California Energy Commission

COMMISSION REPORT

Optimization Strategies for Residential Heat Pump Water Heaters

Gavin Newsom, Governor

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PREFACE

Project Overview

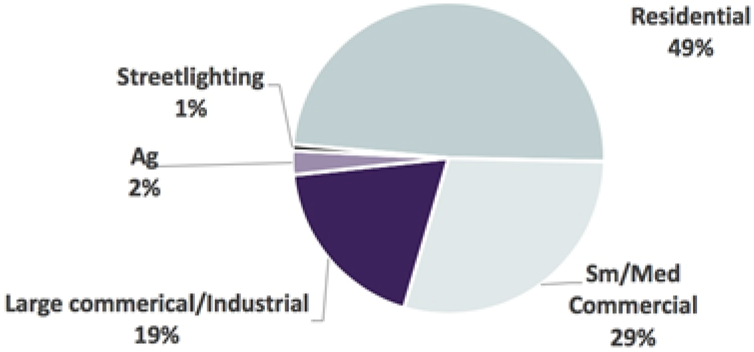
Sonoma Clean Power's (SCP) "Lead Locally" project (Project), funded through the California Energy Commission's (CEC) GFO-17-304 aims to identify strategies and technologies that can assist with the State's goals of doubling the efficiency of existing buildings by 2030. The Project includes applied research and technology deployment activities, each of which will propose innovations that could stimulate the energy efficiency market. With the applied research work, the team is investigating a series of innovative technologies that have the potential to be integrated into existing program models. Lessons learned from the applied research projects will be funneled directly to consumers, contractors, real estate professionals, and building officials through SCP and its local partner organizations. The technology deployment work will be driven in part through the SCP "Advanced Energy Center", a physical storefront where consumers can directly procure energy efficient products and services. The Advanced Energy Center has the potential to speed deployment of energy efficiency, make energy efficiency programs more accessible to all customers, and increase customer knowledge of energy efficiency and energy code requirements.

About Sonoma Clean Power and its Customers

SCP is a public power provider operating as a community choice aggregator (CCA) and the default electricity provider for Sonoma and Mendocino Counties. SCP exists to provide broad public benefits relating to affordability, reliability, climate change and sustainability, coordination with local agencies, customer programs, and to support the local economy. The default service for SCP customers is CleanStart, which provides customer with 45% renewable power and 87% carbon free power (2017 Climate Registry certified values). SCP customers also have the option to select EverGreen service, which is 100% renewable power produced entirely within the SCP service area.

SCP serves just over 220,000 accounts, of which 86% are residential accounts. On an annual basis, SCP's load is comprised of about 50% residential energy use as shown in Figure P-1.

Fig P-1. SCP Customer Load for 2017



Sonoma Clean Power Authority (SCP), its employees, agents, contractors, and affiliates maintain the confidentiality of individual customers' names, service addresses, billing addresses, telephone numbers, email addresses, account numbers, and electricity consumption, except where reasonably necessary to conduct SCP’s business or to provide services to customers as required by the California Public Utilities Commission (CPUC). SCP does not, under any circumstance, disclose customer information for third-party telemarketing, e-mail, or direct mail solicitation. Aggregated data that cannot be traced to specific customers may be released at SCP’s discretion.

Any questions or concerns regarding the collection, storage, use, or distribution of customer information, or those who wish to view, inquire about, or dispute any customer information held by SCP or limit the collection, use, or disclosure of such information, may contact Erica Torgerson, Director of Customer Service, via email at etorgerson@sonomacleanpower.org.

Project Team, Roles and Responsibilities

The applied research team is comprised of the following parties (referenced in this document as the Team), with roles and responsibilities outlined below.

Sonoma Clean Power serves as the prime coordinator with the CEC, and is responsible for identifying project sites, initial outreach to customers, and reporting Project progress to the CEC.

Frontier Energy’s lead roles are management of the applied research activities and associated subcontractors, execution of laboratory testing, installation of instrumentation at test sites, analysis of monitored data, energy modeling, and technical reporting.

DNV provides independent Evaluation, Measurement, and Verification (EM&V) for the Project, specifies required measurement points and accuracy levels for the instrumentation package, and evaluates performance relative to the metrics for success.

California Lighting Technology Center manages the commercial daylighting project, selects and evaluates daylighting technologies in both laboratory and field test settings, and assists in extrapolating field performance to estimate energy savings and peak electricity demand reduction for other space types and locations across California.

Energy Docs and **Rick Chitwood** designs and installs the radiant panels, air-to-water heat pumps (AWHPs), and load reduction retrofits.

Chiltrix serves as the vendor for the AWHPs and provide informal design guidance and field test support throughout the project.

Huvco and Insolcorp serves as a vendor partner for daylight enhancement technologies and phase change materials, respectively, and provides informal design guidance and field test support throughout the project. Additional product vendors may join the Team and provide support as the Project proceeds.

ABSTRACT

Heat pump water heaters, especially those with grid interactivity, offer excellent potential for lowering utility bills by increasing energy efficiency compared to gas water heaters, operating in response to weather and occupant behavior to avoid resistance heating, and shifting electricity use from early-evening high demand periods to mid-day periods with high renewable energy availability. This report provides background on some of the key energy drivers for HPWHs in Northern California, along with the latest technologies and control strategies available to maximize efficiency and minimize energy costs. National, state, and regional incentive programs that encourage conversion from gas water heaters to high efficiency electric models are readily available, and most utilities further incentivize participation in HPWH load shifting and demand response programs. This report also describes progress made on an efficiency optimization algorithm as part of Sonoma Clean Power's Lead Locally program, prior to the patenting of a similar control algorithm by the National Renewable Energy Laboratory.

Keywords: Heat pump water heater, grid integration, grid interactive, load shifting, demand response, electrification, optimization, control algorithm, predictive control, machine learning

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EXECUTIVE SUMMARY

Introduction

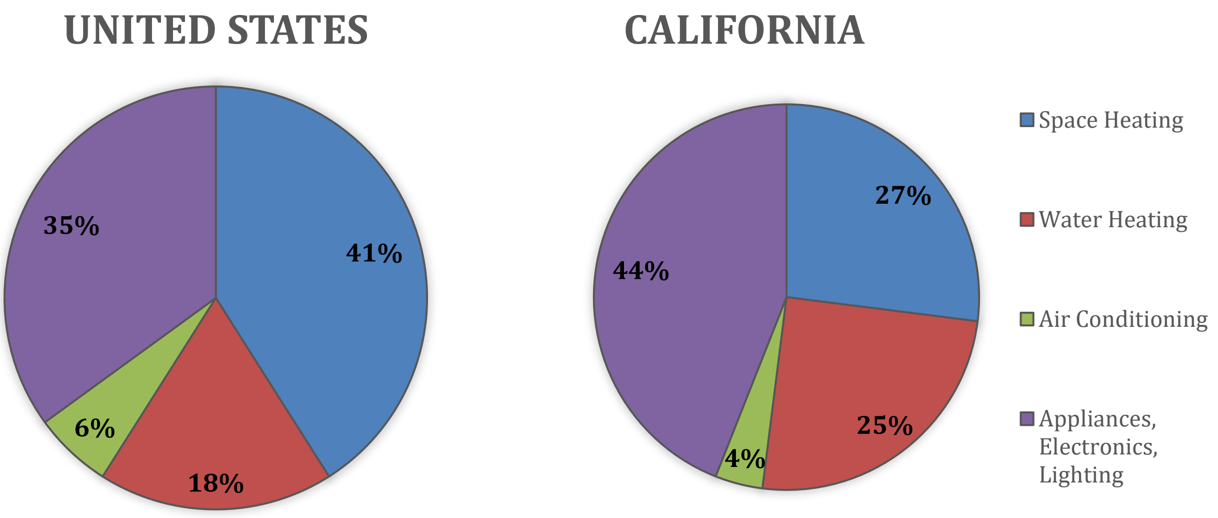
This study examines the energy impacts and load shifting potential for optimized control of heat pump water heaters (HPWHs), including grid interactive heat pump water heaters (GIHPWHs) that feature demand response capabilities. The primary objective was to develop a predictive control algorithm that would optimize the coefficient of performance (COP) by responding to changing weather and operational conditions, leading to reduced energy costs for homeowners. Several months after work began, NREL obtained a patent for a predictive control algorithm with similar functionality to the one being developed for this project, leading to suspension of work to avoid duplication of effort. Although a collaboration with NREL was pursued, NREL was unable to identify a manufacturer willing to include their algorithm in a prototype HPWH that could be tested under Lead Locally within the time frame of the program. Following discussions with the Energy Commission, the Team decided to revise the scope of this applied research project to the following tasks:

1. Synthesis of information from recent studies to provide guidance on how to best optimize the performance of HPWHs with currently available technology, and
2. Summarize demand response and load shifting developments related to GIHPWHs through utility programs such as GridSavvy, and other emerging developments, and
3. Documentation of preliminary findings completed under the original scope.

HPWH Technology

Water heating is the second largest source of household energy consumption after space heating, both nationally and in California (see Figure ES-1). Water heating is likely to make up an even larger fraction of residential energy use in Sonoma County, where the mild climate leads to smaller heating and cooling loads than the majority of California.

Figure ES-1: Breakdown of Residential Energy Consumption by End-Use

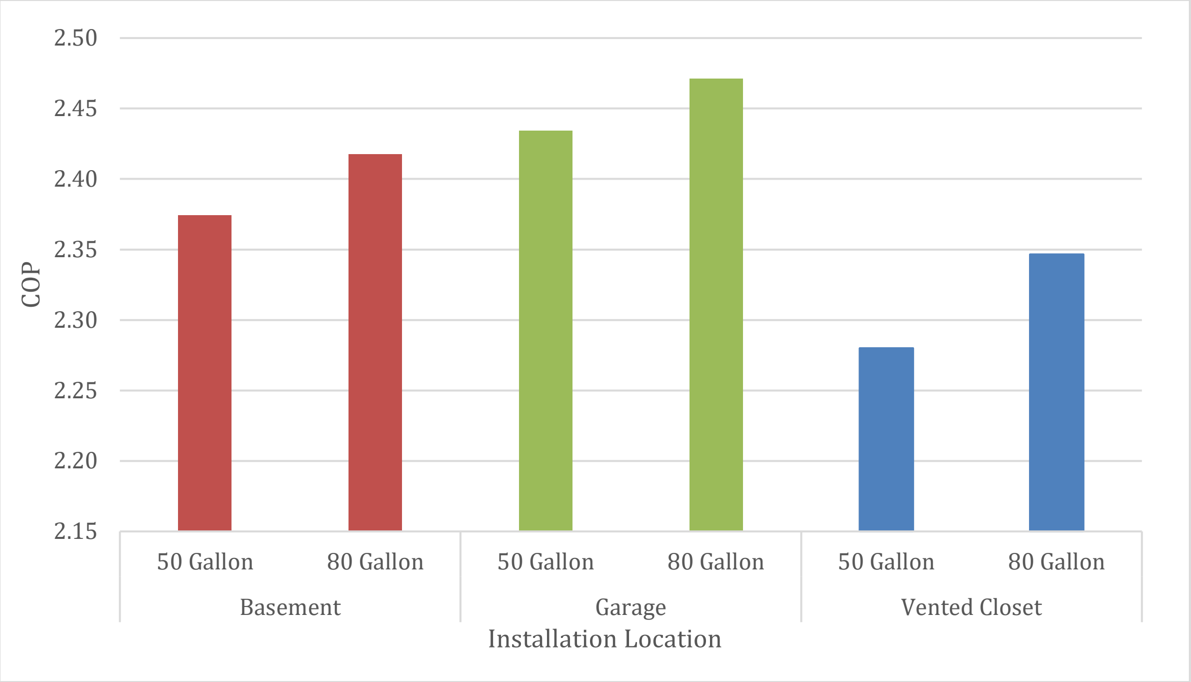


Data Sourced from *Household Energy Use in California* (EIA, 2009)

The most commonly installed water heaters in California are natural gas storage-type units. However, the maximum efficiency of conventional gas and electric resistance storage water heaters is limited to 100%, offering little potential for further energy savings. Heat pump technologies can achieve efficiencies well over 200%, offering significant site energy savings potential over both gas and electric resistance water heaters. HPWHs rely on longer heating duration cycles to satisfy water heating demands and may transition from heat pump heating to backup resistance heating under extreme weather conditions or high usage periods. The amount of energy consumed by a HPWH is primarily determined by the volume of hot water drawn, the inlet air temperature, the inlet water temperature, the tank temperature, the efficiency of the unit, and the operating mode control setting.

