no runouts.

Optimal Price. This strategy only slightly increased savings to a median of 15% for hybrids and 19% for CO2 HPWH. The project team believes there is significant further optimization potential but ran out of time and budget. Under this strategy, electric resistance still represents around 14% of hybrid HPWH energy use (vs. 16% unmanaged). This resistive use is due to a combination of low ambient air temperatures in winter mornings and exceptionally large draws. The first condition could be minimized by loading-up ahead of forecasted cold temperatures, and the second through some occupant behavior predictive analysis and targeted loading-up.

The project team also ran simulations on R134a HPWHs in heat pump-only mode to determine if the use of electric resistance could be avoided entirely. Results showed that meeting customer demand with those HPWH without any electric resistance use requires either upsizing the tank significantly (80 gallons for 1 and 2-bedroom households) or loading-up to higher temperatures for much of the time, which incurs a significant efficiency penalty and is not cost-effective. A modest use of electric resistance appears necessary for optimal consumer economic outcomes in many cases.

Summary of Control Strategies. The results for all three control strategies are summarized below in Figures 5 and 6.

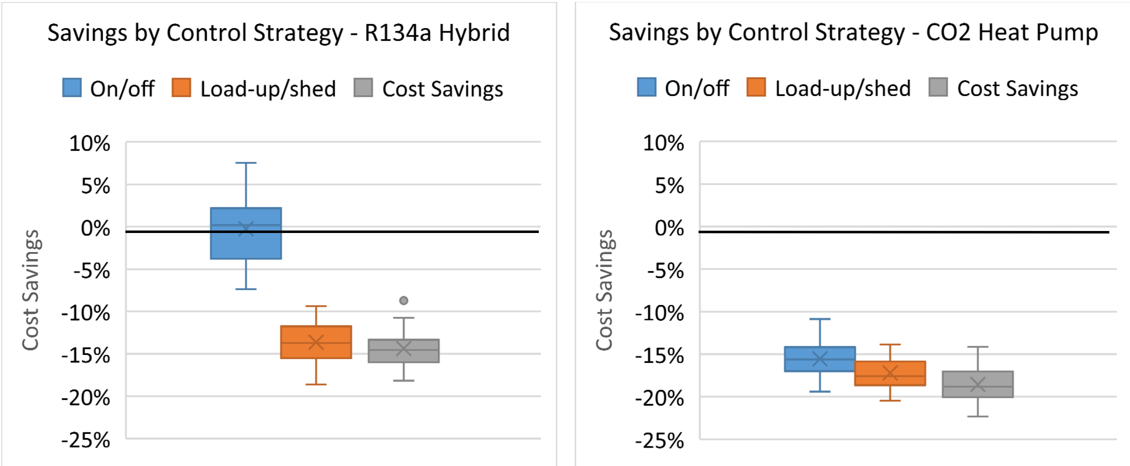

Figure 5: Consumer Cost Saving by Control Strategy. *Source*: Author Calculations.

B. Price Signals

The specific timing of when energy is consumed for water heating depends on the control signal used, as a TOU signal and a grid marginal cost signal may give different indications of when heating should be avoided. This also has implications for the distribution of costs and benefits among consumers and utilities. The times when electricity is expensive for a utility to generate and deliver as measured by their marginal costs may be different from the times when it is expensive for a consumer to use electricity as measured by their TOU rates.

Utility marginal costs provide a more aggressive price signal, which favors more aggressive control strategies and incurs higher efficiency losses. Controlling HPWH using utility marginal costs maximizes grid energy costs and societal savings but reduces customer savings. Using this strategy would require compensating participating customers in a way other than TOU rates. Alternatively, controlling HPWH for TOU rates maximizes customer benefits while still yielding significant grid energy costs/societal benefits. The rest of the findings section is based on using a TOU price signal. These results are summarized in Table 1, below.

Table 1. Comparison of consumer and utility benefits with TOU and marginal cost price signals

	Customer bill savings	**Utility marginal cost savings**
Optimizing for customer costs (TOU)	-\$25 to -\$35/year (-15% to -20%)	-\$20 to -\$30/year (-35%)
Optimizing for grid marginal costs	\$0 to +\$10/year (0% to +5%)	-\$30 to -\$40/year (-60%)

Source: Author Calculations.

