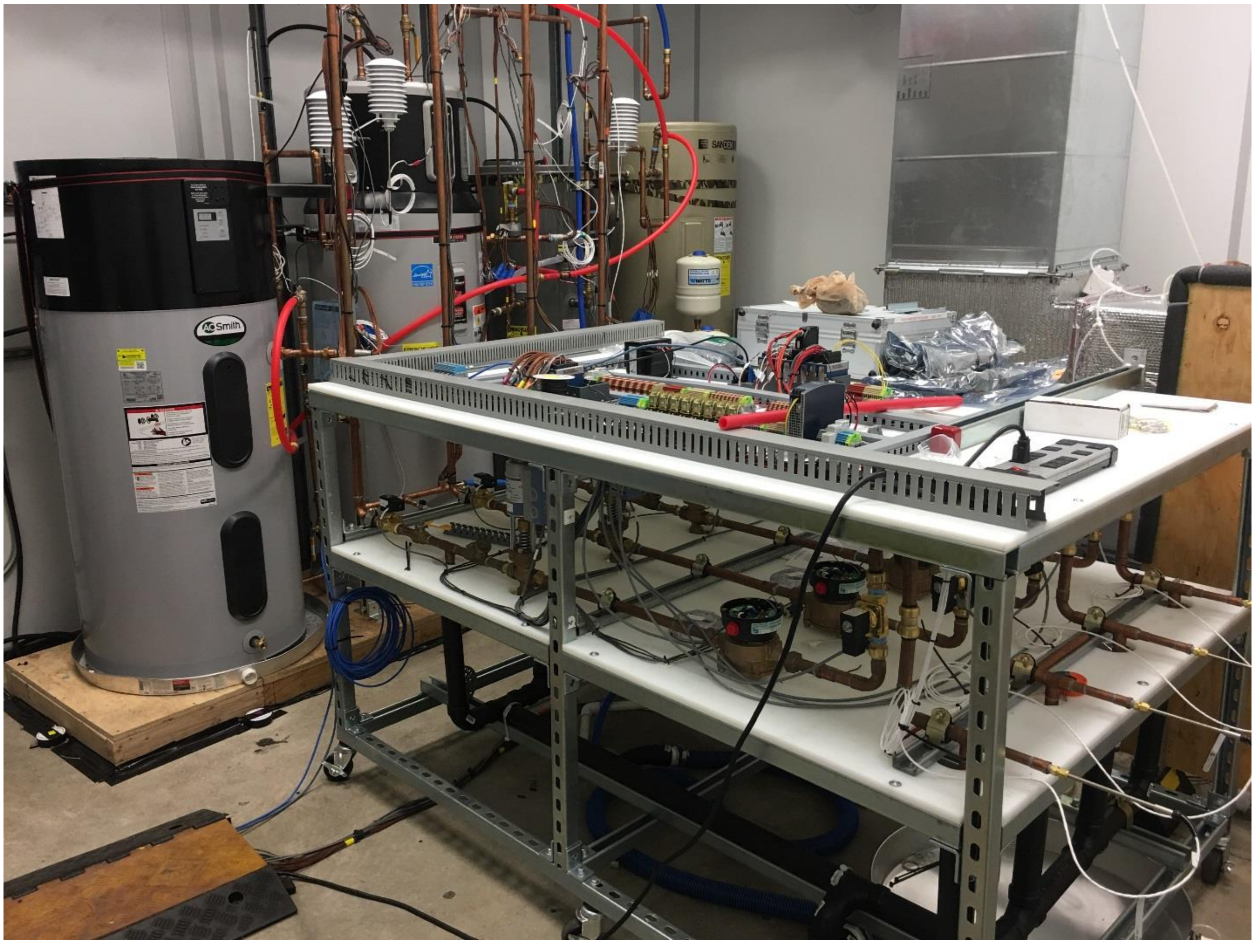
Lab Testing Heat Pump Water Heaters to Support Modeling Load Shifting



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Executive Summary

Hot weather supply and demand challenges caused by ample mid-day renewable generation and afternoon peak loads, as exemplified by the "duck curve", are a well-known problem in California. Utilities and State agencies are supporting existing policies and programs and developing new strategies that shift less essential electrical load from the late afternoon and evening peak demand period to off-peak periods to improve grid reliability and reduce costs. To encourage an adjustment in usage patterns to align with this changing generation and demand patterns, utilities in California have transitioned most commercial, industrial, and agricultural customers to time of use (TOU) rates. Residential customers are transitioning to TOU rates from now until 2020[1]. Under a well-designed TOU rate structure, customers are financially encouraged to minimize electricity use at times when the overall system usage is high[2]. Technologies that have the capability to shift loads will provide potential cost savings for occupants by reducing energy use during the highest cost periods under TOU rates and offer the potential for demand flexibility to the utility and customer.

Heat pump water heaters (HPWHs) show promise to be used in this way. Most HPWHs employ 4 to 5 kW electric resistance elements to supplement heat pump heating. Avoiding operation of the electric resistance element during afternoon and evening periods may be an effective way to reduce their impact on peak load. Additionally, raising the water temperature above the normal set point prior to the peak event, HPWHs can use the stored hot water storage as a thermal battery. This potential also extends to the category of HPWH that does not contain a resistance element.

This project focused on the potential impacts of performing load shifting with HWPHs in California's Building Energy Efficiency Standards (Title 24, Part 6) and supported simulation model enhancement. The project had three objectives:

1. Support a simulation-based study performed by Ecotope and the National Resources Defense Council (NRDC) using Ecotope's HPWHsim[3] model;
2. Demonstrate the feasibility of using HPWHs for load shifting in a laboratory setting; and
3. Identify issues that should be addressed to maximize the impact of this control strategy.

This project does not compare HPWHs to other water heating technologies in terms of price, energy savings or reductions in customer utility bills. Three types of tests were performed on HPWHs from four manufacturers. First, testing was completed to force the compressor to heat water from as low a temperature as possible[4] to the maximum set temperature. The maximum set temperature ranged from 160 °F to 175 °F depending on the manufacturer. These tests yielded detailed data relating the COP as a function of tank temperature, and Ecotope used the data to improve HPWHsim. Second, tests

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[1] https://www.pge.com/en_US/residential/rate-plans/how-rates-work/rate-changes/residential-rate-changes/residential-rate-changes.page

[2] https://www.pge.com/en/about/newsroom/newsdetails/index.page?title=20180108_new_time-of-use_rate_plan_will_support_cleaner_more_reliable_grid_and_enhance_choice_and_control_for_pge_customers

[3] HPWHsim is Ecotope's detailed simulation model of HPWHs. It has not been released publicly, and the best way to obtain a copy is by contacting Ecotope directly. The github repository for documentation is available at https://github.com/EcotopeResearch/HPWHsim/tree/master/Documentation

[4] Even when in heat pump only mode, tested integrated HPWHs engaged the resistance element if the water in the tank was below a certain temperature. This set a lower bound for the test.
Footnote continued on next page.

monitored the compressor and resistance element operation in response to sudden increases and decreases in the set temperature as would occur when load shifting controls are implemented. These results were also used by Ecotope to incorporate the control logic used by four different manufacturers in their model. Finally, tests were performed monitoring the performance of the HPWHs using three different 24-hour draw profiles[5] from the California Building Energy Compliance Calculator for Residential Buildings (CBECC-Res)[6]. Each assumed a 2100 square foot, two-bedroom house in a climate zone within PG&E service territory. This data set was used by Ecotope to validate their model against measured data.

In-depth analysis was performed on the 24-hour draw profiles test results. The performance of the four HPWHs in three different draw profiles were studied when operating with and without load shifting controls. For the load shifting tests the set temperature was increased from 9 AM to 5 PM. This approach had two goals: 1) Use the heat pump to heat the water to an elevated set temperature between 9 AM and 5PM, and 2) Avoid heating from 5 PM to 9 PM. The energy use data collected were used to evaluate the impact on compliance with the Building Energy Efficiency Standards (Title 24, Part 6) based on the time Dependent Valuation (TDV)[7] employed by the 2016 CBECC model, to evaluate grid impacts, and potential compliance with Title 24, Part 6 for builders. Table 1 provides the key characteristics and findings of each draw profile test, and the following bullet points provide further detail.

Table 1: Key Characteristics and Findings from Each Draw Profile

	Highest TDV Penalty Day	Summer Peak Day	Low Challenge Day
Day	March 6	July 10	August 31
Location	Bishop (CZ16)	Sacramento (CZ12)	San Francisco (CZ3)
Inlet Water Temp	40 °F	68 °F	61 °F
Key Characteristic	Largest peak draw: 40' shower at 7:28 PM	Largest peak draw: 40' shower at 7:28 PM	Largest peak draw: 2.16 gallon faucet at 8:09 PM
Maximum TDV Multiplier	363 kBtu/kWh	2751 kBtu/kWh	27 kBtu/kWh
Total Mixed Water Volume	114 gal	114 gal	95 gal
Key Finding	Load shifting decreased compliance penalty by up to 84%	The peak period does not occur at the same time each day; load shifting controls should respond flexibly	Load shifting should not be performed on days when there is no significant peak to avoid

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[5] A draw profile is a table of hot water uses. A 24-hour draw profile lists how occupants use hot water over a one day period.

[6] Draw profiles are shown in Figures 12, 14, and 16.

[7] TDV represents the societal cost of energy used in a building. It is calculated by multiplying the hourly energy consumption on a site, as estimated by Title 24, Part 6 compliance simulation models, and an hourly multiplier. The multiplier reflects the wholesale market cost of energy, delivery, and emissions costs. See Time Dependent Valuation of Energy for Developing Building Efficiency Standards – 2016 TDV Data Sources and Inputs.