The variable of largest influence on HPWH efficiency is the temperature difference between the evaporator (hot water) and condenser (ambient air). Figure ES-2 extrapolates data for California Climate Zone 2 (including Sonoma County) and illustrates the annual COP of HPWHs in response to three HPWH installation locations. For optimal heat pump efficiency, the unit should be locating in a warm indoor environment with the tank maintained at the lowest set point that maintains hot water delivery comfort.

Figure ES-2: HPWH Performance Based on Location of Installation



Units with smaller volume storage tanks are more likely to require use of resistive heating elements in the event of concentrated high water draw periods, causing a reduction in efficiency. Larger volume storage tanks allow for more energy storage, providing a buffer when high volume draws occur within a short period of time. However, larger tanks are more expensive and may not save as much energy in households with low water use due to heat loss during storage. Similarly, the distribution of hot water draw events can significantly affect the recovery rate of the heat pump. Draw profiles with concentrated periods of demand result in greater use of supplemental heating and a decrease in efficiency. Conversely, when water use is spread throughout the day, the heat pump is more likely to be able to meet demand without requiring aid from resistive heating elements.

Another important driver of energy efficiency is the HPWH set point. In general, a higher set point temperature reduces the efficiency of the heat pump by creating a greater temperature difference between the heat source and heat sink. A higher set point also increases the rate of heat loss between stored water and the surrounding air. However, there are situations where increasing the set point temperature would benefit system efficiency. When large quantities of hot water are drawn in clusters, a higher set point would act as a buffer and help reduce the amount of heating from electric resistance. If set point temperatures are raised above the standard temperature range of 120-140˚F, a mixing valve would need to be installed at the outlet in order to ensure safe water temperatures at fixtures.

Most HPWHs allow for the homeowner to choose from several settings that alter the way the unit operates under various conditions, resulting in different levels of efficiency. While terminology for the available modes may differ somewhat between manufacturers, most include some form of a hybrid, heat pump, high demand, and vacation mode.

Hybrid mode is generally considered the default mode for most HPWHs. It prioritizes use of the heat pump compressor except in cases when ambient temperatures are outside the unit's operating range, or the tank temperature falls too far below the set point. In the event these conditions occur, the resistive elements activate to either supplement or fully replace compressor operation. Actual details of the control of the electric element varies among the manufacturers.

In efficiency mode, heating is done through heat pump compressor use alone provided that ambient temperatures are within the specified operational range. While this setting is the most energy efficient, there is an increased likelihood of exhausting the stored hot water resource in the event of a large volume draw. This mode is best suited in a low-volume household where ambient temperatures are regularly warm and water use is spread consistently throughout the day, or in applications where the occupants are amenable to adjusting their use patterns to align with the HPWH performance.

High demand mode operates the water heater as a traditional electric resistance water heater, utilizing only the resistive elements. This setting is the least energy efficient but may be useful in times of increased hot water demand or if malfunctions of the heat pump occur. It is not intended for prolonged use and most models will automatically revert to hybrid mode after a short period of time.

Vacation mode is intended for periods in which the water heater is not used for a long period of time (at least a week), in order to minimize unnecessary energy consumption. In this mode, the tank will be maintained in a lukewarm condition. Depending upon operating conditions, it may take up to 6 hours for the tank to recover from this condition.

The Future of HPWHs and the California Electric Grid

Due to its storage capabilities, a HPWH can act as a thermal battery, allowing for the unit to store additional heat hours before hot water demands occur. Load shifting can utilize storage by biasing operation toward more optimal conditions that allow for greater operational efficiency, lower utility costs, and benefits for the stability of the electric grid. While this generally increases electricity consumption (due to higher tank temperatures), the shifting of energy use reduces customer electricity costs and associated carbon emissions.

Recently, the increasing availability of utility TOU rates has been a way to incentivize homeowners to perform voluntary load shifting. TOU prices are structured to reflect the true costs of generating and transmitting electricity by time of day and are generally the highest during late afternoon and early evening. For Sonoma Clean Power (SCP), peak price periods occur either 3-8 PM or 4-9 PM depending on the chosen rate plan. This form of pricing encourages homeowners to run their appliances during off-peak hours when electricity is least expensive.

Grid integration of heat pump water heaters allows for utilities or third-party aggregators to shift the load from connected units in times of grid stress or imbalance, while minimizing impacts on hot water availability. The capability to shift energy use to mid-day makes HPWHs an effective way to relieve capacity requirements on the grid during high demand or absorb excess power during periods of overproduction. This stabilization would help reduce the need for rolling blackouts and increase utilization of energy from cleaner sources.

During high demand, utilities face higher marginal cost and therefore must impose higher TOU rates on the customer. Through grid integration, the party initiating the demand response can shift HPWH operation to periods when the grid experiences less demand. This coincides with lower electricity rates, effectively reducing operating costs for the customer. Figure ES-3 depicts the potential magnitude of demand reduction that could be achieved by means of grid integration in California. The black line represents the load schedule of an electric resistance water heater (ERWH), and the gold line represents that of a HPWH serving the same load. By switching from a ERWH to a HPWH without load shifting, the amount of energy expenditure that coincides with peak demand is cut from 29% to 14% solely due to its improved efficiency. The green line represents a GIHPWH controlled to avoid the afternoon peak period and consume energy mid-day. The results are a decrease in peak coincidence to only 1% (Delforge & Larson, HPWH Demand Flexibility Study, 2020).

Figure ES-3: Savings Potential of HPWH Load Shifting

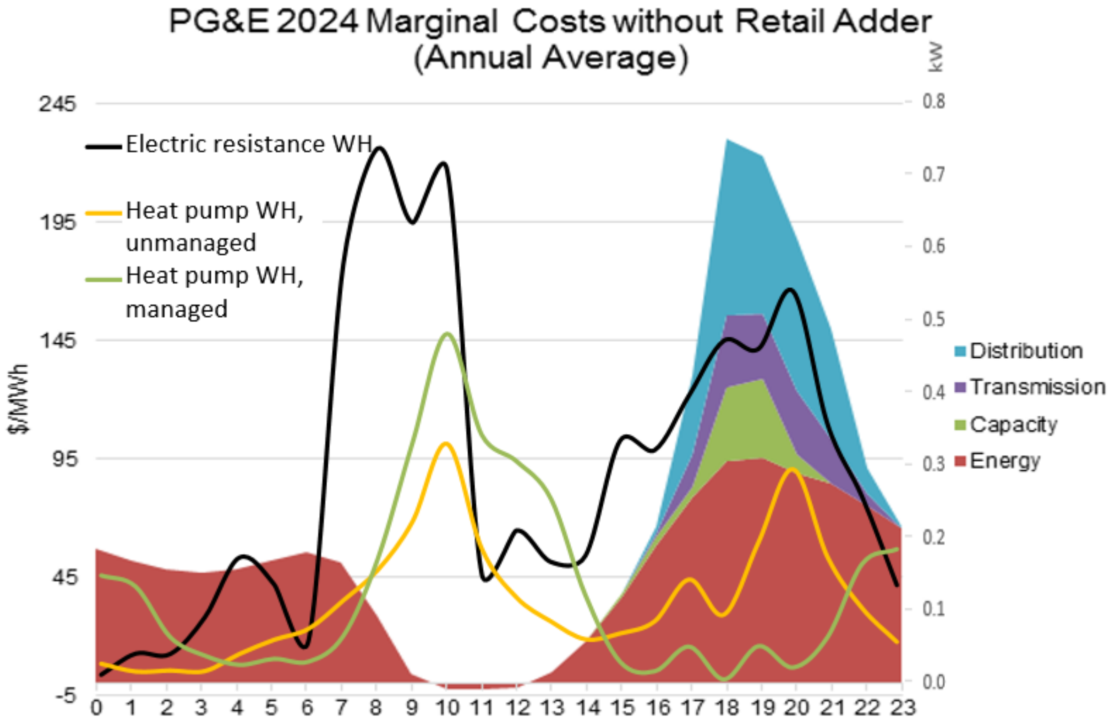


Image Credit: *NRDC*

Multiple programs are available or soon to be available in various regions of California to incentivize homeowners to participate in utility load-shifting or demand response programs. These include initiatives sponsored by PG&E, SMUD, and Sonoma Clean Power. These programs generally require possession of a smart device, generally with Wi-Fi connectivity, although FM signal or other means exist for communication. Since most programs involve pre-heating water heaters above set point during off peak hours, it is essential that a mixing valve be installed at the HPWH outlet to ensure a safe water temperature at fixtures.

Work by the Energy Commission and the National Resources Defense Council led to the development of Joint Appendix 13 (JA13) entitled “Qualification Requirements for Heat Pump

Water Heater Demand Management Systems"[1], which was adopted by the Energy Commission in July 2020. A code change proposal for the 2022 Title 24 code update expanded load-shifting HPWH credits within Title 24 to recognize more advanced strategies beyond what was developed in JA13, increasing benefits that could be realized by a HPWH that responds to local TOU rate schedules. All HPWHs eligible for this proposed 2022 compliance credit would need to be JA13 manufacturer-certified, which includes having a mixing valve installed and having a CTA-2045-A communications port installed on the unit. At the time of this report, the Energy Commission had postponed any action on the proposal until the approved JA13 is updated (expected in mid-2022).

Conclusion

Heat pumps increase the operating efficiency of water heaters above electric resistance or natural gas units, which can reduce the amount of electricity used to heat water by more than half. However, their attainable efficiencies span a wide range based on operating conditions. Consistent across studies, it was found that efficiencies are improved by minimizing the extent of electric resistance heating. Variables responsible for triggering activation of these elements include ambient temperature, tank size, set point and water-use behavior. Draw profiles characterized by consistent water use throughout the day led to performances greater than profiles experiencing infrequent and high concentrated draws. The ability to predict utility costs and behavior could offer an excellent opportunity to reduce utility bills through optimal HPWH control strategies.

Along with a reduction in energy use from improved efficiency, a HPWH's load shifting and grid interactive capabilities offer homeowners and utilities additional flexibility to further reduce costs. Through control of set point temperatures prior to peak demand periods, homeowners can reduce their electricity bills while utilities alleviate excessive peak grid demands.

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[1] https://www.energy.ca.gov/sites/default/files/2020-07/JA13_Qualification_Requirement_HPWH_DM_ADA.pdf

CHAPTER 1:
Introduction

1.1 Scope

The original scope of the project entailed research on the energy impacts and load shifting potential for optimized control of heat pump water heaters (HPWHs), including grid interactive heat pump water heaters (GIHPWHs) with demand response capabilities. Through a combination of modeling and laboratory testing, the goal was to finalize a report that detailed the extent to which several independent variables (e.g. hot water draw profiles, HPWH location, ambient temperatures, and utility energy prices) affect the performance cost-effectiveness of HPWHs, leading to strategies to maximize overall energy cost savings by responding to these variables using a control algorithm that adapts to each unique application. These findings were to be applied to the Santa Rosa area (California Climate Zone 2) to provide guidance on optimal scheduling of HPWHs dispatched in the Sonoma Clean Power (SCP) service area. In order to determine the best control strategies in the presence of external influences, the intent was to develop a predictive control algorithm that would respond to changing conditions and optimize the coefficient of performance (COP) while load shifting, leading to reduced energy costs. A simulation study published in 2014 by the National Renewable Energy Laboratory (NREL) outlined the potential benefits such advanced controls could have on water heating cost savings (Jin, Maguire, & Christensen, 2014). The Lead Locally applied research project led by Frontier Energy was designed to perform a series of experimental studies to build upon these concepts by developing advanced control logic that could be tested in a laboratory setting and identify areas that require additional research prior to deployment in partnership with a HPWH manufacturer.