C. Demand Shifting Potential

Only a portion of California's water heating electricity demand is coincident with peak grid demand. The greatest demand for hot water occurs in the morning, and HPWHs recharge in the afternoon when solar power is abundant. Currently only 15% of HPWH energy consumption is peak-coincident. In order to maximize the potential benefits of grid flexibility, that 15% must be shifted off-peak to the greatest extent possible. The simulation results indicate that with the right strategy this is an eminently achievable goal. Demand flexibility shifted the 15% of HPWH demand that was coincident with peak, and reduced it to 1% peak coincidence. Similarly, the percent of HPWH demand that was coincident with solar generation increased from 55% to 65%. These results are summarized in Table 2 below.

Table 2: Peak coincidence and solar coincidence of HPWH demand

	HPWH Unmanaged	HPWH Managed
Peak coincidence (5pm-9pm)	15%	1%
Solar coincidence (8am-5pm)	55%	65%

Source: author calculations.

Table 2 reflects peak demand as defined by TOU schedules. However, a more flexible utility marginal cost signal could have days with longer peak periods. This would increase the demand shifting potential of HPWHs.

D. Greenhouse Gas Emissions

The study appears to find that the benefits of load shifting on GHG emissions are marginal. This counterintuitive finding is an artifact of the emissions factors used to evaluate GHG impacts. We make the case that these are not the appropriate emissions factors to evaluate the GHG impacts of load flexibility, but used those anyway in the absence of more appropriate emissions factors to evaluate load shifting in California. We therefore flag this issue as an opportunity for further research and policy development.

Study Findings. Although the increased efficiency of HPWHs could lead to reduced GHG emissions as customers adopt them, the study found limited direct evidence that grid flexibility, either for ERWHs or HPWHs, would greatly reduce GHG emissions. Using ERWHs for grid flexibility could reduce emissions by about 7%. If all consumers switched to HPWHs the increased efficiency would reduce GHG emissions by 60%, but adding grid flexibility to that would only save an additional two percentage points. These results are summarized in Table 3.

Table 3. Annual CO2 emissions

	ERWH Unmanaged	ERWH Managed	HPWH Unmanaged	HPWH Managed
CO2e (kg)	700	650 (-7%)	270 (-60%)	265 (-61%/-2%)

Source: author calculations.

Methodology for Calculating Emissions. This study used CPUC's Avoided Cost Model (ACM) to estimate the marginal GHG emissions that would result from grid flexibility (CPUC 2017). A marginal emissions approach was used instead of an average emissions approach which in such situations is prone to large errors (Siler-Evans, Azevedo, and Morgan 2012). A specific change in electricity demand is met by a change in supply by a specific plant or plants. The corresponding change in emissions may differ substantially from the average GHG per kWh depending on the characteristics of the marginal plants.

There are two potential limitations with the methodology employed in the ACM: first, the model deals with short-run, not long-run, marginal emissions. Short-run (or "dispatch") marginal emissions accounting assesses the emissions factor of power plant projected to be on the margin during the time period considered. It assumes that the change in demand is small enough that it does not change the portfolio of power resources supplying the grid, it only affects the marginal power plant. In contrast, a long-run (or "build") marginal accounting accounts for the total change in emissions caused by a large-scale change in demand, including new or reserve power resources that are built or dispatched to meet this new load. We argue that a long-run marginal methodology is more appropriate to assess the GHG impacts of policies that would have large-scale impacts on the grid, and such a methodology is likely to yield much more highly differentiated hourly emissions factors. This would value grid flexibility more highly than the ACM.

Second, the model makes conservative assumptions about longer-term changes to the grid. California law requires all utilities to procure 50% of the power they generation from renewable sources by 2030. The ACM methodology takes this renewable portfolio standard (RPS) into account by assuming that any increase in load will be met 50% by renewable energy an 50% by fossil power plants, whether the load is added in the middle of the day when solar is cheap and abundant, or during the evening peak when additional load taps into reserve gas capacity. However, as the cost of renewables declines, it is increasingly likely that utilities will exceed the RPS when expanding their capacity, in which case the marginal build emissions in the middle of the day become zero as only solar gets added to the resource mix. This is already happening today in California with utilities expected to achieve the 2030 goal of 50% renewables 10 years ahead of schedule (Miller 2017). Strict RPS accounting was right when RPS resources were at a premium, but may no longer be valid as renewable energy reaches cost parity.

These assumptions result in relatively low differentiation in emissions factors over the day, and therefore in significantly undervaluing the GHG benefits of load shifting. Modeling alternative emissions factors that address both of these issues is beyond the scope of this paper.