- Highest TDV Penalty Day: This draw profile showed both the greatest need for load shifting, and the greatest benefit from incorporating the controls. Tests of a HPWH with 50 rated gallons of storage showed that the HPWH used the electric resistance element during the peak period. In addition to potential grid impacts, this affects the TDV score and the way these HPWHs are assigned value in the software that supports the Title 24, Part 6 compliance process. However, the resistance element use during the peak period was reduced enough through load shifting to lower the compliance score penalty that HPWHs are assigned due to the potential use of the electric resistance element on these days by 43%, relative to an uncontrolled HPWH, in the load shifting scenario. This presents a significant benefit to the builder, reduction in grid stress for the utility, and potential for cost savings for a home-owner with TOU rates. The results were further improved by switching to a HPWH with 66 gallons of rated storage; in that case, the electric resistance element did not operate during the peak period, and the compliance score penalty was reduced by 84%, relative to an uncontrolled HPWH.
- Summer Peak Day: This draw profile presents the normal peak load challenge case. This draw profile simulates a typical summer day in the Central Valley, with low grid stress around mid-day and extremely high grid-stress during the peak period. Results on this draw profile were mixed. In every case, electric resistance element use after 5 PM was completely avoided. In many cases, compressor use after 5 PM was also avoided. However, in this draw profile the electric peak period, as evidenced by high TDV rates, began at 4 PM instead of 5 PM and load shifting controls increased the compliance penalty because of the high compliance penalty paid for using the heat pump between 4 and 5 PM. This shows that, in some scenarios, load shifting controls must be more flexible than how they were tested in this project. Strategies designed to improve Title 24 compliance or reduce consumer energy cost can use fixed controls in response to the static TDV penalty or TOU rate structure. However, strategies intended to minimize grid impacts should be able to communicate with the utility, and develop load shifting strategies customized to each day based on anticipated load communicated by the utility.
- Low Challenge Day: This draw profile presented a case with low hot water consumption during the peak period and provided a low bar for each HPWH to meet. Because it is less demanding, each of the HPWHs were expected to avoid all electricity use during the peak period when employing load shifting controls. This was true. However, the grid stress during the peak period of this draw profile was low, and employing load shifting controls again increased the compliance penalty for builders. The results from this draw profile show that load shifting controls should not be used every day and should only be employed on days where high grid stress is anticipated. This presents a problem when TOU rates are consistent each day. The consistent TOU rates will encourage occupants to shift the load, using more lower cost electricity on days when there is no need to shift load from the perspective of the grid.

Key lessons learned included:

- Even under the draw profile with the greatest need for load shifting, all tested HPWHs demonstrated a significant benefit to the builder for compliance with Title 24 relative to an uncontrolled HPWH, reduction in grid stress for the utility, and potential cost savings for occupants by reducing energy use during the highest cost periods under TOU rates.

- Benefits of load shifting increased when switching from a HPWH with 50 gallons to 66 gallons of rated storage.
- HPWH control logic is important to maximize benefits of load shifting. HPWHs favoring the compressor over the resistance element were more likely to obtain significant TDV reductions.
- Strategies designed to improve Title 24 compliance or reduce consumer energy usage during peak TOU rate period can be in conflict with strategies intended to minimize negative grid impacts. For maximum grid benefits, HPWHs must be able to communicate with the utility, and develop load shifting strategies customized to each day based on anticipated load communicated by the utility.
    - Further research into how these communications should proceed, and collaboration with manufacturers to enable these communications and controls will be vital to maximize the potential benefits from load shifting.
- There is potential for home builders to benefit from specifying HPWHs that have load shifting control capabilities in the Title 24, Part 6 compliance process. When the energy system features are entered into the compliance software (CBECC-Res) used to evaluate whether the home design will achieve a passing score, or Energy Design Rating, the HPWHs with this capability will be given more credit towards compliance than those that do not. CBECC-Res currently does not provide credit for these features. Modifying CBECC-Res to provide an appropriate benefit or credit to builders would encourage industry adoption of load shifting controls.

This exploratory laboratory project has provided the data set necessary for simulation studies with heat pump water heaters, demonstrated the technical feasibility of this approach, and identified several continuing research questions. Topics of further research include:

- Identification of High Performing HPWHs: This study tested four HPWHs across a range of storage volumes, manufacturers, and configurations. While this project provided valuable exploratory data, it is not enough to identify the highest performing HPWHs in the market today. Further studies should identify the optimal storage tank volume, manufacturer control logic, and configuration as well as specific models of HPWHs. These answers will likely change across different home sizes and climate zones. To do this thoroughly without prohibitive project costs, it should be performed as a simulation study using HPWHsim and its existing library of validated HPWH models. This study could also analyze the annual energy consumption of the various HPWHs without load shifting controls. Presenting the findings in both scenarios would help consumers choose the HPWH that best fits their needs.
- Derivation of Optimal Control Logic: This study featured control logic where the set temperature was increased from 125 °F to the maximum manufacturer allowed set temperature at 9 AM. The set temperature was returned to 125°F at 5 PM. This yielded the maximum thermal energy storage at the start of the peak period. However, the heat pump operates at lower COP at elevated water temperatures. The increased thermal storage comes at a cost of reduced efficiency, and increased energy use. Additionally, some manufacturers control logic used the resistance element to reach the elevated set temperature instead of the heat pump. This had the same effect of providing more load shifting in exchange for reduced efficiency and increased energy consumption. Further studies should perform simulation-based optimizations to identify the optimal control logic.

- Field Study Validation: The potential for load shifting with HPWHs has now been demonstrated in a laboratory setting, and the next step is to test it in the field. This will provide an opportunity to further explore questions such as control logic and communications, reliability of the system, performance of the system in more draw profiles, and occupant satisfaction. PG&E has proposed a behind-the-meter thermal energy storage program to reduce peak demand by 2 – 5 MW by 2025. This program will target a portion of the incentives for customers in low-income communities and align with the San Joaquin Valley OIR to electrify their water heating and shift that load to off-peak hours. If approved, the program would launch in 2020 and enroll 6,600 customers, who will benefit from energy bill savings. A portion of these customers will benefit from reduced onsite emissions from propane-based water heating.
- Balancing Interests: There are three separate parties interested in load shifting with HPWHs. Home builders want a system that gives them the optimal compliance credit, utilities want a strategy that helps reduce kW demand during peak hours, and occupants want an approach that saves them money while providing hot water when it is needed. A control strategy that optimizes the impact of these systems for all three parties is not currently available. Further research should either identify a strategy that's optimal for all parties, or find a way to balance interests.
- Communications: Testing showed that assuming a constant peak period, whether it's 4 PM to 9 PM or 5 PM to 9 PM, will not be appropriate for all days. Some days the period of peak grid stress begins at a different time, and some days it doesn't occur at all. To create the most effective and flexible system, it is important that utilities communicate with HPWHs informing them of the anticipated peak period for the current day. This will allow HPWH to optimize load shifting so that it occurs only at times and on days when it's beneficial to the grid. Consideration will need to be given the cost impact on occupants on TOU rates who may benefit from a fixed load shifting approach.
- Title 24, Part 6 Compliance Models: There currently is no compliance credit in Title 24, Part 6 for load shifting with HPWHs. Adding this option to CBECC-Res would provide builders with an incentive to include this technology in new home construction. With HPWHsim and TDV profiles already incorporated, CBECC-Res is well positioned to add a detailed simulation platform for this compliance credit. Adding load shifting control logic to the version of HPWHsim included in CBECC-Res would allow simulations predicting the performance of each HPWH in load shifting scenarios. These simulations would lead to accurate TDV credits for builders, encouraging adoption of the technology.

Nomenclature

ρ = Density of water

C_p = Specific heat of water

COP = Coefficient of performance of the HPWH

P = Electrical energy consumed over the period

$P_{Compressor}$ = Electrical energy consumed by the compressor

$P_{Resistance}$ = Electrical energy consumed by the resistance element

$\dot{P}$ = Rate of electrical energy consumption

$\dot{P}_{High}$ = Rate of electricity consumption when above the threshold

$\dot{P}_i$ = Rate of electricity consumption during a specific timestep

$\dot{P}_{Low}$ = Rate of electricity consumption when below the low threshold

$\dot{P}_{Peak}$ = Electrical power consumed during the peak period

$\dot{P}_{Peak,Max}$ = Maximum rate of electricity consumption during the peak period

P_{Total} = Total electrical energy consumed over the test

ΔQ = Change in stored energy in the tank

$\Delta Q_{Timestep}$ = Energy withdrawn from the tank during a single timestep

$\Delta Q_{Profile}$ = Energy withdrawn from the tank during the entire draw profile test

$T_{Avg,Tank}$ = Average temperature of water in the tank

$T_{Avg,Tank,i}$ = Average temperature of water in the tank at a certain time

$T_{Avg,Tank,Time}$ = Average water temperature in the tank, averaged over 5 minutes

$T_{Avg,Tank,Time}$ = Time averaged average water temperature in the tank at time t

$T_{Avg,Tank,t-1}$ = Time averaged average water temperature in the tank at the previous timestep

T_i = Temperature of water in node i

T_{In} = Temperature of water entering the tank

T_{Out} = Temperature of water leaving the tank

ΔTDV = TDV savings when implementing load shifting in the draw profile tests

$TDV_{Penalty}$ = TDV multiplier for a specific hour in the draw profile test

TDV_{Total} = The total TDV accrued

$TDV_{Total,Dynamic}$ = The total TDV accrued in the Dynamic case

$TDV_{Total,Static}$ = The total TDV accrued in the Static case

$T\dot{D}V$ = Rate at which the HPWH accrues TDV

V = Volume of water in the tank

Introduction

In recent years California has made significant strides in incorporating renewable energy technologies into the utility grid[8]. While this helps to achieve California's ambitious energy and climate goals, it also changes the operation of the electric grid. With increased customer electricity generation, utilities must be prepared to manage customer usage as well exports to maintain a safe and reliable grid.

The increase in solar power on California's electricity grid is dramatically changing the net megawatt demand curve that the utilities experience on a typical day. Solar panels reach peak production around noon, then decrease through the afternoon. Increasing solar power installations can result in midday overproduction. A few hours later, solar power production typically decreases during times when summer electricity usage often increases due to increased space conditioning loads in homes and commercial buildings. These two factors can cause a dramatic spike in electricity demand. The late afternoon peaks can introduce stress on the generation, transmission, and distribution systems of the electricity grid and may require demand management strategies to be put into place to mitigate problems. These factors have been visualized in a graphic known as "the duck curve" [1]. Figure 1 presents an example of the duck curve for a typical spring day, with predictions for the period from 2012-2020.

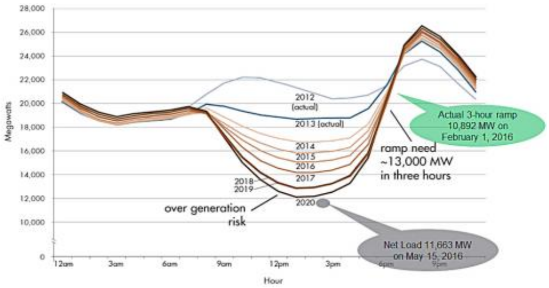

Figure 1: Net Load Curve Predictions for a Typical Spring Day, 2012-2020 [1]

Load shifting serves to mitigate the challenges of the duck curve which is exacerbated by the increased inclusion of solar power on the electricity grid. Load shifting typically employs energy storage to hold it for future use. Electric batteries are one example of storage; either utility-scale batteries, or residential battery products that can be charged during the mid-day period and discharged during the peak demand period when it is needed. Effectively applying this strategy has the potential to fill the mid-day bottom of the curve and reduce the height of the late afternoon and evening peak.

Electric water heaters, particularly heat pump water heaters (HPWHs), are a potential contributor to a successful load shifting strategy. HPWHs employ a vapor compression cycle with coefficient of performance (COP) typically ranging from 2 to 3 as a main heating source with resistance element as a second stage or backup heating source. The compressors typically draw ~0.5 kW when operating while the resistance elements use on the order of 4 to 5 kW. HPWHs employ a 40 to 80 gallon storage tank holding hot water for when people need it, thereby avoiding needing much larger heating capacity.