Shortly after Frontier began work on control algorithm development, NREL announced that it had filed a patent disclosure for a predictive control algorithm with similar functionality as the one in progress by Frontier staff. This led to a suspension of work under the initial scope to avoid duplication of effort with federally funded NREL research. Attempts were made to establish a partnership with NREL and a manufacturer willing to include the NREL algorithm in their equipment, but that collaboration proved unrealistic within the time frame of the Lead Locally grant. The project team, in consultation with the Commission, then decided to revise the scope of this applied research project to the following tasks:

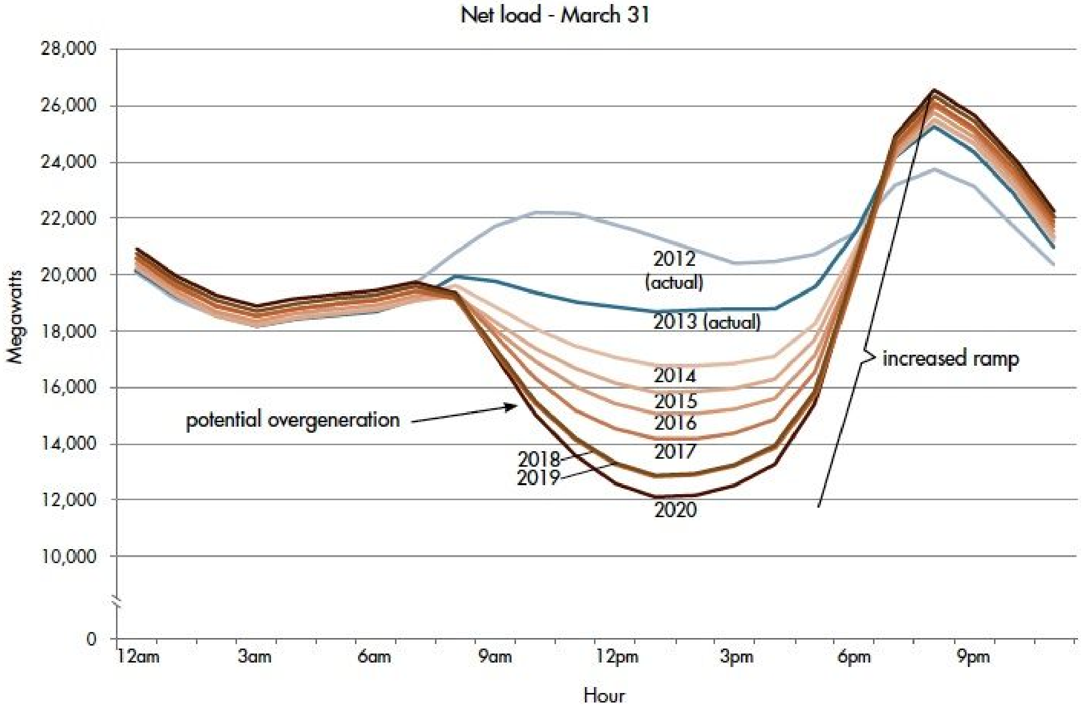
1. Synthesis of information from recent studies to provide guidance on how to best optimize the performance of HPWHs with currently available technology (see CHAPTER 2: Heat Pump Water Heater Overview), and
2. Summarize demand response and load shifting developments related to GIHPWHs through utility programs such as GridSavvy, and other emerging developments (see CHAPTER 3: The Future of HPWHs and the California Electric Grid), and
3. Documentation of preliminary findings completed under the original scope (see CHAPTER 4: Original Scope and Work Completed).

1.2 Purpose

The purpose of the *Optimization Strategies of Residential Heat Pump Water Heaters* report is to outline the benefits and limitations of emerging electric HPWH technology and identify ways for homeowners within the SCP service area to achieve optimized energy performance and lower their utility bills through informed purchasing decisions, leveraging of local and federal incentive programs, and effective use of available controls. Over the past decade, significant modeling, laboratory, and field testing has investigated the ways in which HPWHs respond to certain conditions, and how these factors influence efficiency. This report will analyze studies that consider the impacts of various control strategies in Sonoma County and extrapolate the data to other locations in the Northern California region.

The report will also discuss the ways that HPWHs can aid in electric grid resilience and building decarbonization in support of California's long-term climate change goals as laid out in Assembly Bill 3232, which mandates a 40% reduction in California buildings' greenhouse gas emissions by 2030 relative to 1990 levels. California's push to achieve grid carbon neutrality by 2045 (Senate Bill 100) requires high-level electrification across all sectors. This aggressive planned shift to a clean energy grid brings about a new set of challenges related to electrifying the grid. Figure 1 shows the California Independent System Operator (CAISO) representation of the daily net load and how the energy supply and demand balance has evolved over the past decade. As ever more renewable energy is incorporated into the electric system, periods of energy surplus occur mid-day when solar energy production is at its peak and the electrical demand is low. This is most pronounced in the spring and fall periods when overall consumption is reduced and renewable output remains high. The near-term trend as highlighted in Figure 1 is that mid-day curtailment of renewables becomes more likely and the resulting late afternoon ramp (as renewable generation falls off) becomes steeper.

Figure 1: CAISO Daily Net Load



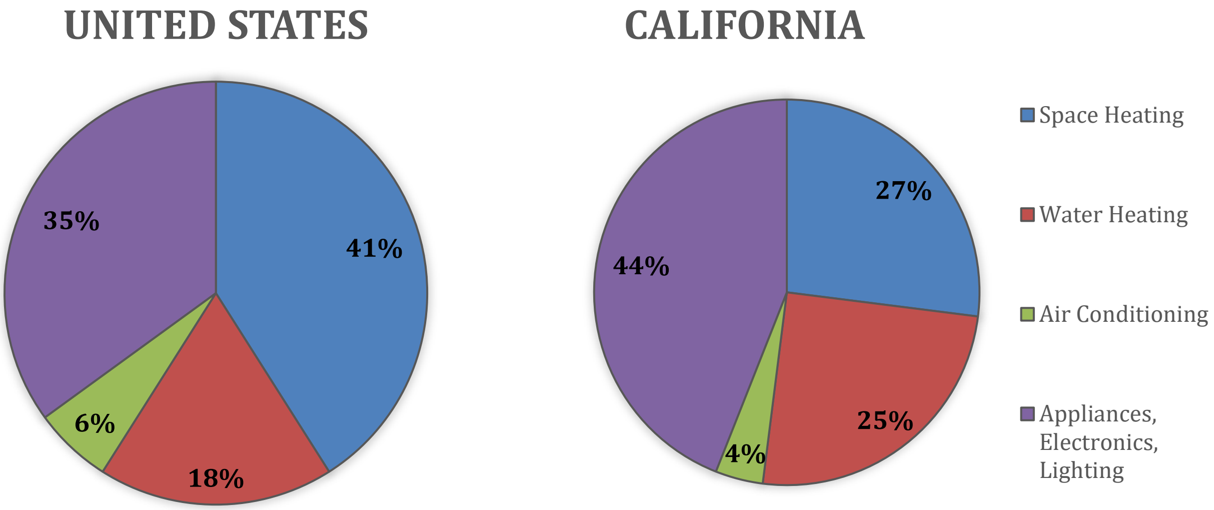
As the state continues in the electrification process, oversupply and curtailment is expected to occur more often. In order to maximize use of clean energy sources, energy storage systems and flexible resources are desirable to increase mid-day consumption and reduce peak consumption. HPWHs have the potential to be a balancing resource within the residential sector and is garnering increased interest from utilities and others via programs and incentives to advance grid integration. Actions taken by homeowners can further support the potential benefits of the HPWH technology.

CHAPTER 2:
Heat Pump Water Heater Overview

2.1 Background

Within the residential sector, water heating is the second largest source of total household energy consumption after space heating, both nationwide and in California (see Figure 2). Water heating is likely to constitute an even larger percentage of residential energy use in Sonoma County, where space conditioning loads are lower than average in California due to the mild climate. At the same time, the push for California decarbonization has increased economic and regulatory incentives for consumers to convert from electric resistance and gas heated tanks to more efficient HPWHs. Many local jurisdictions have begun requiring all-electric new homes (https://localenergycodes.com/content/map), making efficiency and flexibility of HPWHs an even more urgent priority for California.

Figure 2: Breakdown of Residential Energy Consumption by End-Use



Data Sourced from *Household Energy Use in California* (EIA, 2009)

The California residential market has long been dominated by gas water heaters due to the widespread availability of relatively low-cost natural gas through much of the state. Approximately 83% of residential customers have natural gas water heating with most of the remainder being electric (DNV GL Energy Insights USA, Inc, 2021). The vast majority of these water heaters are storage water heaters, although in the past ten years, gas tankless water heaters have made significant inroads in new construction, due primarily to Title 24 Building Standards requirements.

The theoretical efficiency of conventional gas and electric resistance storage water heaters is capped at 100%, offering little potential for further energy savings. However, heat pump technologies which utilize a compressor to extract “free” energy from surrounding air (or water) can achieve efficiencies well over 200%, offering significant energy savings potential over electric resistance water heaters. All residential water heaters are rated based on the Uniform Energy Factor (UEF) test procedure as laid out by the U.S. Department of Energy (DOE)[2]. The UEF prescribes a standardized test procedure that takes into account standby and recovery losses. As of 2017, DOE mandated that UEF be the new standard for specifying consumer water heater efficiency, replacing the older Energy Factor (EF) metric. The UEF rating more accurately reflects real-world operational scenarios that impact performance.

As opposed to traditional electric resistance storage water heaters that rely solely on resistive heating elements, HPWHs extract heat from the surrounding air by incorporating a compressor-based vapor-compression cycle. The hybridization of these two heating methods (resistive element serving as a back-up to an energy efficient heat pump) significantly reduces energy consumption without compromising domestic hot water (DHW) availability. Most currently available HPWHs have compressors of capacity less than a half ton (<6,000 Btu/hr) which is lower than the nominal 4.5 kW (15,350 Btu/hour) capacity of a standard electric resistance element. Therefore, HPWHs rely on longer heating duration cycles to satisfy water heating demands. Under extreme weather conditions or high usage periods, a HPWH may transition from heat pump heating to backup resistance heating. The fact that HPWHs can heat at two distinctly different heating efficiencies means that performance varies based on a range of operational conditions. As a result, the in-situ efficiency of a HPWH tends to be much more variable that other residential water heater types that are generally only affected by load magnitude.

HPWH performance is characterized by its first hour rating, capacity and energy efficiency. The first hour rating (FHR) is a measure of the amount of hot water that can be supplied in one hour by a full heated tank. It is determined by the storage volume, source of heat, and size of the heating element. For equipment rating purposes, minimum federal efficiency values are provided in terms of UEF and FHR as shown in the Water Heater Efficiency Guide provided by the Energy Commission[3].

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[2] https://www.energy.gov/sites/prod/files/2016/08/f33/Water%20Heaters%20Test%20Procedure%20SNOPR.pdf

[3] https://www.energy.ca.gov/sites/default/files/2020-07/2019_WaterHeating_Guide.pdf

Manufacturer's often also provide efficiency data in the form of the Coefficient of Performance (COP), which reflects the dimensionless thermal energy output divided by energy input at a certain operating condition. There are no standard rating conditions for COP, therefore it is commonly used when providing data on performance variation as a result of external variables.

Recent changes to federal regulations have also contributed to the market advancement of HPWHs. As of 2015, DOE requires electric storage water heaters with storage volumes greater than 55 gallons to have UEFs that are only achievable with heat pump technology[4]. Limited market penetration in the past has been mainly attributed to the greater upfront costs of HPWHs compared to alternative technologies. In an effort to support market transformation, in 2020 the U.S Internal Revenue Service (IRS) began providing consumers with a tax credit of $300 for purchasing an electric HPWH that yields a minimum UEF value of 2.2 (Department of the Treasury Internal Revenue Service, 2020). Additionally, many manufacturers offer rebates upon purchase, and utilities have developed incentive programs that reward customers through credits on monthly energy bills. More information regarding customer programs is discussed in Section 3.4: Programs and Incentives

2.2 Operation

HPWHs are considered hybrid systems because they combine traditional heat pump components (compressor, heat exchangers, expansion device, and controls) with single or dual resistive heating elements. Most currently available HPWHs use conventional refrigerants as the working fluid in the heat pump cycle (typically R-134a), although Sanden offers an advanced high efficiency unit that uses environmentally friendly CO_2 [5]. The contained working fluid of the system is heated in the evaporator and pressurized by the compressor into a superheated vapor which passes through condenser coils that distribute the heat throughout the hot water tank, as shown in Figure 3.