E. Applicability to California and Other Regions

As discussed in the background section, California is well-placed to explore HPWH flexibility for several reasons: 1) its previously mentioned commitment to renewable energy; 2) its aggressive GHG reduction goals; 3) California's grid and demand characteristics, particularly the duck curve. However, the effectiveness of this strategy will be limited by the extent to which hot-water demand in California coincides with peak grid demand in the evening.

Other regions with different grid demand profiles may benefit to an even greater degree. A region with peak grid demand in winter mornings would be a particularly strong candidate for grid flexibility. Hot water demand is greatest in winter, and a grid with a morning peak means that peak hot water demand is virtually coincident with peak grid demand. Unmanaged HPWH can already reduce this peak coincidence due to their longer recharge time relative to ERWH, and load management can further reduce it by pre-heating ahead of peak and delaying recharge during the peak period.

F. Sensitivity of Findings

Sensitivity analysis was conducted by climate zone, water draws/occupancy, and HPWH model (hybrid technology only), with a base case of a 65-gallon HPWH in a 3-bedroom household, in climate zone 10 (Riverside) which represents the median savings case. For water draws, the number of bedrooms (1 to 5) was used as a proxy for different draw levels. The analysis showed least sensitivity to HPWH models with a range of 14% to 16%, medium sensitivity to climate zone with a range of 13% (climate zone 13 - Fresno) to 17% savings (climate zone 3 – Oakland), and the highest sensitivity to occupancy with a range of 11% (5 bedrooms) to 17% savings (4 bedrooms).

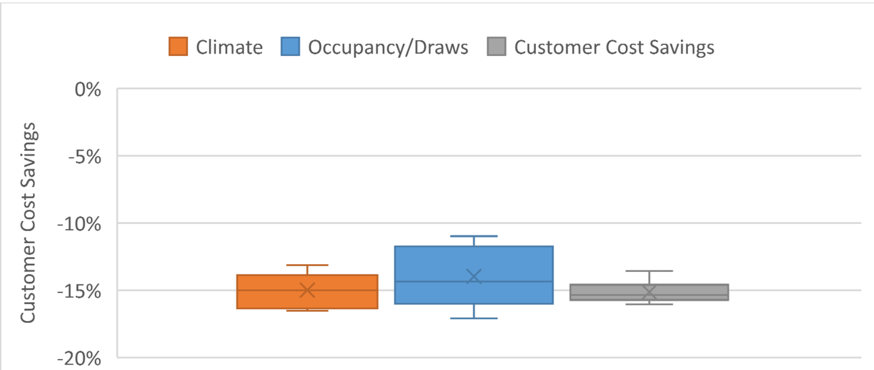

Figure 8: Customer savings sensitivity analysis

We did not analyze sensitivity by electricity price schedule because savings obviously depend directly on the price schedule, particularly the differential between peak and off-peak prices. The price schedule developed for this study is reflective of utility marginal costs and therefore a reasonable modeling assumption, but rate design will be critical to incentivize customers to participate in load shifting programs.

IV. Conclusion

HPWH demand flexibility represents an important opportunity to help integrate renewable energy, and reduce GHG emissions, customer costs, and grid costs. But unlocking its potential requires concerted action by utilities, manufacturers, policymakers, and researchers. Utilities should ramp up efforts to deploy managed HPWH, including pilots, larger-scale deployment where appropriate, tariffs and other mechanisms that incentivize and reward customer participation, and load management infrastructure. Manufacturers should continue to invest on HPWH technology including load management technology that facilitates large-scale utility programs. Policy makers should remove regulatory barriers that may hinder HPWH and thermal storage deployment, align utility and customer incentives so that they stand to benefit from HPWH efficiency and demand flexibility, value HPWH load management in building energy codes, and implement market development policies for HPWH load management. Finally, researchers can help directly reduce the uncertainty in this area. Developing a more sophisticated long-run marginal emissions model, for instance, would help not only with grid flexibility but many other grid-relevant policy areas as well. These tasks are not simple, but they are not insurmountable either. The benefits of unlocking HPWH flexibility are worth the effort.

References

CARB (California Air Resources Board). 2017. *California's 2017 Climate Change Scoping Plan.* Sacramento, CA: CARB. www.arb.ca.gov/cc/scopingplan/scoping_plan_2017.pdf.