These products are conducive to load shifting efforts for three reasons:

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[8] http://www.energy.ca.gov/portfolio/

1) The high COP of the compressor means that the equivalent 2 to 3 kWh of energy can be added to the tank for every kWh of electricity consumed creating the potential for high efficiency storage;
2) The high power demand of the electric resistance elements can be avoided during peak periods, with use of appropriate control technologies, which would have a dramatic impact on the peak load curve at the site; and
3) Storage tank water heaters are well-insulated, minimizing thermal losses during standby.

While the optimal detailed control strategy for this approach has not yet been determined, the fundamental approach is simple and can be implemented with controls. Engaging the compressor during mid-day will consume electricity when photovoltaic energy is abundant and electricity costs are low. Increasing the storage tank set point temperature above the typical 125° F[9] results in more energy storage. When the peak period begins, the compressor disengages and hot water draws are met using the increased storage capacity from higher temperature storage. The goal is to avoid using electricity during the late afternoon and evening peak. As will be discussed, there is a degradation of the COP when the heat pump heats the storage to higher temperatures, but it can be economical with proper controls. When controlled well, the value of the stored energy is higher than the energy penalty to heat the water to a higher temperature.

Figure 2 presents a visual, conceptual representation of this control strategy.

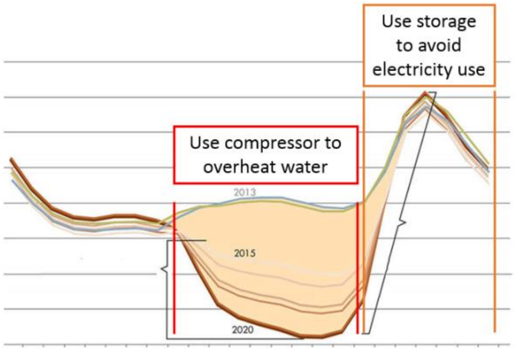

Figure 2: Visual Representation of Load Shifting with Heat Pump Water Heaters Concept

The 2019 California Building Energy Efficiency Standards (Title 24, Part 6) includes options to encourage adoption of this technology in new residential building construction. Since 1977, builders in California have needed to demonstrate compliance with Title 24, Part 6 to obtain a building permit [2]. Title 24 compliance is demonstrated using the California Energy Commission (CEC) approved simulation model, California Building Energy Compliance Calculator for Residential Buildings (CBECC-Res) [3]. The CEC uses the Time Dependent Valuation (TDV)[10] metric to account for the fact that the cost of providing energy

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[9] A tempering valve is recommended to avoid creating a scald risk with elevated water temperatures.

[10] TDV is defined as the time varying energy caused to be used by the building to provide space conditioning and water heating and for specified buildings lighting. TDV energy accounts for the energy used at the building site and consumed in producing and in delivering energy to a site, including, but not limited to, power generation, transmission and distribution losses.

used to a building varies across every hour of the year, and across the 16 different climate zones. Electricity use during peak summer hours has TDV rates which are much higher than electricity used in low demand hours, such as at night. If HPWHs with load shifting control technologies are being simulated, the TDV will be lower during the day, when the energy storage are being utilized and higher during the late afternoon and evening ramp. Builders employing load shifting with CEC approved strategies, such as the described HPWH control strategy, will have lower annual TDV numbers and a higher likelihood to comply with Title 24, Part 6.

This project is part of a larger effort by researchers to find the best way to employ this strategy in the state of California, and enhance compliance options in CBECC-Res. The National Resources Defense Council (NRDC) and Ecotope are collaborating on a simulation study comparing various control strategies to determine their impacts. Their study will identify the impacts of each control strategy on electric utilities in terms of TDV, customer cost savings, and total load shifting [4]. As a simulation study, their project is only as accurate as the simulation model driving it. The model being used is HPWHsim [5]. HPWHsim is considered a very good model of HPWHs, with accurate simulation of energy consumption, hot water temperature, and manufacturer controls. However, it was not designed to be used to predict performance in load shifting scenarios and is being modified for the NRDC/Ecotope project. Specific limitations are:

1) HPWHsim was designed to be used with set temperatures below 130 °F, and
2) A constant set temperature is assumed and may not accurately simulate the control logic employed when responding to changing set temperatures.

Supporting the NRDC/Ecotope project is a focus of this project. This project includes laboratory experimentation that Ecotope will use to improve and validate HPWHsim as needed to pursue their simulation study. It includes a study of the TDV impacts of load shifting with HPWHs using the hot water draw profiles from selected days in CBECC-Res. These activities support the NRDC/Ecotope researchers in improved simulation of load shifting. The project also provides evidence for homebuilders that employing these technologies will help them achieve Title 24, Part 6 compliance. Finally, this project identified some complexities that arise when incorporating load shifting strategies with HPWHs.

Methods

The following sections describe the test plans used to address the goals of the project, how those test plans dictated the design of the test apparatus, the details of the test apparatus itself, the tested HPWH units, and the calculations used to analyze the data.

Test Plan

The test plan was designed to support the following objectives:

1. Measure the COP of the HPWHs as a function of storage tank average temperature to enable Ecotope to expand the range of the COP curves in HPWHsim;
2. Monitor the behavior of the four selected HPWHs when responding to changing setpoints for Ecotope to emulate those controls in HPWHsim,
3. Collect lab test data sets of 24-hour draw profiles, including all of the previously stated effects, for use by Ecotope in validating their improvements to HPWHsim; and
4. Provide estimates of the TDV benefit builders should earn when incorporating load shifting with HPWHs in new homes.

These objectives were met with three different types of tests. The names of the tests, and general descriptions are provided here, while following sections provide the details of each test.

1. COP f(T): These tests focused on identifying the COP of the compressor as a function of the internal tank temperature. Ecotope will use these results to improve the curves in HPWHsim.
2. Behavior with Changing Setpoint: The main feature of these tests was observing the control logic in response to changing set temperature. Ecotope will use these results to improve the modeling of HPWH control logic in HPWHsim.
3. CBECC-Res Draw Profiles: These tests monitored the performance of the HPWHs over the course of 24-hour hot water draw profiles. Specific draw profiles were taken from CBECC-Res, allowing calculation of the impact of load shifting on TDV benefits to builders. Ecotope will also use this data as their validation data set.

COP f(T)

The COP f(T) tests consisted of the following steps:

1. Put the HPWH in HP only mode[11];
2. Fill the HPWH storage tank with cold water[12];
3. Adjust the setpoint to the highest possible setting. This setting varied across manufacturers from 160 °F to 175 °F.
4. Allow the HPWH to bring the water to the setpoint. Measure electricity draw and temperature in the storage tank as the water is being heated.
5. When the HPWH reaches the set temperature, the test is complete.

Measuring the temperature of water in the tank allowed calculation of the average temperature of water in the tank, and the rate of change of the average tank temperature. Combined with the electricity draw, this allows identification of the COP of the compressor as a function of the average tank temperature.

To create a performance map, this test was performed for each HPWH at three different sets of ambient conditions. These conditions match the specifications in the Northwest Energy Efficiency Alliance (NEEA) Advanced Water Heater Specification [5]. The three test conditions are as follows:

1. 50 °F air temperature, 58% relative humidity;
2. 67.5 °F air temperature, 50% relative humidity; and
3. 95 °F air temperature, 40% relative humidity.

Behavior with Changing Setpoint

The Behavior with Changing Setpoint tests consisted of the following steps:

1. Control the ambient conditions to 67.5 °F and 50% relative humidity;

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[11] Electric resistance elements are not supposed to engage in heat pump only mode.

[12] The three integrated HPWHs may activate resistance elements when more than 50% of the storage tank volume is drawn from the heater, even when in Heat Pump Only mode. The threshold temperature varied by manufacturer. The coldest possible water was used in all cases, instead of a standard temperature.
Footnote continued on next page.

2. Turn on the HPWH with a set temperature of 125 °F and ensure that it is in hybrid mode to emulate the operation of HPWHs installed in homes[13];
3. Allow the HPWH to reach the setpoint and stabilize;
4. Increase the setpoint to the maximum setting. This will vary across manufacturers, with the products selected for this test ranging from 160 °F to 175 °F;
5. Observe behavior as HPWH heats water. Specific observations include:
    a. Measure internal water temperature at 12 depths, and calculate the average temperature;
    b. Measure electricity draw and cumulative electricity consumption; and
    c. Identify compressor or resistance element operation.
6. After water reaches temperature setting and stabilizes, reduce setpoint to 125 °F to emulate the set temperature change at 5 PM in the load shifting use case; and
7. Draw water at 3 gallons per minute for 5 minutes. This draw is design to fill the bottom of the tank with cold water, while ensuring that the top of the tank remains filled with water at the elevated set temperature. The heating behavior in response to this draw demonstrates how the control logic reacts in these unique scenarios. If the compressor has not turned on during that 5 minute draw, repeat for another 5 minutes.

Measuring the electricity draw during the tests allows identification of compressor operation and resistance element operation. Comparing the compressor or resistance element operation to the internal temperature of the storage tank allowed identification of the control logic as a function of tank temperature. Monitoring the electricity draw also allowed identification of the cumulative resistance element power use compared to the cumulative compressor use.

CBECC-Res Draw Profiles

The final test protocol utilized draw profiles from 2016 CBECC-Res to perform full-day experiments with realistic draw profiles. Draw profiles from CBECC-Res added additional value, because they allowed the tests to demonstrate the potential TDV benefits to builders when they use CBECC-Res to demonstrate Title 24 compliance.

The draw profile tests were performed on each of the four different HPWHs. Three draw profiles were selected, representing three different climate zones in PG&E territory and the diversity of draw profiles. A test was performed for each HPWH/draw profile combination, yielding twelve different scenarios. Each HPWH/draw profile scenario was tested twice, once using a “static” setpoint, and once using a “dynamic” setpoint. The “static” setpoint represented current practice, with the HPWH set to 125 °F at all times. The “dynamic” test used two set temperatures as shown in Table 2.

Table 2: Set Temperature Pattern in Dynamic Tests

Time of Day (hr)	**Set temperature (°F)**
Midnight – 9 AM	125
9 AM – 5 PM	Maximum
5 PM – Midnight	125

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[13] In hybrid mode the HPWHs control logic will determine when to use the heat pump and when to use the resistance element.

Table 2 shows that the set temperature from 9 AM – 5 PM was “Maximum.” This indicates that the maximum temperature available on the water heater was used for the test. The maximum temperature varied across manufacturers, ranging from 160 °F to 175 °F.