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[4] 10 CFR 430.329(d))

[5] https://www.smallplanetsupply.com/sanc02

Figure 3: HPWH Component Diagram

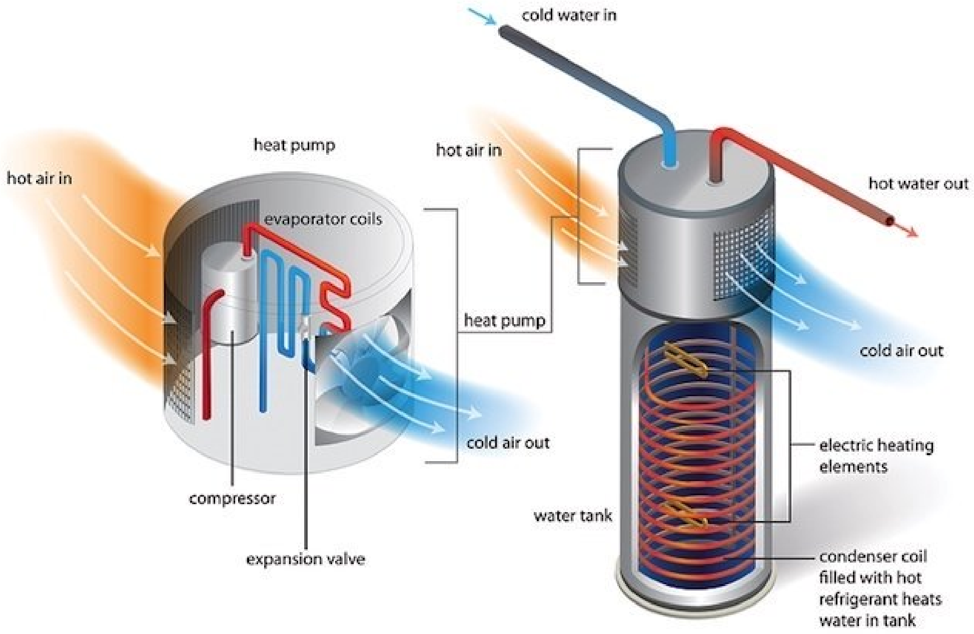

Image Credit*: Marjorie Schott/NREL*

Designed as the primary heating mechanism, the heat pump transfers thermal energy from the incoming inlet air surrounding air the tank and exhausts cooled, dehumidified air as a byproduct. Virtually all currently available residential HPWHs have compressors that are less than ½ ton (6,000 Btu/hr) in capacity. Since the capacity is relatively low compared to other mainstream water heater types, a HPWH relies on longer steady operating cycles to satisfy the heating signal. Long cycles increase the likelihood of subsequent hot water draws further reducing the tank temperature, and possibly triggering backup electric resistance heating. A 240V electrical circuit provides electricity to run the compressor, the evaporator fan (that draws ambient air across the evaporator coil), the backup electric element, and the unit's controls. There are currently efforts to develop additional 120V HPWHs targeted for the retrofit market, avoiding the need for electrical panel replacements for the added 240V circuit.

The tradeoff associated with heat pump compressor operation is a slower recovery rate. To ensure sufficient hot water is available at all times, the system incorporates backup resistive elements. In the event where water temperature falls too low due to high hot water demand, the unit will activate the auxiliary heating to boost the heating capacity. Most models on the market have "smart" features which allow the user to adjust resistance heating operation and set point. These adjustments influence when the system utilizes the heat pump instead of the less efficient resistive heating elements and can be important for managing energy use and tailoring consumption to favorable off-peak utility periods.

2.3: Drivers of Energy Use

The amount of energy consumed by a HPWH is primarily determined by the volume of hot water drawn, the inlet air temperature, the inlet water temperature, the tank temperature, the efficiency of the unit, and the operating mode control setting. Each of these is discussed in more detail in the following sections to inform the relationship between the various parameters, and to better understand the methods available to enhance overall system efficiency and demand flexibility.

2.3.1: Climate and Installation Location

When trying to optimize the efficiency of a HPWH, the variable of largest influence is the temperature difference between the evaporator (hot water) and condenser (ambient air). The larger this temperature difference is, the more efficiency is reduced. Heating the tank storage volume to a high temperature under cold ambient conditions will consume considerably more energy than heating water to lower temperature under warm ambient conditions. Results from a series of laboratory tests shown in Figure 4 clearly displays this relationship (Carew, Larson, Piepmeier, & Logsdon, 2018) with COP of the compressor plotted at three ambient air temperatures and a range of water temperatures between 70°F and 160°F. As ambient conditions get colder or tank temperatures increase, efficiency drops, and more energy is required by the compressor.

Figure 4: Effect of water and air temperature on compressor COP

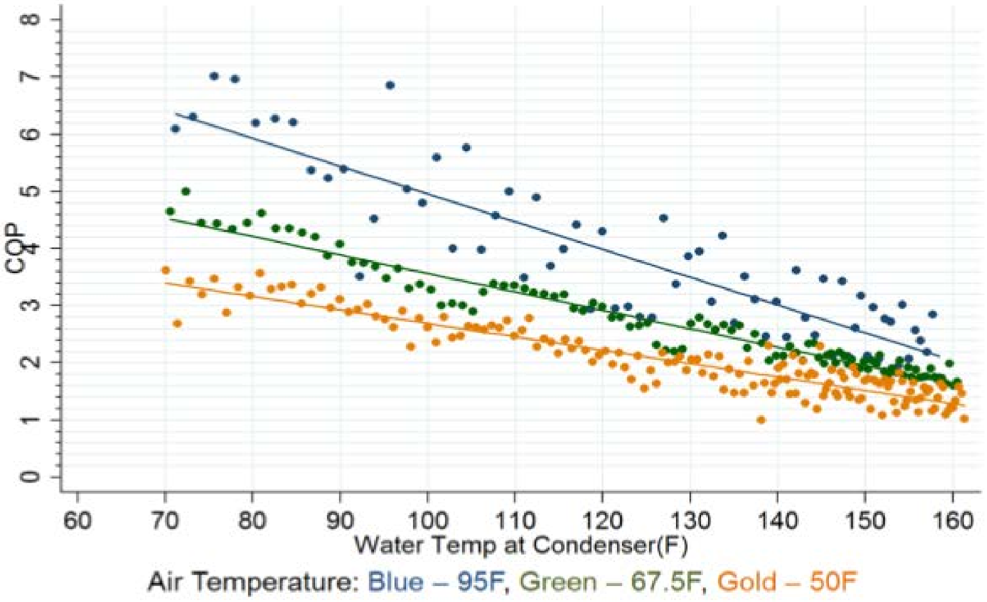

Image Credit: *Ecotope Load Shifting Study*

Additional energy is required to offset tank standby heat losses associated with tank losses to the surrounding air. These standby losses are one of the primary factors that reduce operating

COPs from 3 or 4, down to a 2.5 UEF[6]. Higher setpoints create a larger temperature difference from tank to ambient, increasing the rate of tank heat loss. For optimal heat pump efficiency, the unit should be located in a warm environment and at a low setpoint. This is not easily done in many situations as many California water heaters are located in garages. However, since HPWHs are hybrid systems that contain back-up auxiliary heating elements, additional considerations must be accounted for when trying to minimize energy consumption.

Since HPWHs extract thermal energy from the surrounding air, ENERGY STAR® recommends ambient temperatures remain between 40-90°F year-round for most efficient operation. As air and inlet water temperatures decrease, the compressor heat output decreases leading to a greater likelihood that resistance electric elements will be needed. Below a certain low temperature threshold and above a high temperature threshold, the heat pump will switch off entirely[7]. In extreme climates, selection of the HPWH model and placement of the unit both become important considerations. ENERGY STAR guidelines suggests that in cold climates, the ideal location would be in a semi-conditioned interior space, such as a basement, near a furnace that maintains a relatively warm environment throughout the winter. Installing the unit in a conditioned space may increase the system's performance in colder environments, however, modeling studies have shown that this can have a significant impact on the home's total energy use. In colder climates, the HPWH will likely add to household energy consumption by increasing the heating load. In warmer climates such as most of California, the installation of a HPWH could potentially decrease the home's total energy consumption by reducing the cooling load.

The Pacific Northwest National Laboratory (PNNL) examined this interaction by comparing the total energy effects caused by different forms of HPWH intake or exhaust air ducting (Widder, Parker, Petersen, & Baechler, 2014). This study conducted in the Pacific Northwest compared an unducted HPWH to one case with ducting on the exhaust and a second case with ducting on both the intake and exhaust. The results concluded that the fully ducted unit reduced the home's total energy consumption by 4.2% whereas the unit with only ducting of the exhaust increased the home's energy consumption by 2.9%. PNNL makes the hypothesis ducting the water heater's exhaust had depressurized the house causing increased infiltration of outdoor air. Since the average ambient temperature during the study's heating season was 34.2 ± 4.2°F and the average HPWH exhaust air temperature was 54.5 ± 3.1°F, the HVAC system experienced a much higher thermal load from the infiltration than it would have from the exhaust.

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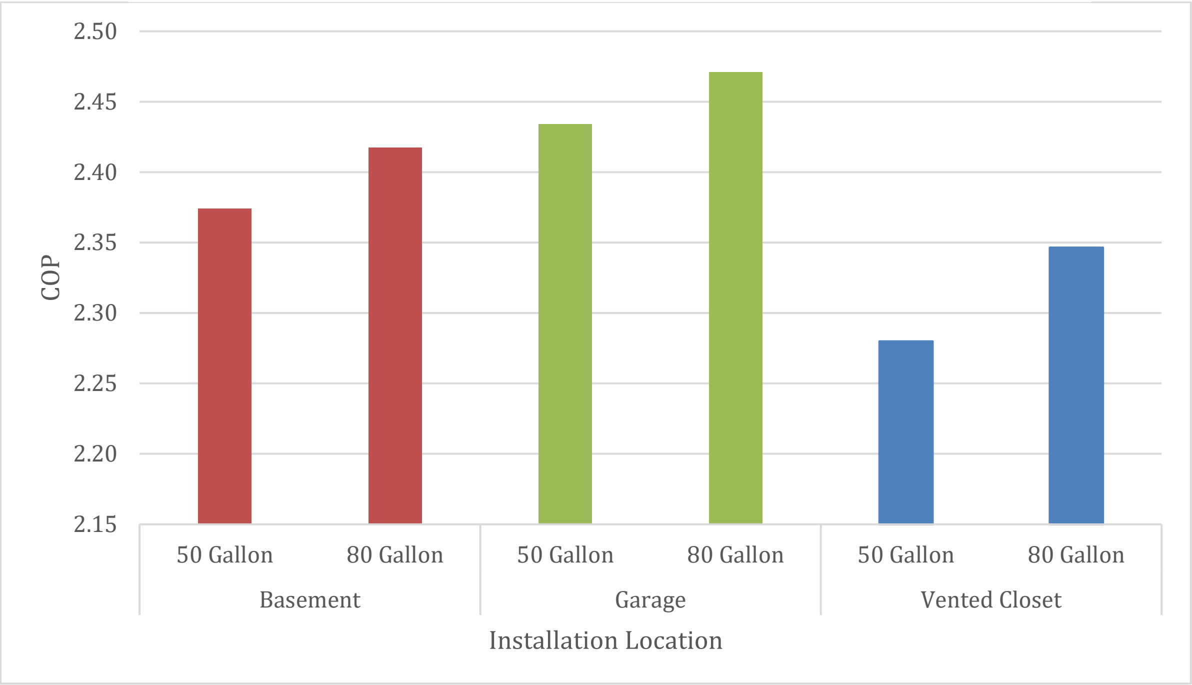
[6] UEF includes standby losses, while COP is an instantaneous measure of performance

[7] Four of the leading HPWHs can operate up to 108°F or higher, but minimum cut out temperatures vary from 35-45°F. The Sanden CO2 HPWH can also exceed 108°F, but can operate down to -20°F.