CEC (California Energy Commission). 2014. *2013 Residential Compliance Manual*. Sacramento, CA: CEC. www.energy.ca.gov/2013publications/CEC-400-2013-001/chapters/05_Water_Heating_Requirements.pdf.

———. 2016. *CBECC-Res 2016 User Manual*. Sacramento, CA: CEC. http://www.bwilcox.com/BEES/docs/2016%20CBECC%20User%20Manual%20Sep%202016.pdf.

CPUC (California Public Utility Commission). 2016a. "PG&E General Rate Case Phase 2." Accessed March 2018. http://www.cpuc.ca.gov/General.aspx?id=12142.

———. 2016b. *Order Instituting Rulemaking to Develop a Successor to Existing Net Energy Metering Tariffs Pursuant to Public Utilities Code Section 2827.1, and to Address Other Issues Related to Net Energy Metering*. San Francisco: California Public Utilities Commission. docs.cpuc.ca.gov/PublishedDocs/Published/G000/M158/K181/158181678.pdf.

———. 2017. *2017 Avoided Cost Model*. San Francisco: California Public Utilities Commission. http://www.cpuc.ca.gov/General.aspx?id=5267.

DOE (Department of Energy). 2018. "Heat Pump Water Heaters." Accessed March 2018. www.energy.gov/energysaver/water-heating/heat-pump-water-heaters.

EIA (Energy Information Administration). 2013. "Energy Use in Homes." Accessed March 2018. https://www.eia.gov/energyexplained/index.cfm?page=us_energy_homes.

EPA (Environmental Protection Agency). 2017. "Energy Star Unit Shipment and Market Penetration Report: Calendar Year 2016 Summary." Washington, DC: EPA. https://www.energystar.gov/ia/partners/downloads/unit_shipment_data/2016_USD_Summary_Report.pdf?5c18-e996.

FERC (Federal Energy Regulatory Commission). 2016. "Assessment of Demand Response and Advanced Metering." Washington, DC: FERC. https://www.ferc.gov/legal/staff-reports/2016/DR-AM-Report2016.pdf.

Gurlaskie, G. 2016. "Heat Pump Water Heaters for Demand Response." https://aceee.org/sites/default/files/pdf/conferences/hwf/2017/Gurlaskie_Session7A_HWF17_2.28.17.pdf.

Hiller, C.C. 1998. "New Hot Water Consumption Analysis and Water-Heating System Sizing Methodology." ASHRAE Transactions, 1998, p 1864-1877. Atlanta, GA: American Society of Heating, Refrigerating and Air Conditioning Engineers.

Hledik, R., J. Chang, and R. Lueken. 2016. "The Hidden Battery: Opportunities in Electric Water Heating." Washington, DC: The Brattle Group. http://www.electric.coop/wp-content/uploads/2016/07/The-Hidden-Battery-01-25-2016.pdf.

Miller, P. 2017. "Good News: California Set to Eclipse Renewable Energy Target." Washington, DC: NRDC. www.nrdc.org/experts/peter-miller/good-news-california-set-eclipse-renewable-energy-target.

NEEA (Northwest Energy Efficiency Alliance). 2015. "Heat Pump Water Heater Model Validation Study." Seattle: NEEA. neea.org/resources/heat-pump-water-heater-model-validation-study.

Pierpont, B., D. Nelonson, A. Goggins, and D. Posner. 2017. *Flexibility: The Path to Low-Carbon, Low-Cost Electricity Grids.* San Francisco: Climate Policy Initiative. climatepolicyinitiative.org/wp-content/uploads/2017/04/CPI-Flexibility-the-path-to-low-carbon-low-cost-grids-April-2017.pdf.

Siler-Evans, K., I. Lima Azevedo, and M. Granger Morgan. 2012. "Marginal Emissions Factors for the U.S. Electricity System." *Environmental Science and Technology* 46: 4742−4748. cedmcenter.org/wp-content/uploads/2017/10/Marginal-Emissions-Factors-for-the-U.S.-Electricity-System.pdf.

Zhang, J., Y. Qin, and C. Wang. 2015. "Review on CO_2 Heat Pump Water Heater for Residential Use in Japan." *Renewable and Sustainable Energy Reviews* 50: 1383-1391. https://www.researchgate.net/profile/Chi_Chuan_Wang2/publication/281799760_Review_on_CO2_heat_pump_water_heater_for_residential_use_in_Japan/links/59d847ada6fdcc2aad0659af/Review-on-CO2-heat-pump-water-heater-for-residential-use-in-Japan.pdf.