Test Approach

Each draw profile test consisted of the following steps:

1. To create a consistent start condition, a large draw was performed at 5 PM the day before the test was performed. The size of this draw was not specified, only that it be large enough to engage the compressor but small enough to avoid use of the resistance element. This process brought the stored water up to the set temperature shortly before the start of the test in all cases;
2. To provide some down time between tests for troubleshooting as needed, the actual draws of the test were started at 8:15 AM. All draws in the draw profile being tested from 12:00 – 8:15 AM were combined into a single, startup equivalent draw. This draw was performed using automated LabVIEW™ controls, ensuring the same energy content was withdrawn as called for in the CBECC-Res draw profiles. The data from this portion of the day was not used in the analysis;
3. After the startup draw was completed, an automated LabVIEW script implemented the draw protocol for the remainder of the test. Draw flow rate, duration, and volume were followed as closely as possible; however, the time required for control valves to find the right flow rate introduced some variance from the computer simulation draw schedule. To compensate for this difference, draws were ultimately controlled based on the energy content of each draw. When the amount of heat withdrawn from the tank matched that specified in the draw profile, the draw was completed;
4. In the case of dynamic tests, the set temperature was increased to the maximum at 9 AM;
5. In the case of dynamic tests, the set temperature was decreased to 125 °F at 5 PM; and
6. In all cases, the test was completed at midnight.

In each draw profile test, the required measurements were as follows:

1. The temperature of water at 12 different heights in the storage tank. This assumes that the water temperature only changed vertically;
2. The outlet water temperature;
3. The water flow rate during draws;
4. The electric draw of the HPWH; and
5. The inlet water temperature.

Selection of Draw Profiles

The three draw profiles were selected using the following criteria:

1. Draw profiles must represent different climate zones in PG&E service territory;
2. One draw profile represents the day that generates the highest TDV usage as dictated by both the TDV profile and HPWH electricity use characteristics, a second is for a summer day of peak grid stress, and a third a low use day.

3. The draw profiles were selected by using CBECC-Res simulations to identify the TDV penalty across each day.

Test Apparatus Development

These tests dictated that the testing apparatus needed to have the following capabilities:

1. Measure the following:
    a. Temperature at 12 depths in each of the HPWHs;
    b. Outlet temperature of each HPWH;
    c. Inlet temperature of each HPWH;
    d. Flow rate through each HPWH;
    e. Electric draw of each HPWH; and
    f. Heat content of draws through each HPWH.
2. Ability to adjust the water flow needle valves to find the desired flow rate;
3. Open/close solenoid valves to start/stop draws;
4. Automation to allow the modified 24-hour draw profiles;
5. Identification of heat content of each draw;
6. Ambient temperature and humidity control; and
7. Inlet water temperature control.

Test Apparatus

Laboratory Facility

All testing described in this report was performed in the HVAC testing apparatus in the Advanced Technology Performance Lab (ATPL) at PG&E's San Ramon Technology Center. The testing apparatus consists of two side-by-side environmental chambers. Each chamber has an independent space conditioning system to control temperature and humidity, consisting of packaged commercial heat pump units with electric resistance heating elements to fine-tune the temperature. To further control humidity, each room has a humidifier. The packaged units are equipped with economizers that allow the test chambers to be flushed with outside air, which can provide stability when a test unit is cycled.

The smaller of the two chambers (left side of Figure 3) is designated the "indoor room.". All heat pump water heaters under test were installed in the indoor room. For the split system, the tank and condensing unit were both installed together in the same conditioned space. This choice ensured that the split system and integrated units were tested under the same ambient conditions. PEX piping connected the tank to the outdoor unit, which was placed in a location to mitigate any disturbances to the airflow through the outdoor unit. Water was supplied to and drawn from the tank of the split system in the same manner as the integrated HPWH's.

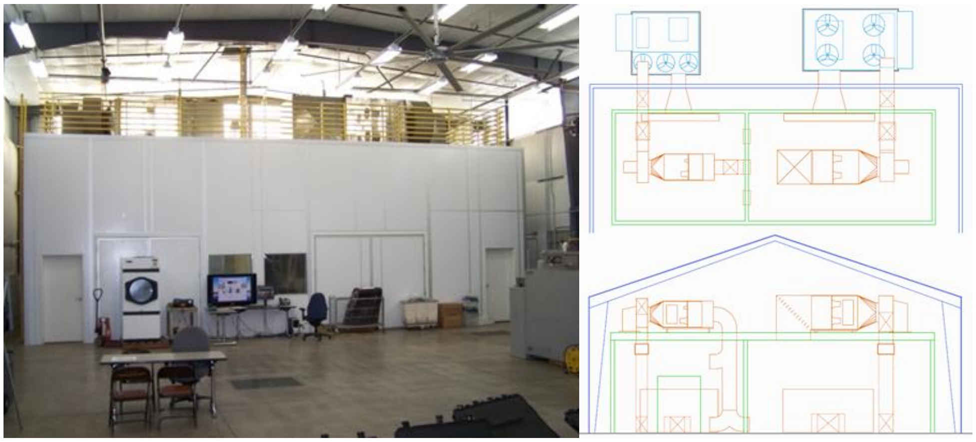

Figure 3: PG&E HVAC Test Laboratory

Data Acquisition System

All of the instruments were connected to signal conditioning modules based on the National Instruments C-series architecture, connected to Compact-RIO chasses. The modules included different units for voltage, thermocouples, and resistance temperature detectors (RTDs). In addition, both analog and digital output modules were used to control the room conditioning systems. One of the Compact-RIO chasses was connected by serial cable to a power meter to record measurements digitally. The default chassis internal scan rate for reading the module inputs is 10 Hz, although the power meter and dew point sensor digital readings updated once every second.

The Compact-RIO chasses communicate over an Ethernet network to a central host computer, which ran a custom data acquisition and control program developed with National Instruments LabVIEW graphical programming language. The program acquired readings from the chasses at a rate of once per second, applied calibration scaling and maintained a running average for each measurement, and logged the averages to a file every 5 to 15 seconds. The scaled values and other calculated values were also displayed on screen in both text and graphical form, and used to generate feedback control signals to the space conditioning systems. The program also included the ability to run scripts that could change the set points for the chamber conditioning systems at specific times of the day or after specific time intervals.

The logged data were saved in a text format to make it easily imported into Microsoft Excel or Python scripts for analysis.

Test Automation and Control

As part of the data acquisition and control program built in LabVIEW, a user interface was designed for the test operator to visually monitor the test apparatus. The interface integrates both manual and automatic controls where a draw profile script is programmed to automatically run on the system.

Isolation of each individual draw point was accomplished with a solenoid valve. Modulation of flow was accomplished with a magnetically actuated needle valve to achieve the desired static flowrate. Feedback from inlet and outlet water heater temperature probes and outlet water flow rate were used to calculate BTU delivery. The test system can implement scripting that controls draws in terms of delivered volume or delivered BTU.

A complete list of instrumentation is listed in Table 3 below.

Table 3: Heat Pump Water Heater Test Instrumentation Plan

Measurement Parameter	Instrument	Measurement Location
Tank Inlet/Outlet Temperature	4-wire RTD	Per DOE UEF
Internal Tank Temperature	Type T Thermocouple	12 Evenly Spaced Readings
Water Heater Input Power	Hioki Power Meter	Per DOE UEF
Tank Water Outlet Flow Rate	Nutating Disc Flowmeter	Per DOE UEF
Tank Inlet Water Pressure	Pressure Transmitter	Per DOE UEF
Ambient Dry Bulb Temperature	4-wire RTD	Per DOE UEF
Ambient Dew Point Temperature	Chilled Mirror Hygrometer	Per DOE UEF
Barometric Pressure	Pressure Transmitter	Per DOE UEF

Tested Units

Four different units were tested for this project. To test the impact of storage volume on these control strategies, different volumes were used for the project. HPWHs from four different manufacturers were tested to determine the impact of manufacturer design and control logic on performance.[14] A third difference was the refrigerant and design of the HPWH; three units used R-134A in an integrated configuration; and one used CO_2 as a refrigerant in a split system. The specifics of the HPWHs are provided in Table 4.

Table 4: Characteristics of Tested HPWHs

HPWH Unit	Manufacturer	Storage Volume (gal)	Refrigerant	Heat Exchanger Type	Resistance Element
1	1	66	R-134A	Integrated	Yes
2	2	80	R-134A	Integrated	Yes
3	3	50	R-134A	Integrated	Yes
4	4	80	CO_2	Split	No

While most HPWHs in this study were integrated units, HPWH #4 was a split system. This different configuration has some impacts on operation and the COP of the system. Figure 4 shows the configuration of an integrated heat pump water heater in standard operation. Figure 5 presents the same implication for a split heat pump water when a) There are distinct regions of hot and cold water in the tank, and b) When the storage tank is filled with hot water.

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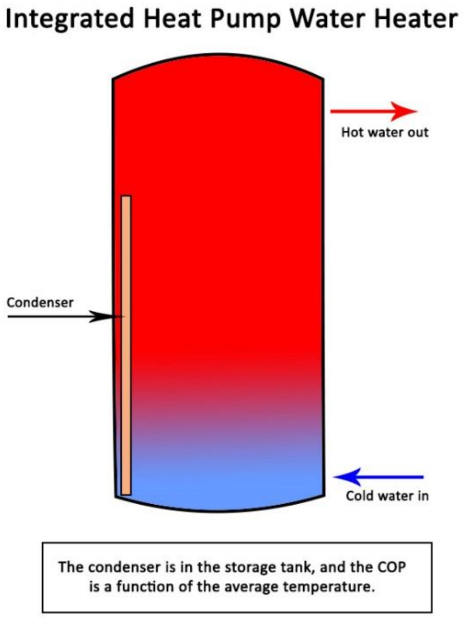
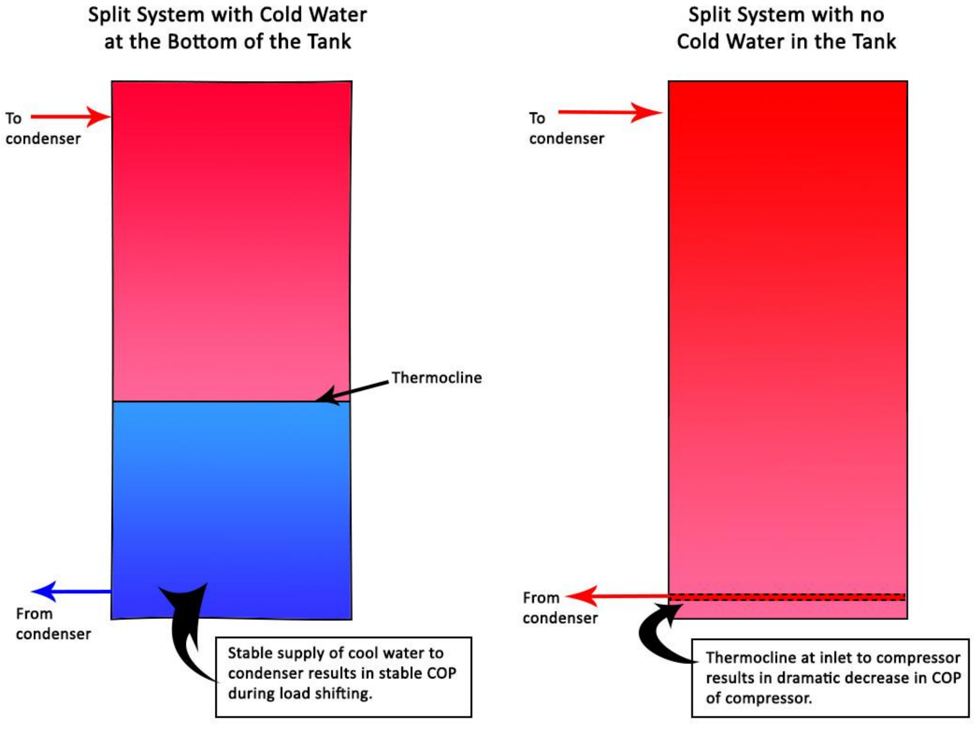
[14] Because storage volume has a significant impact on performance in this case, manufacturer names will be withheld in this report. Comparisons across manufacturers could not be made because HPWHs with different storage volumes were tested.