The results from the Pacific Northwest experiment conclude that the effect an interior located HPWH has on a home's HVAC system is much less significant than previous modeling studies have predicted. Interior home temperatures subject to different forms ducting varied by less than 1°F in both the heating and cooling seasons. Instead, experimental data shows that only the temperature of the storage closet's interior was significantly lower than the rest of the house. The walls enclosing the unit had a buffering impact which localized the cool air within the enclosed space. While this may decrease the effect a HPWH has on heating loads, the localized cooling reduces the efficiency of the HPWH. This was confirmed as the HPWH with the ducted exhaust consumed 7%-8.3% less energy than the unducted unit because of the higher surrounding temperatures. While the findings would vary across different climates zones, it stands to reason that installing in a space with proper ventilation improves the HPWH's efficiency.

An NRDC/Ecotope modeling study used the HPWHsim hourly simulation model to generate performance projections based on a range of operating conditions and hot water loads (Delforge, 2016). Figure 5 extrapolates data for California Climate Zone 2 (including Sonoma County) and illustrates the annual COP of HPWHs in response to three HPWH installation locations. The highest efficiencies are obtained when the HPWH is installed in unconditioned or semi-conditioned spaces such as a garage or basement. Units located in vented closets show the lowest operating COP, likely due to restricted airflow and localized cooling. In California, basements are rare, and most water heaters are therefore installed in garages. However, indoor water heaters and exterior water heater closets are not uncommon, depending on the vintage of the home and local construction practices.

Figure 5: HPWH Performance Based on Location of Installation



2.3.2: Tank Volume

A second influence on energy consumption is tank volume with smaller storage tanks more likely to require use of resistive elements in the event of concentrated water draw periods, causing a reduction in efficiency. Larger volume tanks allow for more energy storage, providing a buffer when high volume draws occur within a short period of time. Smaller volume tanks lose less heat to the surroundings because the surface area is smaller. One study on HPWH field performance in the Northeastern U.S. compares performance data of three different models of HPWHs installed at fourteen sites (Shapiro & Puttagunta, 2016). Monitoring data revealed models with basement-located 60/80-gallon tanks experienced less than 6% (of total kWh) resistance heating and had an average COP of 2.1 to 2.4. Conversely, the models with 50-gallon tanks experienced 44% resistive heating and had an average COP value of 1.61. This observation is supported by the NRDC/Ecotope modeling results in Figure 5. Across all locations, HPWHs with an 80-gallon capacity show a higher performance than those with a capacity of 50 gallons. The larger tank size does result in higher first costs and a greater likelihood of installation challenges with indoor units in cramped locations. Exceptions to the larger net tank benefits may occur in households with low water use, as the added efficiency benefits may be outweighed by the increased standby energy loss.

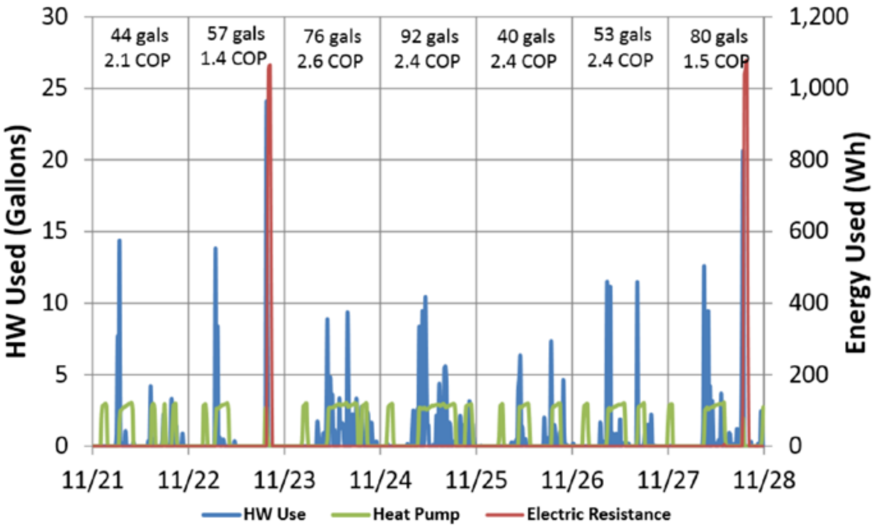
2.3.3: Patterns of Water Use

The distribution of hot water draw events is also a significant indicator of HPWH energy consumption, as well as the total volume removed from the tank. Because of the slower recovery rate of the heat pump, draw profiles with concentrated periods of demand result in greater use of supplemental heating and a decrease in efficiency. Conversely, when water use is spread throughout the day, the heat pump is more likely to be able to meet demand without requiring aid from resistive elements.

The previously mentioned study of HPWH performance in the Northeast analyzed the effect of draw profiles on COP. Figure 6 shows the performance of one site with a 50-gallon General Electric HPWH operating on hybrid mode. The blue line refers to the domestic hot water draw profile. The green and red lines show the heat pump and electric resistance use respectively. On Day 1 and Days 3-6, the hot water demand is distributed throughout the day, with concentrated draws remaining below 15 gallons within a short time frame. The resulting COP on these days remained high, ranging between 2.1 and 2.6

On Days 2 and 7, concentrated water draws occurred in the evening, requiring activation of auxiliary heating. This pattern of sporadic and concentrated demand resulted in lower COP values of 1.4 and 1.5. Despite Day 4 requiring the greatest volume of water (97 gallons), the even distribution led to a higher efficiency than that of Day 2 where only 57 gallons were drawn. When it comes to using energy more efficiently, controlling when water is used has a greater influence than the volumetric amount.

Figure 6: Performance of a HPWH in Hybrid Mode



Credit: *Field Performance of Heat Pump Water Heaters in the Northeast*

According to the Building America Research Benchmark Definition (Hendron & Engebrecht, 2010), the activities shown to demand the most hot water per event are showering, baths, and clothes washing. Grouping multiple water intensive events within a short time frame would likely instigate use of resistive heating elements. Spreading out water-use events that are not time-sensitive, one can effectively increase the efficiency of the HPWH without necessitating a significant change in habits. This could look like running the dishwasher and clothes washer overnight rather than during the morning or evening when usage is more likely to overlap with showers.

2.3.4: Tank Set Point

The final major variable of influence is the HPWH set point temperature. In general, a higher setpoint temperature reduces the efficiency of the heat pump by creating a greater temperature difference between the heat source and heat sink. A higher set point also increases the rate of heat loss between stored water and the surrounding air. However, there are situations where increasing the set point temperature would benefit system efficiency. When large quantities of hot water are drawn in clusters, a higher set point would act as a buffer and help reduce the amount of heating from electric resistance. This is especially true when a mixing valve is installed[8]. Increasing the set point is also a strategy used when trying to reduce energy use during hours when time of use (TOU) prices are maximum. More details on pre-heating effects are provided in CHAPTER 3: *The Future of HPWHs and the California Electric Grid*. The factory default set point of a HPWH is typically 120°F. With the exception of vacation periods, it is not advised to enact a setpoint lower than 120°F. During periods of high demand, tank temperatures may drop 10°F or more below the set point, which would result in delivered water below the minimum acceptable temperature of 110°F (Shapiro & Puttagunta, 2016). If set point temperatures are raised above the standard temperature range of 120-140˚F, a mixing valve would need to be installed at the outlet in order to ensure safe water temperatures at fixtures.

2.3.5: HPWH Control Mode

Most HPWHs allow for the homeowner to choose from several settings that alter the way the unit operates under various conditions, resulting in different levels of efficiency. While terminology for the available modes may differ somewhat between manufacturers, most include some form of a hybrid, heat pump, high demand, and vacation mode. A brief description of the various modes is provided in the following sections.

2.3.5.1: Hybrid Mode

Hybrid mode is generally considered the default mode for most HPWHs. It prioritizes use of the heat pump compressor except in cases when ambient temperatures are outside the unit's operating range, or the tank temperature falls too far below the set point. In the event these conditions occur, the resistive elements activate to either supplement or fully replace compressor operation. Actual details of the control of the electric element varies among the manufacturers.

While this default hybrid setting strives to sustain a high level of performance without sacrificing hot water availability, the actual efficiency of the HPWH can vary significantly with the usage patterns and surrounding air temperatures, resulting in suboptimal overall performance. In the hybrid mode, the instantaneous COP can range from that of a traditional electric resistance water heater (ERWH) to that of a high-efficiency heat pump depending on the operating conditions and loads. To ensure optimum efficiency in this mode, high volume hot water loads should be reasonably spaced out rather than clustered, to minimize the occurrences of backup element operation.

A study by NREL evaluated the laboratory performance of residential HPWHs in hybrid mode. Four HPWH models were subjected to a range of ambient conditions and two draw profiles in

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[8] A mixing valve is a valve that is piped with cold potable water and hot water from the storage tank. The valve is set to provide a safe (non-scalding) outlet temperature, nominally 120°F, which is sent to serve the fixtures in the house. While maintaining safety, it also allows the tank to serve as an added thermal energy reservoir, since the tank can be heated 10-20°F above the mixing valve set point.

order to analyze how each unit would respond to different external variables (Sparn, Hudon, & Christensen, 2014). One of the draw profiles included more clustered hot water events, while the other draw profile was more dispersed throughout the day. The study concluded that the COP of a HPWH in hybrid mode is largely dependent on the manufacturer's control logic, specifically whether shorter recovery rate or efficiency is prioritized and the allowable temperature range for heat pump operation. It was also concluded for all models that the best way to optimize their operation was to reduce the amount of resistive heating. In addition, it was found that many models prevent simultaneous use of heat pump and resistive elements. In the event that conditions initiated resistive heating, the heat pump compressor could not reactivate until the tank returned to set point. This resulted in a significant drop in efficiency since much of the tank recovery could still be accomplished by the compressor. For such situations, an effective approach to maximize COP is to prevent conditions that trigger resistance element activation.

One preventative measure to improve efficiency in hybrid mode is to increase the set point temperature of the tank. Doing so increases the amount of hot water available, allowing the unit to keep up with the heat pump when periods of high demand occur. The drawback of an increased set point temperature is that standby losses will increase, and the compressor will operate less efficiently. However, even at these conditions, the amount of power consumed is still one-third to one-half that consumed by resistive heating. A second measure could be for occupants to spread out water use so that the system has the chance to recover by sole use of the heat pump.

2.3.5.2: Efficiency Mode

In efficiency mode, heating is done through heat pump compressor use alone provided that ambient temperatures are within the specified operational range. While this setting is the most energy efficient, there is an increased likelihood of running out of hot water in the event of a large volume draw. This mode is best suited in a low-volume household where ambient temperatures are regularly warm and water use is spread consistently throughout the day, or in applications where the occupants are amenable to adjusting their use patterns to align with the HPWH performance.

2.3.5.3: High Demand Mode

High demand mode operates the water heater as a traditional ERWH, utilizing only the resistive elements. This setting is the least energy efficient but may be useful in times of increased hot water demand or malfunctions of the heat pump occur. It is not intended for prolonged use and most models will automatically revert to hybrid mode after a short period of time.

2.3.5.4: Vacation Mode

Vacation mode is intended for periods in which the water heater is not used for a long period of time (at least a week), in order to minimize unnecessary energy consumption. In this mode, the tank will be maintained in a lukewarm condition. Depending upon operating conditions, it may take up to 6 hours for the tank to recover from this condition.

CHAPTER 3:
The Future of HPWHs and the California Electric Grid

3.1: Load Shifting

Due to its storage capabilities, a HPWH can act as a thermal battery, allowing for the unit to store additional heat hours before hot water demands occur. Load shifting can utilize storage by biasing operation during more optimal conditions that allow for greater operational efficiency, lower utility costs, and benefits for the stability of the electric grid. While this generally increases electricity consumption (due to higher tank temperatures), the shifting of energy use reduces customer electricity costs and associated carbon emissions[9].