Integrated Heat Pump Water Heater

The condenser is in the storage tank, and the COP is a function of the average temperature.

Figure 4: Configuration of an Integrated Heat Pump Water Heater



Split System with Cold Water at the Bottom of the Tank

Split System with no Cold Water in the Tank

Stable supply of cool water to condenser results in stable COP during load shifting.

Thermocline at inlet to compressor results in dramatic decrease in COP of compressor.

Figure 5: Operation of a Split HPWH Under Two Tank Temperature Scenarios

The differences in system design have significant impacts on the results of these tests. Integrated HPWHs utilize a vertical heat exchanger immersed in the storage tank. It is exposed to approximately half of the water in the tank, depending on the design of the specific unit. Since the temperature of water at the condenser impacts the COP of the heat pump, this means that the COP is a function of the average water temperature in the bottom half of the tank. When hot water is withdrawn the bottom half of the tank will be full of cold water, yielding high COPs. As the heat pump heats the water, the temperature in the bottom half of the tank will increase and the COP will gradually decrease.

The split system uses an external condenser, and a water flow path from the bottom of the storage tank, past the condenser, and back into the top of the storage tank. The condenser is only exposed to the cold water at the bottom of the tank, and the COP is determined by the temperature at the very bottom of the tank instead of the average temperature of the bottom half. When hot water is withdrawn, cold water fills the bottom of the tank yielding high COPs. As the split system removes cold water from the bottom of the tank and adds hot water to the top of the tank, the thermocline moves progressively lower. The COP of the heat pump is not impacted until the thermocline reaches the bottom of the tank. When it does, the temperature of water passing the condenser suddenly increases causing a sudden decrease in COP.

Calculations

Each test utilized different sets of calculations. The following sections provide details for each case.

COP f(T)

The first calculation in the COP f(T) tests identified the average water temperature in the tank. This was necessary for identification of the rate of change of energy stored in the tank and was calculated using Equation 1.

$$T_{Avg,Tank} = \frac{1}{12}\sum_{i=1}^{12} T_i \tag{1}$$

Since there are 12 thermocouples in the storage tank, Equation 1 calculates the average by summing the temperatures of all 12 measurements and dividing by 12. This method assumes that each thermocouple represents a volume of water at uniform temperature. HPWHs with integrated heat exchangers provide heat at a nearly uniform rate along the depth of the tank, and this assumption likely causes a small amount of error. In the case of top-fed HPWHs such as the tested split system this assumption is not as accurate. To minimize errors in average tank temperature it important to use as many temperature measurements as possible. Twelve thermocouples proved to be a practical limit for these tests.

The temperature of stored water in a HPWH does not change rapidly during compressor operation, and standard noise can make the COP f(T) plot appear quite uncertain. To address this issue, Ecotope recommended using a 5-minute time averaged tank temperature to smooth the data. This equation is shown in Equation 2.

$$T_{Avg,Tank,Time} = \frac{1}{60}\sum_{i=1}^{60} T_{Avg,Tank,i} \tag{2}$$

Equation 2 sums the calculated average tank temperature for each timestep over 60 measurement periods, and divides by 60 to find the average over that period of time. The calculation uses 60 measurement periods because the timestep was 5 seconds, corresponding to 12 samples per minute and 60 samples in a 5-minute period.

The time-averaged average tank temperature was then used to identify the change in stored energy over time. This was done using Equation 3.

$$\Delta Q = V * \rho * C_p * (T_{Avg,Tank,Time,t} - T_{Avg,Tank,Time,t-1}) \tag{3}$$

Finally, time COP of the heat pump was calculated at each timestep using Equation 4.

$$COP = \frac{\Delta Q}{5 * P} \tag{4}$$

In Equation 4, the 5 in the denominator converts the electric power consumption from Btu/s to Btu consumed in a single five second timestep.

After completing those calculations, both the average tank temperature and the COP of the heat pump had been identified for each timestep. This allowed plotting of the COP as a function of internal tank temperature.

Behavior with Changing Setpoint

The first calculation in the Behavior with Changing Setpoint tests was, again, identifying the average tank temperature throughout the test. This was calculated using Equation 1.

The second calculation identified the total electricity draw over the course of the test. It was calculated using Equation 5.

$$P_{Total} = \sum 5 * \dot{P} \tag{5}$$

In Equation 5, the 5 term is again converting Btu/second to Btu/timestep. This conversion allows direct summing to find the energy consumed over the course of the test.

Another goal of the Behavior with Changing Setpoint tests was to identify the HPWHs choices regarding use of the compressor or resistance element. Therefore, the electricity consumed by the resistance element and compressor were summed separately. They were calculated using Equations 6 and 7.

$$P_{Resistance} = \sum 5 * \dot{P}_{High} \tag{6}$$

$$P_{Compressor} = \sum 5 * \dot{P}_{Low} \tag{7}$$

CBECC-Res Draw Profiles

Some of the calculations used in the CBECC-Res Draw Profile tests are identical to calculations in previous tests. The average tank temperature, and time-averaged average tank temperature were calculated using Equations 1 and 2. The total electricity consumption during the test was calculated using Equation 5.

Other calculations were performed specifically for the draw profile tests. The total energy withdrawn from the tank during the tests was calculated using Equations 8 and 9.

$$\Delta Q_{Timestep} = \dot{V} * \rho * C_p * (T_{Out} - T_{In}) \tag{8}$$

$$\Delta Q_{Profile} = \sum_{i=1}^{17,280} \Delta Q_{Timestep} \tag{9}$$

The sum in Equation 9 runs from 1 to 17,280, representing the number of 5 second timesteps in the 24-hour draw profile.

One major goal of the draw profiles tests was to identify the TDV impacts of load shifting controls. This was calculated using Equations 10 through 12. 17,280 equals 24 hours multiplied by 3,600 seconds per hour divided by 5 seconds per timestep.

$$T\dot{D}V = \dot{P} * TDV_{Penalty} \tag{10}$$

$$TDV_{Total} = \sum_{i=1}^{17,280} \frac{T\dot{D}V}{720} \tag{11}$$

$$\Delta TDV = TDV_{Total,Static} - TDV_{Total,Dynamic} \tag{12}$$

Equation 10 used TDV rates taken from CBECC-Res to define $TDV_{Penalty}$. This allowed the TDV calculations to match what would be returned by CBECC-Res in a compliance situation. The TDV multipliers in CBECC-Res yield values in kBtu/hr. In Equation 11, the 720 factor converts the kBtu/hr value from Equation 10 to kBtu/timestep. 720 equals 3,600 seconds divided by 5 seconds per timestep. Similarly to Equation 9, the sum then finds the cumulative kBtu TDV value over the 17,280 5 second timesteps in the 24 hr draw profile. Equations 10 and 11 are calculated for both the static and dynamic set temperature control case. Equation 12 compares the TDV_{Total} values from the static and dynamic cases to identify the change in TDV when implementing load shifting controls.

The final calculations were used to identify both the total electric consumption, and the peak electricity draw rate during the afternoon peak period. They were identified using Equations 13 and 14.

$$P_{Peak} = \sum_{i=12,240}^{15,120} 5 * \dot{P}_i \tag{13}$$

$$\dot{P}_{Peak,Max} = \max_{12,240 => 15,120} (\dot{P}_i) \tag{14}$$

Equation 13 sums the electricity consumption from timesteps 12,240 to 15,120. This corresponds to a period from 5 PM to 9 PM. The conversion factor of 5 converts the electricity consumption from a rate to a total over the 5 second timestep. Equation 14 identifies the maximum electricity draw rate during the peak period in the data set.

Results

The following sections present the findings from the project. Each section and subsection provide the results from different aspects of the testing, following the structure presented in Methods.

COP f(T)

The COP f(T) results were provided to Ecotope for use in expanding the temperature range of COP curves in HPWHsim. As an intermediate step, the data was plotted to visualize the impacts of increasing set temperature on COP of the compressor.

Different COP curves and behaviors were identified depending on the HPWH tested. Figure 6 provides an example result, showing the COP as a function of average tank temperature in HPWH #2 under ambient air conditions of 67.5 °F and 50% relative humidity. At the minimum average tank temperature of 110 °F, the COP starts at a maximum value of 5. As average tank temperature increases to a maximum of 160 °F, the COP exponentially decays to a minimum of 1.8.

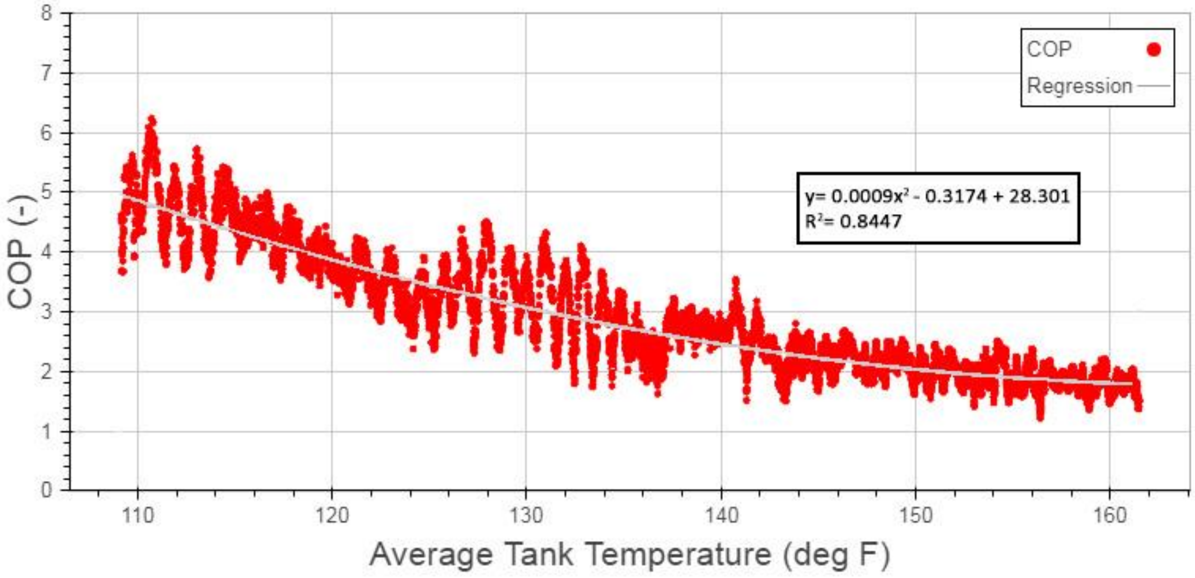


Figure 6: COP f(T) Results for HPWH #2 at 67.5 °F and 50% Relative Humidity

Figures 7 and 8 show the same plot for HPWH #3 in the 67.5 °F and 95 °F test conditions. The COP of the compressor in HPWH #3 was typically slightly lower than in HPWH #2. The compressor in HPWH #2 also started at a COP of 5, but with a lower average tank temperature of 107 °F. At 160 °F the compressor in HPWH #3 has a COP of 1.4, compared to the 1.8 of HPWH #2. This implies that HPWH #2 will perform at higher efficiency than HPWH #3 when using load shifting controls. On the other hand, HPWH #2 reached a maximum average tank temperature of 162 °F while HPWH #3 reached 168 °F. This indicates that HPWH #3 would be able to store more energy in the tank than HPWH #2 if both had the same storage capacity. Higher storage capacity would likely yield higher load shifting performance.

Figure 8 shows the same results for HPWH #3 in the ambient conditions of 95 °F and 40% relative humidity. The maximum COP, at an average tank temperature of 107 °F increased to 6.2. In the test the HPWH only reached an average tank temperature of 159 °F, but the COP increased from 1.6 to 2.2.

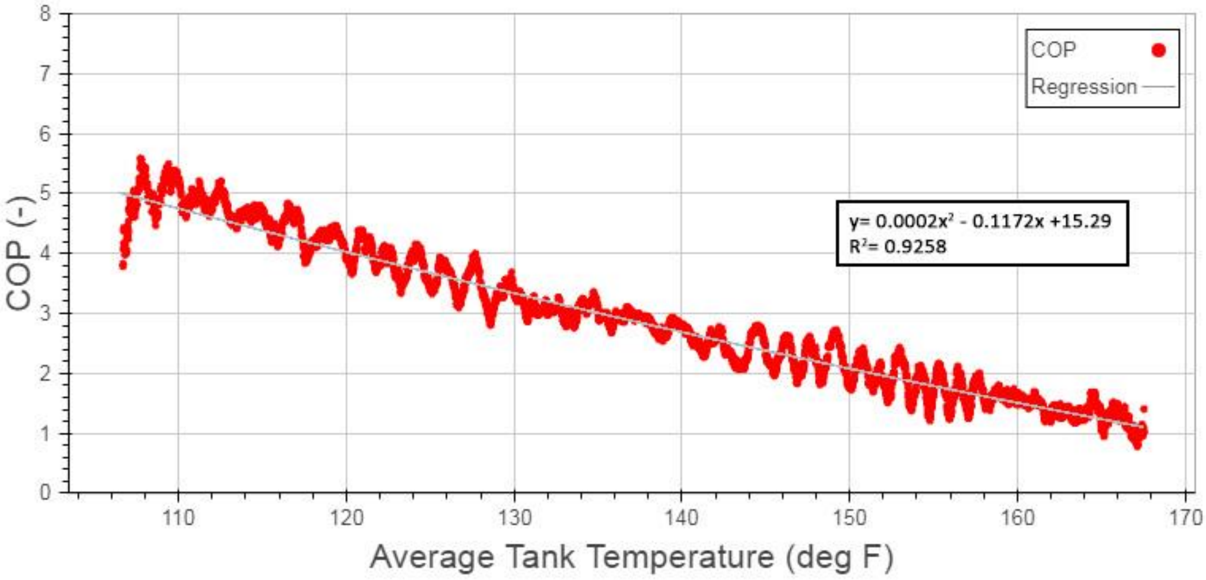


Figure 7: COP f(T) Results for HPWH #3 at 67.5 °F and 50% Relative Humidity

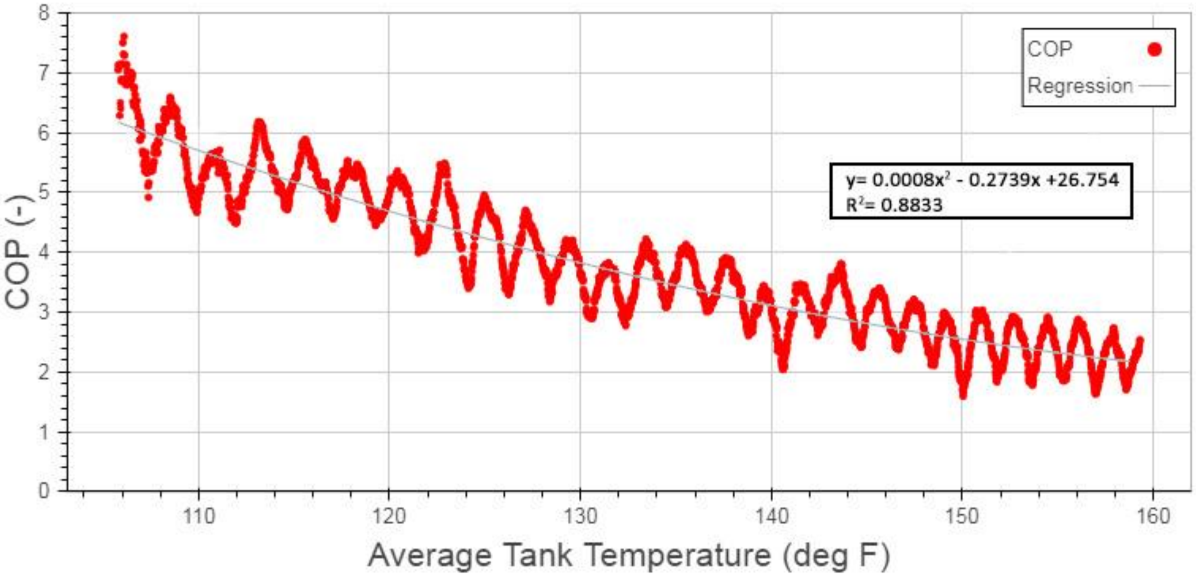


Figure 8: COP f(T) Results for HPWH #3 at 95 °F and 40% Relative Humidity

Figure 9 presents the COP f(T) results for HPWH #4 at 95 °F and 40% relative humidity. The shape of the curve is fundamentally different because HPWH #4 is a split system, while the rest of the units employ integrated heat exchangers. This means that the heat exchanger in most HPWHs is exposed to the average water temperature in the tank but, because HPWH #4 circulates cool water from the bottom of the storage tank past the condenser and to the top of the tank, in HPWH #4 the condenser is only exposed to water being drawn from the bottom of the tank. As this process progresses a stratification thermocline develops separating hot and cold water which gradually moves down the tank until it reaches the bottom. This leads to a more stable COP when load shifting is implemented and provides potential for higher efficiency operation. After the stratification layer reaches the bottom of the tank the COP of the compressor decreases dramatically because of the higher temperature water reaching the condenser. This is evident in Figure 9, as the COP decreases when the average tank temperature is above 144 °F.

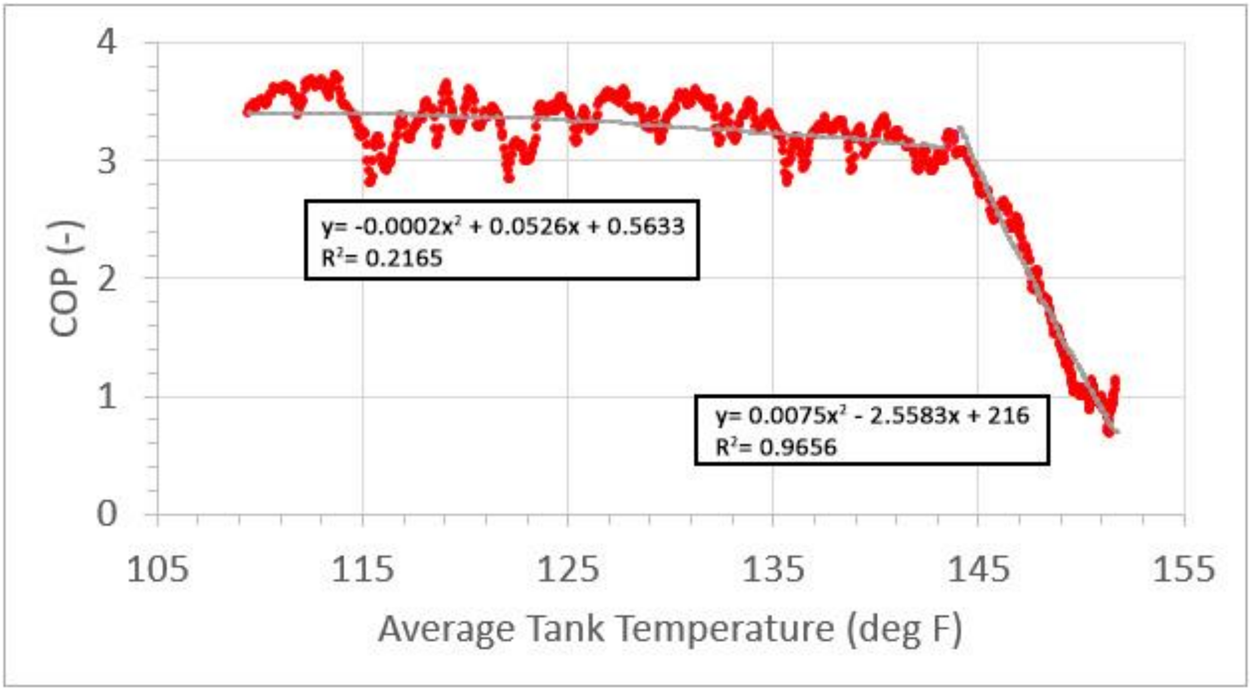


Figure 9: COP f(T) Results for HPWH #4 at 95 °F and 40% Relative Humidity

The COP f(T) results indicate an optimization challenge for load shifting with heat pump water heaters. Higher storage tank temperatures yield more thermal storage, more load shifted, and less chance of consuming electricity during the late afternoon/evening peak period. However, the increased storage tank temperatures also yield lower COPs at the heat pump, and increased energy consumption for the same amount of hot water provided. There will be an optimization control strategy, in terms of elevated set temperature, that yields the best load shifting performance at the lowest energy cost. This study did not explore enough permutations to identify an optimal control strategy, and further investigation is justified.