Recently, the increasing availability of utility TOU rates has been a way to incentivize homeowners to perform voluntary load shifting. TOU prices are structured to reflect the true costs of generating and transmitting electricity by time of day and are generally the highest during late afternoon and early evening. For Sonoma Clean Power (SCP), peak price periods occur either 3-8 PM or 4-9 PM depending on the chosen rate plan. This form of pricing encourages homeowners to run their appliances during off-peak hours when electricity is least expensive. From a grid efficiency standpoint, preferable operating times for HPWHs occur mid-day when solar and wind energy is most abundant, allowing for more energy to be consumed from a clean source. Recent research has studied numerous load-shifting strategies to identify which operational schedules best manage cost and energy use without compromising hot water availability.

3.2: Optimized Load Shifting Schedules

A Pacific Northwest focused study by Ecotope utilized simulation, modeling and laboratory testing as a strategy to compare the energy savings of three different methods of load shifting to avoid peak demand windows (Carew, Larson, Piepmeier, & Logsdon, 2018).

The simplest of the three strategies used an external timer that prevented the water heater from running during the 4-hour peak price period while maintaining a constant set point during all other hours. Results revealed this strategy to be unfavorable since complete shutoff during the 4-hour window led to frequent hot water runout events with minimal cost or energy savings.

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[9] When renewables are most present on the grid during the middle of the day, the associated carbon content per unit of kWh is very low.

The second, more advanced method of load shifting incorporated both “load-up” and “shed” events. This strategy involves raising the tank temperature above set point prior to peak periods, then dropping the set point when rates are highest. The goal is to be able store enough energy when prices are low so that the system can still provide sufficient hot water to meet the homeowners demand throughout the shed period. The study simulated three set points and various shed durations to determine the optimal schedule that minimizes runouts without causing excess energy consumption. Since TOU prices vary with season and day of the week, different schedules had to be established for winter weekdays, winter weekends, summer weekdays and summer weekends. The first approach disabled operation for the 9-hour block consisting of the 4-hour peak, 2-hour pre-peak shoulder, and 3-hour post-peak shoulder. Shoulder periods sometimes occur on either side of the peak incurring elevated prices less expensive than the 4-hour peak window. Findings confirmed that the water heater could not provide sufficient hot water for such an extended period of time. However, it was possible to make it through the 7-hour peak and post-peak periods following a load-up without requiring additional energy. To prevent activation of auxiliary elements, a progressive ramp up of set point temperature prior to peak period was required.

The results of the study concluded that a baseline set point of 125°F with “load up” and “shed” temperatures of 135°F and 110°F respectively led to a 14% customer savings and a 34% marginal cost savings for the utility. Higher maximum temperatures provided an increase in the utility marginal savings but a decrease in customer savings. The optimal weekly control schedules established from the study are shown in Figure 7 and Figure 8 below. Because of the lower air and inlet water temperatures during the winter season, the modeled HPWH could not directly raise the set point temperature from 110°F to 135°F without initiating a resistive heating element. Therefore, the system stabilized at 125°F during early morning hours before ramping up to the maximum temperature 135°F prior to the shed period.

Figure 7: Summer Load Shifting Schedule Based on TOU pricing

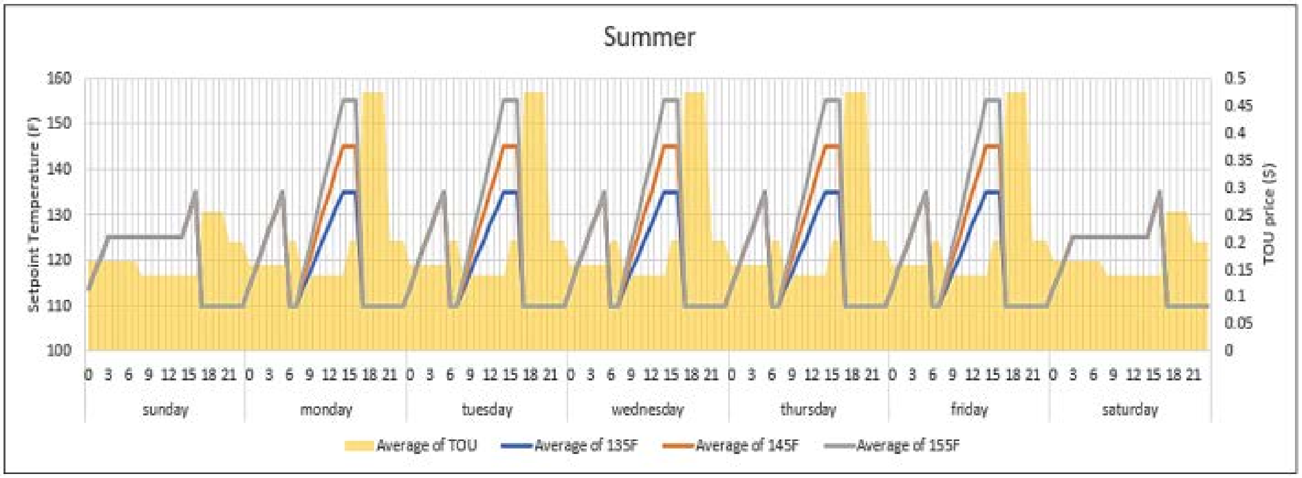


Image Credit: *Ecotope Load Shifting Study*

Figure 8: Winter Load Shifting Schedule Based on TOU pricing

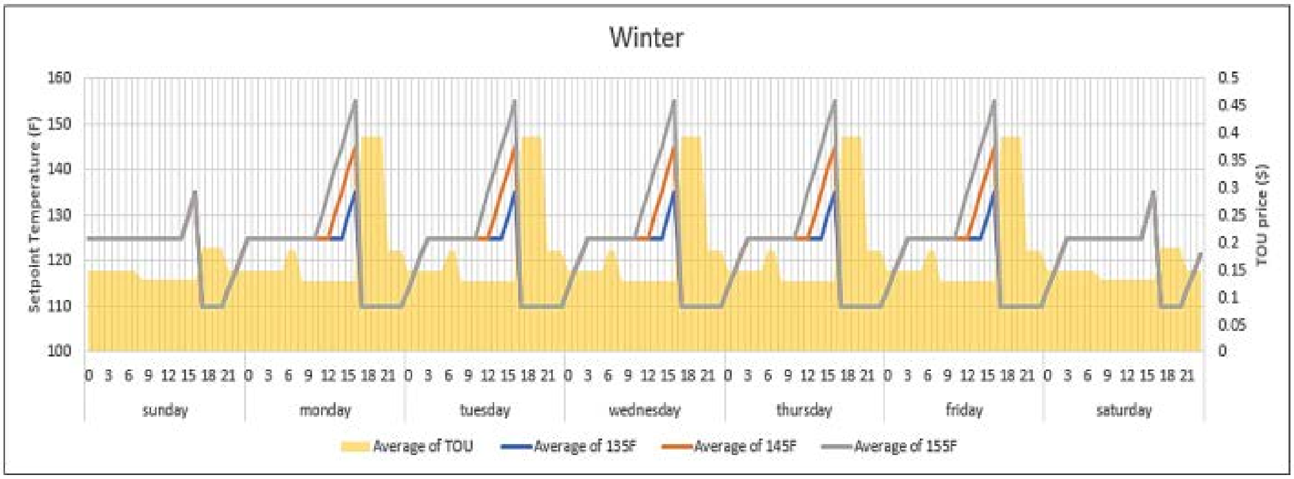
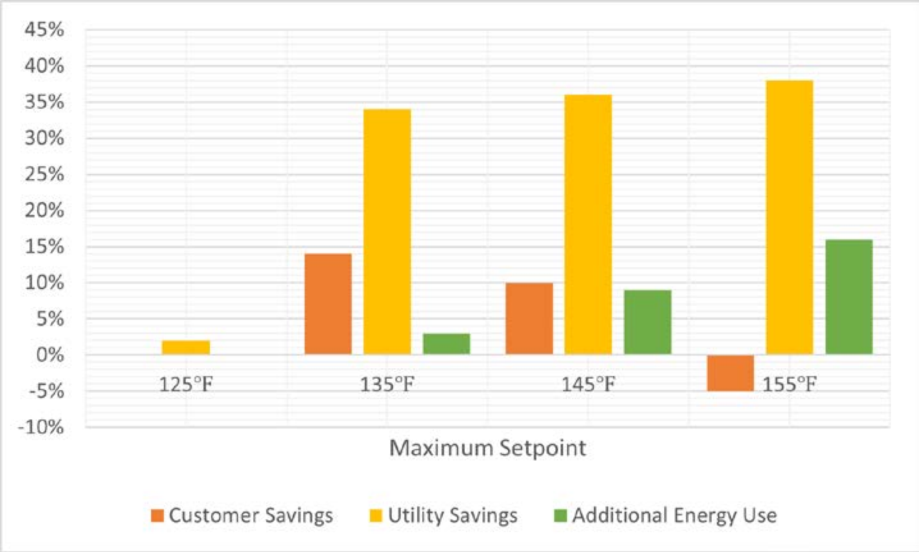


Image Credit: *Ecotope Load Shifting Study*

The third strategy is similar to the one previously described, with the goal to expend energy during periods of low prices by raising and lowering the set point temperature. The only difference is the algorithm is able to look ahead at the price signal sent by a third party to load-up and shed accordingly. This Optimal Price strategy produced similar savings to the load-up and shed strategy, incentivizing both homeowners and utilities. However, the study concluded that a significant difference in savings occurred depending on which price schedule the algorithm is optimized against. These results are shown in Figure 9. Basing the algorithm on TOU rates can induce customer savings of 15% to 20% and utility marginal cost savings of 35%. If, instead, the algorithm optimizes based on utility marginal costs, the utility experiences a marginal cost savings of 60% with customers experiencing a 5% increase in costs. While optimizing based on UMC rates may be appealing to a utility, this would require some form of customer incentive to motivate homeowners.

Figure 9: Cost and Energy Savings Based on Set Point for Optimal Price Strategy



3.3: Grid Integrated Demand Response

Grid integration of heat pump water heaters allows for utilities or third-party aggregators to shift the load from connected units in times of grid stress or imbalance, while minimizing impacts on hot water availability. The capability to shift energy use to mid-day makes HPWHs an effective way to relieve capacity requirements on the grid during high demand or absorb excess power during periods of overproduction. This stabilization would help reduce the need for rolling blackouts and increase utilization of energy from cleaner sources. There are a number of demand response programs made available through utility companies, community choice aggregators or third parties that provide customers with financial incentives in exchange for allowing control to reduce or shift HPWH energy use during times of peak demand, high temperatures or other stressed grid conditions.

Grid-integrated HPWHs (GIHPWHs) not only provide a benefit for the utility but also reduce energy costs to the homeowner. Figure 10 illustrates the typical combined daily hot water use profile for residential buildings (Hendron & Engebrecht, 2010). The graph shows a peak in hot water use once around 8 AM and again around 7 PM. Comparing this to Figure 1 illustrating the CASIO daily net load, it is evident that that the grid experiences morning and evening peak loads around the same time that water heating energy reaches its peak.

Figure 10: Domestic Hot Water Use Profile

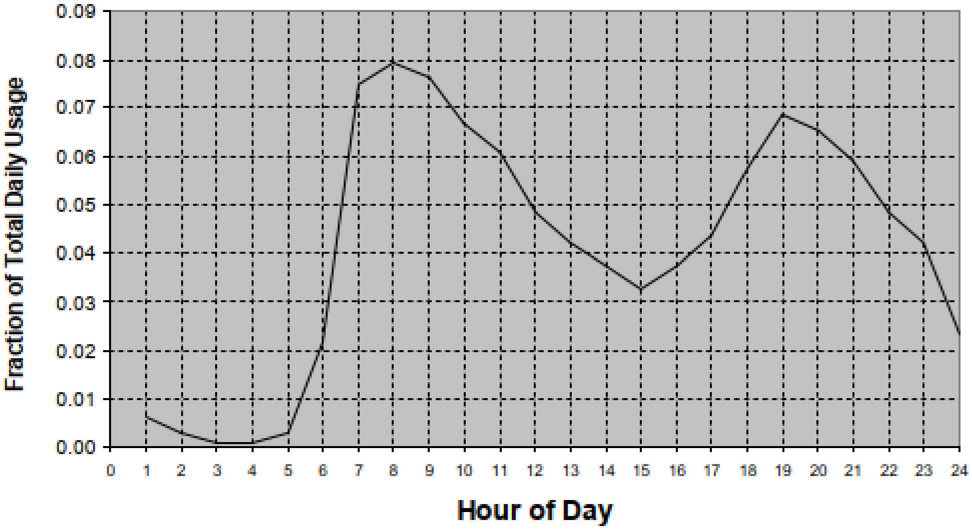


Image Credit*: Building America Benchmark*

During high demand, utilities face higher marginal cost and therefore must impose higher TOU rates on the customer. Through grid integration, the party initiating the demand response can shift HPWH operation to periods when the grid experiences less demand. This coincides with lower electricity rates, effectively reducing operating costs for the customer. Figure 11 depicts the potential magnitude of demand reduction that could be achieved by means of grid integration in California. The black line represents the load schedule of an ERWH, and the gold line represents that of a HPWH serving the same load. By switching from a ERWH to a HPWH without load shifting, the amount of energy expenditure that coincides with peak demand is cut from 29% to 14% solely due to its improved efficiency. The green line represents a GIHPWH controlled to avoid the afternoon peak period and consume energy mid-day. The results are a decrease in peak coincidence to only 1% (Delforge & Larson, HPWH Demand Flexibility Study, 2020).

Figure 11: Savings Potential of HPWH Load Shifting

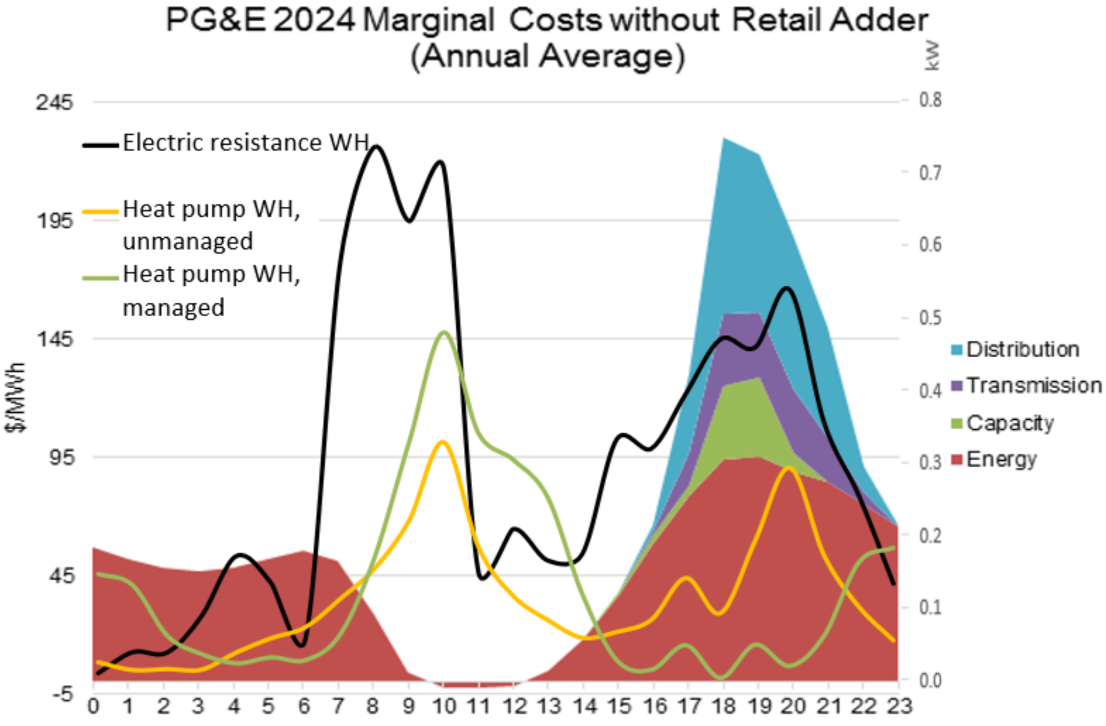


Image Credit: *NRDC*

3.4: Programs and Incentives

Multiple programs are available or soon to be available in various regions of California to incentivize homeowners to participate in utility load-shifting or demand response programs. These require possession of a smart device, generally with Wi-Fi connectivity, although FM signal or other means exist for communication. Since most programs involve pre-heating water heaters above set point during off peak hours, it is essential that a mixing valve be installed at the HPWH outlet to ensure a safe water temperature at fixtures.

Pacific Gas and Electric (PG&E) currently offers customers with an existing ERWH a $300 rebate per unit upon replacement with a certified ENERGY STAR HPWH with a UEF value 3.09 or greater and a storage capacity between 40 and 55 gallons (Pacific Gas and Electric, 2020). They are also in the process of developing a behind-the-meter (BTM) thermal energy storage program, WatterSaver (Jacobson , 2020) in late 2021. The goal of the program is to reduce peak load by two to five megawatts by 2025 through installment of smart control devices on HPWHs. PG&E anticipates providing customers an initial incentive of $50 upon enrollment in the program and $5/month for satisfactory participation. The control strategy of WatterSaver will be optimized based on the customer’s current TOU rate plan to ensure no increased costs will result from load shifting. The program also aims to educate participants on the ways they can optimize usage to maximize bill savings on a TOU rate, likely resulting in additional savings due to behavior alone.

Sonoma Clean Power, in partnership with the BayREN Home+ program, provides a $1,700 rebate to standard customers, and a $2,000 rebate to low income customers that purchase a HPWH through the SCP webstore (Sonoma Clean Power, 2020b).) Their demand response program, GridSavvy, enables their customers to receive a $5/month bill credit for allowing SCP to remotely control connected devices, including GIHPWHs, smart thermostats, and electric vehicle charging stations. Their control strategy entails preheating the water heaters in the afternoon when there is maximum solar energy available, so that there is sufficient hot water stored for use during the evening peak period.

Sacramento Municipality Utility District (SMUD) offers customers a rebate of $1,500 when replacing an existing gas water heater with an approved HPWH attaining a minimum UEF of 2.87 (SMUD, 2020a). They are currently implementing a pilot program, PowerMinder, that offers a one-time incentive of $150 upon enrollment and $2/month for continual participation (SMUD, 2020b). The program requires homeowners to possess a compatible system which currently consist of Rheem models. The control strategy optimizes connected water heaters a few days out of the week to consume more renewable or lower cost energy.

TECH Clean California launched in summer of 2021 and will provide matched funding to double the magnitude of clean heating incentives funded by utilities, initiative administrators, and third-parties. All TECH matching incentives will be provided at the contractor level (regardless of where the base program incentive is provided). TECH will host a centralized incentive platform to make it easy for customers to find trade allies, and for market and trade ally partners to find incentives and submit a single application for all eligible programs. TECH is partnering with the statewide marketing campaign The Switch Is On to educate customers and contractors about the benefits of heat pumps for water heating and space conditioning.

3.5: Title 24 Code Impacts

During the development of the 2019 Title 24 code, the Energy Commission was planning to implement a compliance credit for HPWHs which provide load shifting capabilities in response to utility or third-party initiated demand response signals. This strategy is an important element of integrating the expected increasing number of all-electric homes with the California grid, which is moving steadily toward renewable generation. HPWHs will add load to the grid relative to conventional gas water heating systems, and load shifting will allow that added demand to be focused on times of day when renewables are predominant. This avoids both peak times and middle of the night periods when the grid is more reliant on fossil fuel based generation.

As part of the 2019 code development activities, the Energy Commission was coordinating with the National Resources Defense Council and a wide range of stakeholders who were leading an effort to adopt a framework for load shifting HPWHs. This work led to the development of Joint Appendix 13 (JA13) entitled “Qualification Requirements for Heat Pump Water Heater

Demand Management Systems"[10], which was adopted by the Energy Commission in July 2020. As JA13 was under development, the Statewide Codes and Standards Enhancement Team was working on code change proposals for the 2022 Title 24 code update. An area of interest was to develop expanded load-shifting HPWH credits within Title 24 to recognize more advanced strategies beyond what was developed in JA13. The 2022 code development activity was complicated by the fact that the work intended to be completed under the 2019 code cycle (i.e. JA13 and implementation of algorithms within the CBECC-Res compliance software) was not completed until later in 2021.

The primary goal of the 2022 HPWH compliance credit development was to recognize the increased benefits that could be realized by a HPWH that responds to local TOU rate schedules to bias operation to mid-day periods (off-peak) when excess renewables are available on the grid. The HPWH would "load-up" during this pre-peak period by heating storage 10-15˚F above the normal set point, increasing the likelihood the unit could coast through the subsequent peak period. Alternative approaches that would be treated equivalently to this strategy include installing a HPWH with increased storage volume[11] or a HPWH with integrated mixing valve[12] and with the tank set point at a minimum tank temperature of 130˚F. All HPWHs eligible for this proposed 2022 compliance credit would need to be JA13 manufacturer-certified, which includes having a mixing valve installed and having a CTA-2045-A communications port installed on the unit. At the time of this report, the Energy Commission had postponed any action on the proposal until the approved JA13 is updated (expected in mid 2022).

Applicable Standards

- OpenADR: Automated demand response
- CTA 2045: Physical port at water heater + standard control commands
- JA13: Storage and load shifting requirements:
    1) Local TOU capability
    2) Advanced control capability
    3) Storage and load shifting requirements

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[10] https://www.energy.ca.gov/sites/default/files/2020-07/JA13_Qualification_Requirement_HPWH_DM_ADA.pdf

[11] The California Plumbing Code (and JA13) has a table which ties the FHR for a water heater to the number of bathrooms and bedrooms in the dwelling. The 2022 proposal would require the installed HPWH to move up one step in the FHR sizing. As an example, a case where a 40 gallon HPWH is compliant with the JA13 FHR requirement would need a 50 gallon unit to achieve the proposed 2022 compliance credit.

[12] GE is planning to come out with a new line of HPWHs in 2021 which will feature integrated mixing valves. Integrated valves may be more common in the future as it eliminates any concerns with field installation issues.

Local TOU Control

- Permanent grid connectivity not required
- Lower entry point: opt-out, designed for mass adoption
- Protects utility customers from peak TOU prices, significant grid value

Advanced Control (Grid-Interactive)

- Higher grid value potential
- Requires availability of load shifting program in local area + customer opt-in = lower adoption
- Connectivity challenges: Wi-Fi reliability and persistence issues, cellular still expensive, FM radio (1-way)

CHAPTER 4:
Original Scope and Work Completed

4.1: Objectives of Original Scope

Due to the variability of occupant behavior, usage patterns, and environmental conditions, it is difficult to pre-program a HPWH with a fixed control strategy at the manufacturing stage that would optimize its efficiency across all applications. The original research plan (Hendron, et al., 2019) entailed investigating load shifting strategies to respond to in-situ variables by means of machine learning and model predictive control (MPC). A typical MPC consists of a modeled version of the system, a recording of previous operations, and an objective function that is to be minimized under certain constraints. In the case of this project, the control approach would be comprised of machine learning techniques, HPWHsim, and an optimization algorithm consisting of a cost function based on utility rates. The system would record data related to ambient temperature and previous hot water draws to learn the conditions the system typically experiences. Based on this information, HPWHsim would predict the energy consumption and hot water availability that the HPWH will experience in the future. While holding hot water availability paramount, the optimization algorithm would be able to work in tandem with the modeling simulation to determine hourly set points that minimize the electricity cost to homeowners by increasing the COP and shifting the load to periods of lower energy rates.