Behavior with Changing Setpoint

The fundamental purpose of the Behavior with Changing Setpoint tests was to provide data for Ecotope to more accurately represent HPWH control logic in HPWHsim. Two sample plots are provided below, showing the types of behavior observed during the testing. Figure 10 shows the results for HPWH #2 while Figure 11 shows the same for HPWH #3. In both cases the top sub-plot shows the temperature data, both measurements and calculated average, with Temperature_1 representing the measurement at the top of the tank and Temperature_12 showing the measurement at the bottom. The bottom sub-plot shows the control response of the HPWH by plotting the electricity draw. Higher electricity draws indicate resistance element use, while lower draws indicate heat pump use.

In Figure 10, the data shows the pre-conditioning period of the test. From 0 seconds to ~7,500 seconds (~2 hours) HPWH #2 was bringing the water in the tank to the set temperature of 125 °F. In this case it was using the electric resistance element, as evidenced by the 4 to 4.5 kW electric draw rate. At 7,500 seconds (~2 hours) HPWH #2 reached the set temperature and disengaged the resistance heating elements. The set temperature was increased to 160 °F at 10,600 seconds (~3 hours) and HPWH #2 engaged the compressor to heat the water to the new set temperature. This was one of the key findings of the test; HPWH #2 uses the compressor to respond to changes in the set temperature. At 34,300 seconds (~9.5 hours) the water reached the new set temperature, and the compressor disengaged. The draw called for in Step 7 also commenced at this time, as evidenced by the rapidly decreasing water temperatures in the tank. At 36,100 seconds (~10 hours) the electric resistance element engaged to bring the water up to the new, reduced set temperature of 125 °F. This was another important finding of this test; HPWH #2 used the resistance element to reheat the water when exposed to this draw. It also correctly responded to the decreased set temperature. But this type of control will use more energy than if the compressor was operated, at a potentially higher cost to the occupant.

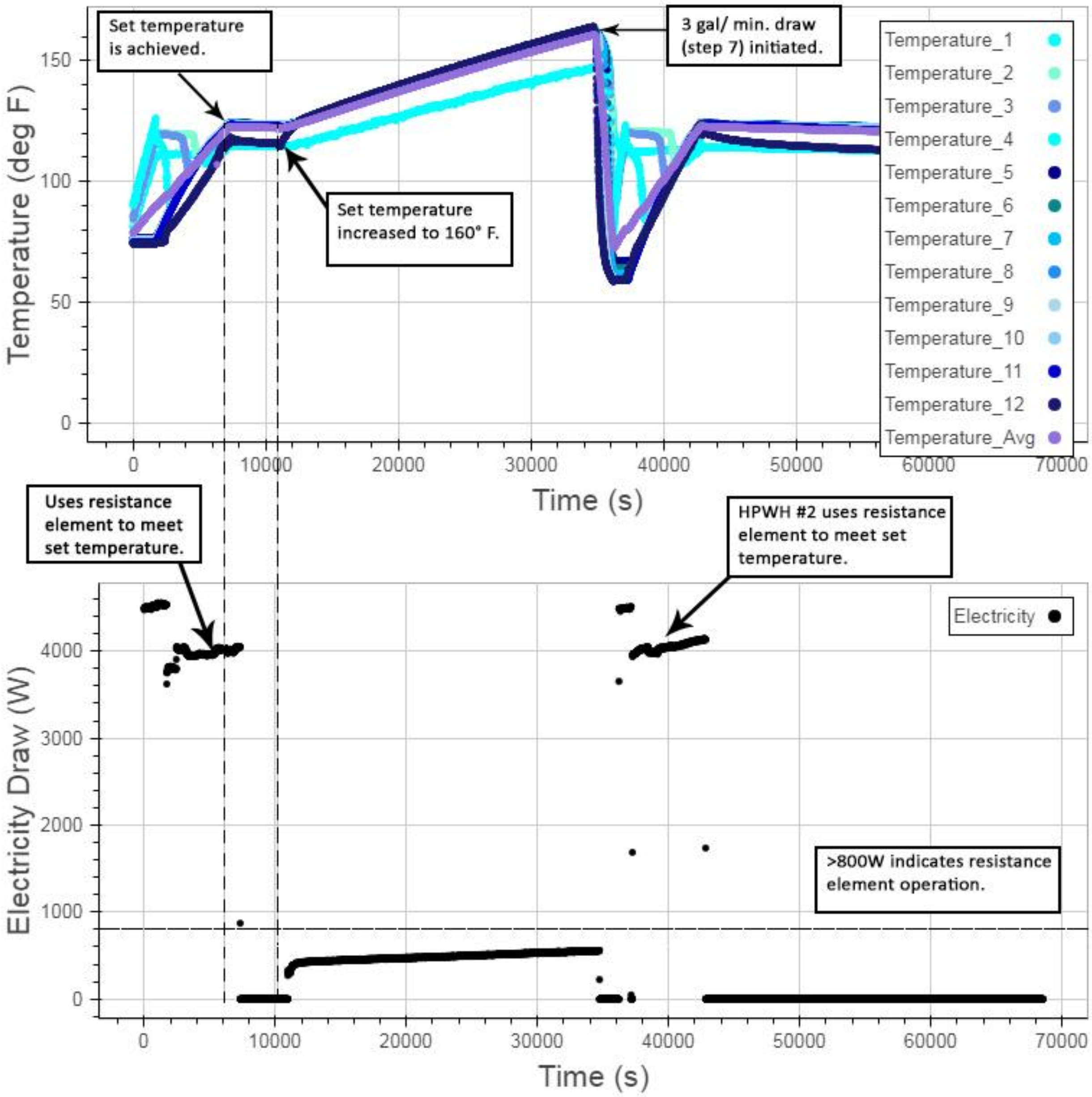
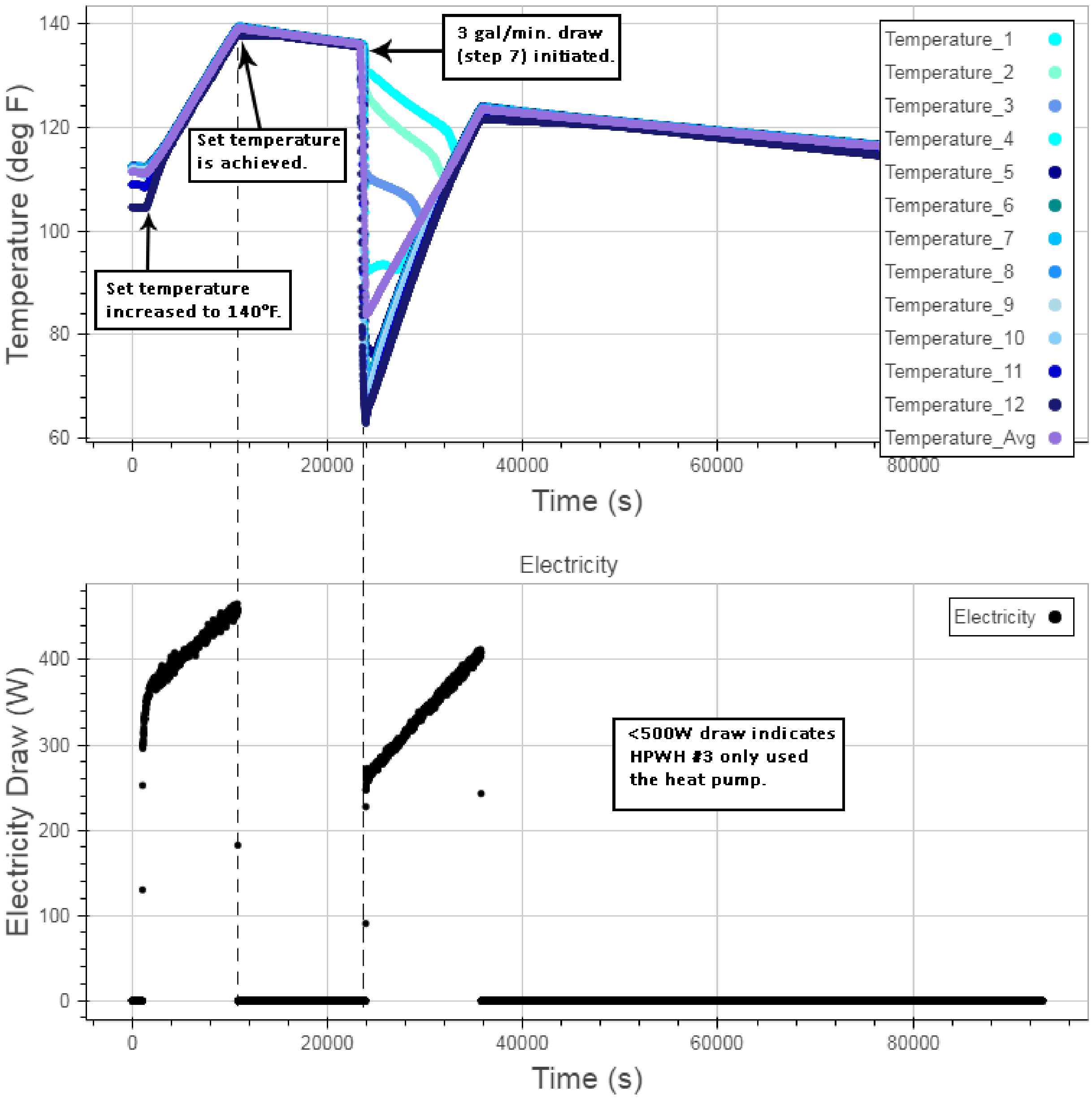


Figure 10: Results from a Behavior with Changing Controls Test for HPWH #2

Figure 11 shows the same data for HPWH #3. In this case, the data is filtered to remove the start-up period and begins shortly before the set temperature is increased. At 1,500 seconds (~1/2 hour) the compressor engages and heats the water to the new set temperature of 140 °F. A major finding from this project is that HPWH #3 used the compressor, and not the resistance element, in response to the increased set temperature. At 11,400 seconds (~3.2 hours) the water reaches the set temperature and the compressor disengages. At 23,800 seconds (~6.6 hours) the draw specified in Step 7 was initiated, and the average tank temperature rapidly drops to 84 °F. At that point, the compressor engaged again to return the water to the new set temperature of 125 °F. HPWH #3 used the compressor during both heating cycles in this test. This control logic returns the lowest cost for home-owners, the highest compliance benefit for builders, and the least stress on the electric grid.



3 gal/min. draw (step 7) initiated.

Set temperature is achieved.

Set temperature increased to 140°F.