Five key components of the idealized control logic are as follows:

1. The machine learning algorithm would predict periods of large hot water draws, allowing for the HPWH to load up in advance. Doing so would reduce or eliminate the need for lower efficiency resistive heating to meet hot water needs. It would also allow for a lower temperature set point outside the periods of high demand, reducing wasted energy due to standby losses.
2. The machine learning algorithm would also identify periods of low hot water use and perform pre-heating during times when the surrounding air temperatures are highest, resulting in higher average COPs.
3. The optimization algorithm would respond to seasonal and daily temperature variations, anticipating periods during which external temperatures fall outside the heat pump operating conditions. This would ensure that enough energy is stored to prevent the need for resistive heating.
4. The optimization function would account for local TOU electric rates and identify optimal heating periods at which prices are lowest. These periods tend to occur mid-day which aligns to periods of abundant solar power generation and high ambient temperatures.
5. Prioritize grid-integrated control signals from the utility or third-party implementer

4.2: Completed Work

Frontier Energy completed many of the preliminary steps toward achieving the goal of efficiency optimizing control of HPWHs prior to suspending the work in 2019, when the NREL patent disclosure was discovered.

- Completed the Phase 2 Research, Instrumentation, and Monitoring Plan covering efficiency optimizing heat pump water heaters, among other applied research technologies.
- Completed a literature review for the HPWH COP optimization project, studying machine learning techniques that can be applied to predict daily hot water draw profiles. Techniques investigated included template matching, Markov chains, and the averaging bin method.
- Completed design of the hot/cold water supply plumbing for the Building Science Research Laboratory and assembled the plumbing system that would have been used for testing the efficiency optimizing HPWH control strategy.
- Completed the expanded electrical supply capabilities for lab test rigs and HPWH equipment that would be tested in the BSRL environmental chambers (see Figure 12).
- Developed template matching algorithms to predict occupant hot water use, for use in model predictive control to optimize the COP of heat pump water heaters.
- Began preliminary simulations with HPWHsim to assist with HPWH test planning.
- Developed a detailed laboratory test matrix for efficiency optimizing HPWHs based on the required inputs and outputs of the HPWHsim software. The lab tests will be used to validate the HPWHsim results and the optimization strategy.
- Analyzed machine learning techniques studying occupant hot water use. The Averaging Bin Method, Averaging Bin Method – Previous 10 days, and Template Matching algorithms were evaluated analytically, and the Averaging Bin Method – Previous 10 days returned the best results. Figure 13 shows an example result. The green bars show the prediction in gallons for each 30-minute period, while the blue data shows the actual hot water consumption in those periods. The prediction very closely matches the consumption data before 11 AM and would enable a model predictive controller to help avoid resistance element use. It does not match the period in the evening as well but total consumption in that period is lower.
- Peter Grant presented at the 2019 ACEEE Hot Water Forum on the progress of using machine learning techniques to predict occupant hot water use. Researchers and manufactures in attendance provided Grant input on other ways to pursue this project. At the Forum, Grant learned of the NREL patent disclosure for a similar efficiency optimizing control algorithm.
- In April 2019, Frontier Energy met with NREL to secure their support as a Lead Locally partner rather than duplicate their work using California taxpayer funds. Frontier tracked their search for a manufacturing partner to develop a prototype based on their model predictive controller that could be field tested as part of Lead Locally. A number of options were explored for continuing the research project using the NREL technology.
- NREL made minimal progress licensing their technology despite their best efforts and would have been unable to secure DOE funding to develop a prototype HPWH on their own within the time frame of Lead Locally. As a result, Frontier consulted with the Energy Commission and SCP, and it was decided in August 2019 that the project should be rescoped and the remaining funds would be used for other promising applied research activities.

Figure 12: Electrical modifications in the BSRL large environmental chamber

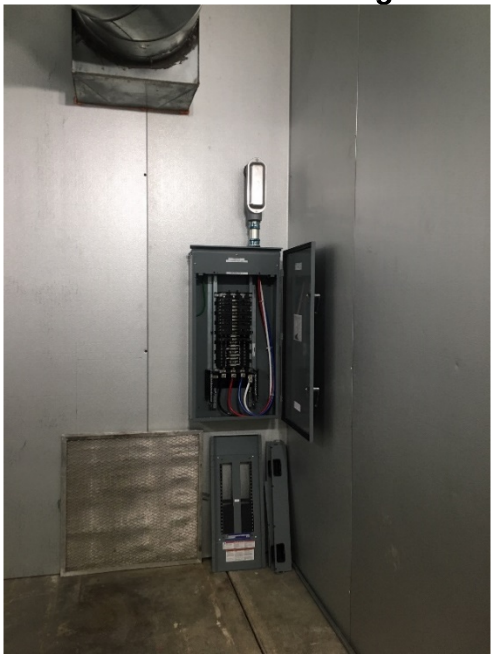
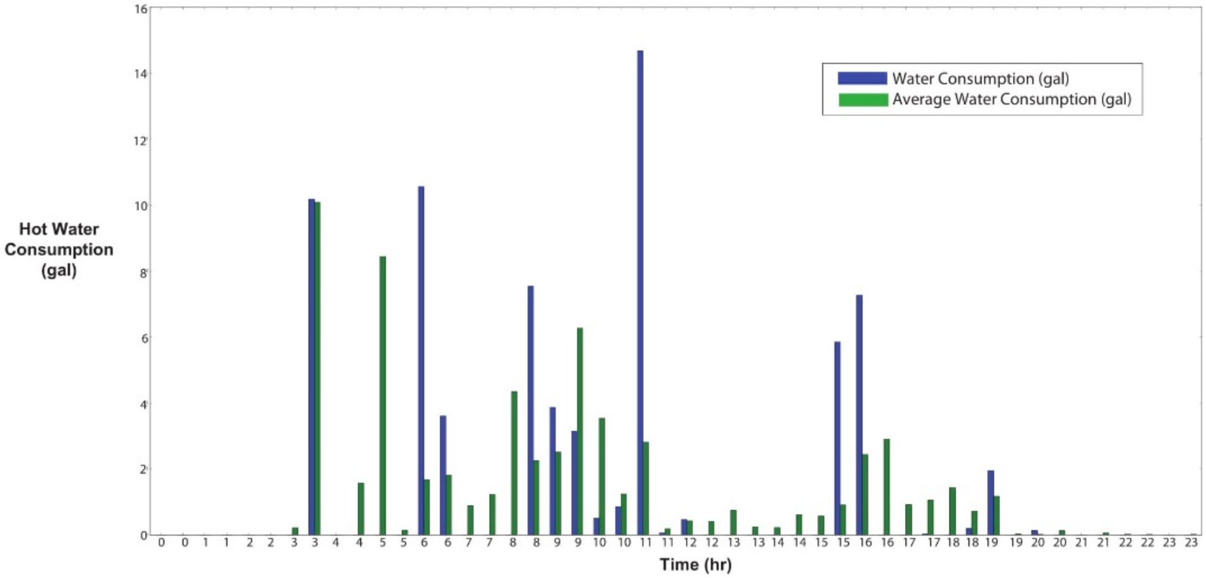


Figure 13: Comparison Between Hot Water Consumption and Predicted Hot Water Consumption on Oct 7, 2010 Using the Averaging Bin Method – 10 Previous Days Algorithm



4.3: Expansion of the GIHPWH Project

Once further work on the research elements of this project were suspended, Frontier decided to expand the monitoring plan for the GIHPWH tech demo project under Lead Locally in order to learn more about the performance of more standard load shifting algorithms and homeowner satisfaction with the technology. Although the efficiency optimizing HPWH applied research project would have focused on energy cost savings for the homeowner using sophisticated controls, the knowledge gained from a more detailed study of GIHPWHs would be valuable data for future algorithm development.

In Frontier Energy's technology demonstration of GIHPWHs, Frontier has installed nine Rheem and Ruud HPWHs in the Sonoma Clean Power territory. The goal for these installations was to facilitate the ability to implement load shifting, so most sites were outfitted with either a Rudd PROUH80 T2 RU375-30 or Rheem PROPH8 T2 RH375-30 80-gallon water heater, depending on the customer's preference. The selection of the 80-gallon water heater was to ensure that there would be a significant reserve of hot water when the load shifting was active, since the heat pump mode cannot respond quickly to large demand requirements. For sites where there were space constraints or particularly low water use, smaller capacity units were installed. All HPWHs installed were from a Rheem or Ruud line, which was necessary to implement load shifting.

Given the limited grid interfacing options present at the start of the project, Frontier Energy chose to implement the load shifting program through Rheem's API network, with special access permission from the manufacturer. Frontier Energy thus adopted the role of the utility in a GIHPWH program, automating the daily load shifting switch to heat pump only mode during the customer's hours of peak electricity costs, depending on the customer selected rate plan with the utility. An hour prior to the load shifting period, the HPWH would be signaled to preheat the water to its highest temperature setting, to ensure the customer had the largest possible reserve of hot water to last them through the period. A thermostatic mixing valve was installed with each HPWH to ensure that all hot water was delivered at a safe temperature of 120F. All water heaters resumed normal operation at the end of the load shifting period.

Results from the GIHPWH study will be presented as part of the Lead Locally Technology Demonstration final report scheduled for release in April 2022.

CHAPTER 5: Conclusions and Recommendations

5.1: Key Findings

Current research on the performance of HPWHs identifies two ways the technology impacts energy use within the residential sector. For one, heat pumps increase the operating efficiency above electric resistance or gas water heaters. This can reduce the amount of electricity used to heat water by more than half. However, unlike ERWHs, their attainable efficiencies span a wide range based on operating conditions. Consistent across studies, it was found that efficiencies are improved by minimizing the extent of electric resistance heating. Variables responsible for triggering activation of these elements include ambient temperature, tank size, setpoint and water-use behavior. Findings from an NREL field study of HPWHs in the Northeast showed that the daily pattern in which water is drawn had a larger effect on the COP than the total daily volumetric amount drawn from the HPWH. Draw profiles characterized by consistent water use throughout the day led to performances greater than profiles experiencing infrequent and high concentrated draws. The ability to predict utility costs and behavior could offer an excellent opportunity to reduce utility bills through optimal HPWH control strategies.

Along with a reduction in energy use from improved efficiency, a HPWH's load shifting, and grid interactive capabilities offer homeowners and utilities additional flexibility to further reduce costs. Through control of set point temperatures prior to peak demand periods, homeowners can reduce their electricity bills while utilities alleviate excessive peak grid demands.

5.2: Future Research Needs

The expected release of 120V HPWHs designed for the California retrofit market represents a new product type which is not yet well understood in terms of performance under varying real-world conditions. The 120V products are expected to reach the market by the end of 2021. Some manufacturers will rely on larger compressors with no electric backup, while other manufacturers will rely on reduced second stage heating. Understanding the performance of these units is important to determine how viable they are for the California retrofit market.

The 2022 Statewide Codes and Standards team developed a compliance option proposal that the Energy Commission is expected to evaluate in coordination with an expected JA13 update in 2022[13]. The compliance option proposal includes a strategy where the HPWH would operate

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[13] https://title24stakeholders.com/measures/cycle-2022/single-family-grid-integration/

in response to TOU rates to prioritize operation to midday periods (i.e. off-peak), when solar generation is most prevalent on the grid, and would not need to rely on utility or aggregator control signals to prioritize operation. This offers the advantage of allowing the HPWH to operate independently of external controls.

5.3: Opportunities for Utilities

Utilities should continue to investigate ways to incentive HPWHs in terms of utility rates and incentives, especially for those units that can load shift from on to off-peak periods. Utilities also have opportunities to leverage emerging HPWH control technologies installed by manufacturers to complement ongoing demand response programs while offering greater value to their customers.

5.4: Opportunities for Manufacturers

It will be important to track the features and capabilities that the industry will provide for JA13 compliant HPWHs. The industry in general is hoping for significant growth in the California market to offset development costs to date. The flexibility and ease of use of advanced control options that HPWH manufacturers provide will help determine how effective they will operate in a grid harmonized manner.

In addition, manufacturers should carefully study real-world HPWH operating data to determine how best to optimize their control strategies. This may be of less interest to the industry as their primary motivation may be to obtain the best UEF ratings, rather than actual field performance.

Finally, the NREL efficiency optimizing control algorithm is available for licensing to manufacturers. This may be an opportunity for manufacturers to secure a high value feature for future HPWH models.

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