<500W draw indicates HPWH #3 only used the heat pump.

Figure 11: Results from a Behavior with Changing Controls Test for HPWH #3

CBECC-Res Draw Profiles

Most of the tests studied the performance of HPWHs when using a simplified form of load shifting controls while serving the loads specified by draw profiles from CBECC-Res. The following research questions were addressed:

1. Which draw profiles from CBECC-Res should be used to study these systems?
2. How much TDV savings can builders expect if implementing load shifting with these controls?

3. How does load shifting impact hot water delivery performance?
4. What are some characteristics of HPWHs that yield high performance operation with this control strategy?
5. How much is total energy use increased by the simplified load shifting control strategy?

The following sections address each of these questions.

Draw Profile Selection

Three different draw profiles from CBECC-Res were selected to meet the previously listed testing criteria. They were:

- Highest TDV Penalty Day: The draw profile with the highest single day TDV penalty occurs on March 6, in Climate Zone 16, in a 2-bedroom house. First, Climate Zone 16 has a TDV spike from Mar 5-7 causing significantly higher TDV penalties for those days. Coincidentally, the draw profile in a 2-bedroom house on March 6 has the highest volume of hot water use during the peak period of all draw profiles. In addition to typical evening hot water use, it also includes a 40-minute shower starting at 7:28 PM. Finally, the March 6th date in Climate Zone 16 means that the inlet water temperatures are quite cold for the state of California, at 40°F. These impacts result in any HPWH currently in CBECC-Res using the electric resistance heating element for several hours during the peak period, and account for 14% of total annual water heating TDV. This draw profile represents the hardest condition in CBECC-Res. Figure 12 shows the hot water draw profile for a 2 bedroom house on March 6th and Figure 13 shows the TDV multiplier for each hour of the day on March 6th in Climate Zone 16.

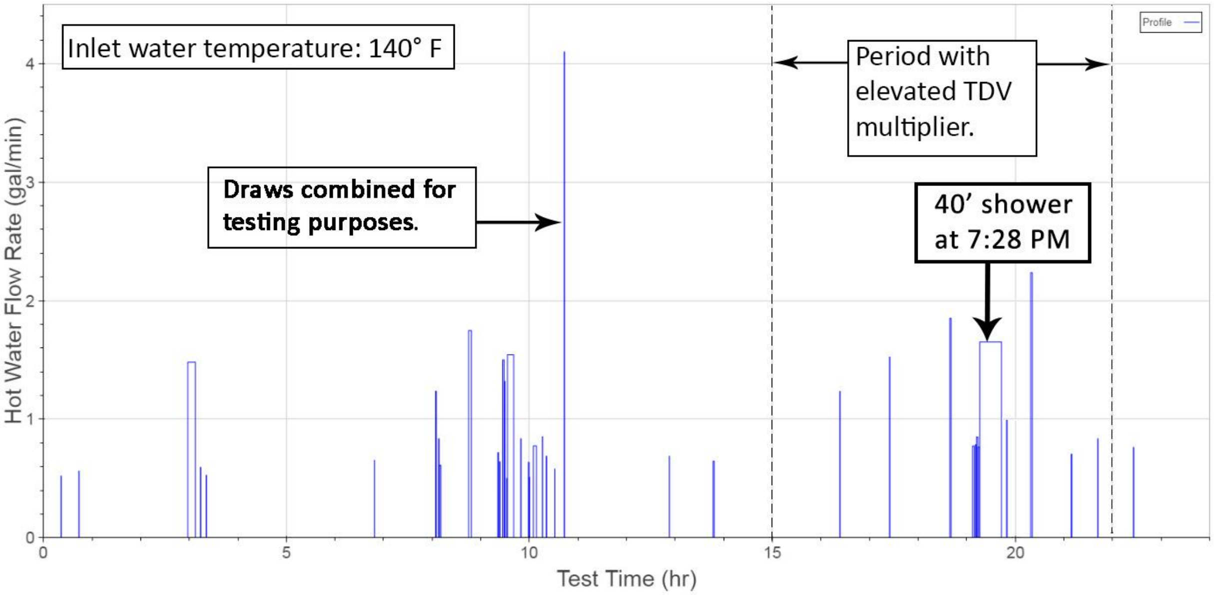


Figure 12: Hot Water Flow Rate in two-bedroom house Climate Zone 16 Draw Profile on March 6th

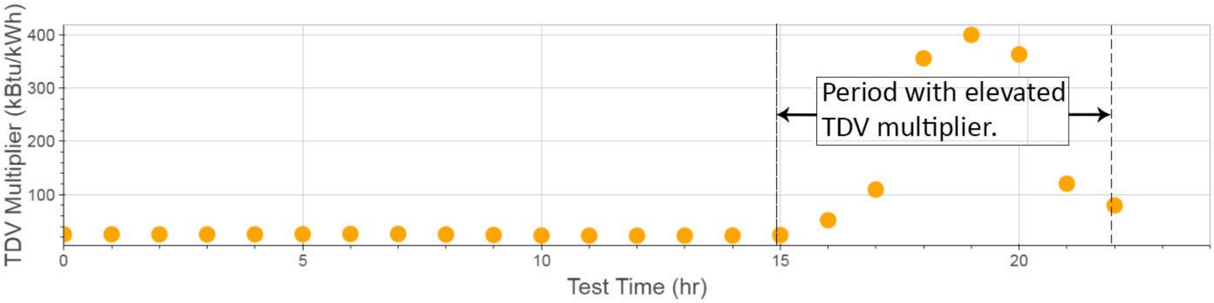


Figure 13: Hourly TDV Multiplier for March 6th in Climate Zone 16

- Summer Peak Day: This draw profile was selected because it represents a similar challenge, in a more traditional demand reduction scenario. It takes place on July 10, in Climate Zone 12, in a two-bedroom house. Simulating a summer day in the Central Valley, this situation represents a hot day which typically stresses the electricity grid in California. As a result, the TDV multiplier late in the day reaches 2571 kBtu/kWh, significantly higher than the max TDV multiplier of 400 kBtu/kWh on March 6 in Climate Zone 16. This case uses the same high peak water use draw profile, with the 40-minute shower at 7:28 PM, creating a situation where builders may pay a significant TDV penalty from electric resistance elements engaging to meet the hot water demand during such a high TDV spike. On the other hand, inlet water temperatures during the summer in the central valley are significantly warmer at 68 °F, leading to this draw profile representing a more moderate challenge than the first draw profile despite representing a summer period of high grid stress. Figure 14 shows the hot water draw profile for a 2 bedroom house on July 12th, and Figure 15 shows the TDV multipliers for the same day.

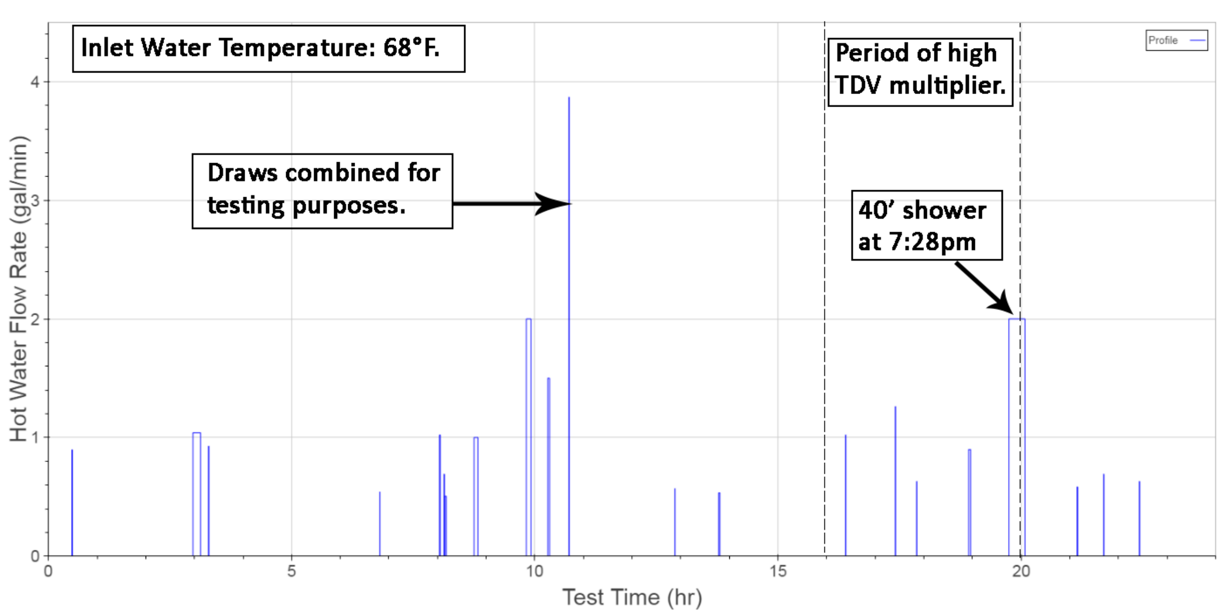


Figure 14: Hot Water Flow Rate Draw Profile for a two-bedroom house in Climate Zone 12 on July 12th

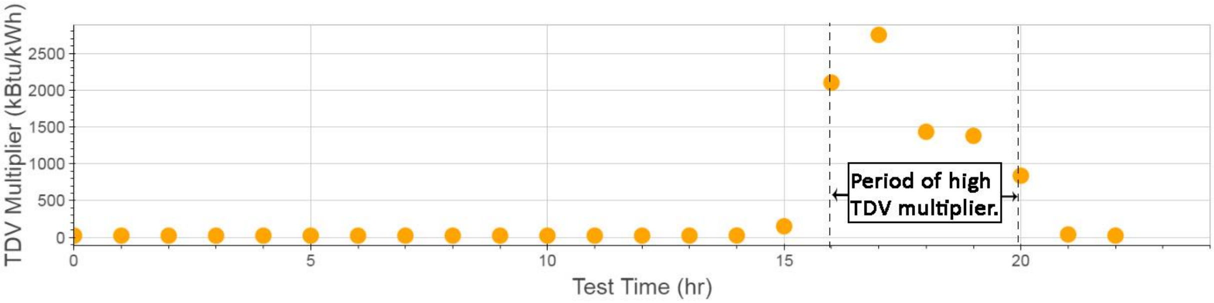


Figure 15: Hourly TDV Multiplier for July 12th Climate Zone 12

- Low Challenge Day: This draw takes place on August 31, in Climate Zone 3, based on a two-bedroom house. Simulating a home in in San Francisco on August 31st would mean that the inlet water temperatures are quite warm, at 61 °F, and TDV penalties are low. The draw profile in this case is not particularly challenging, and most HPWHs were expected to be able to coast through the peak period without engaging their resistance elements. Figure 16 shows the hot water draw profile for a two-bedroom house on August 3rd, and Figure 17 shows the hourly TDV multipliers for that day in Climate Zone 3.

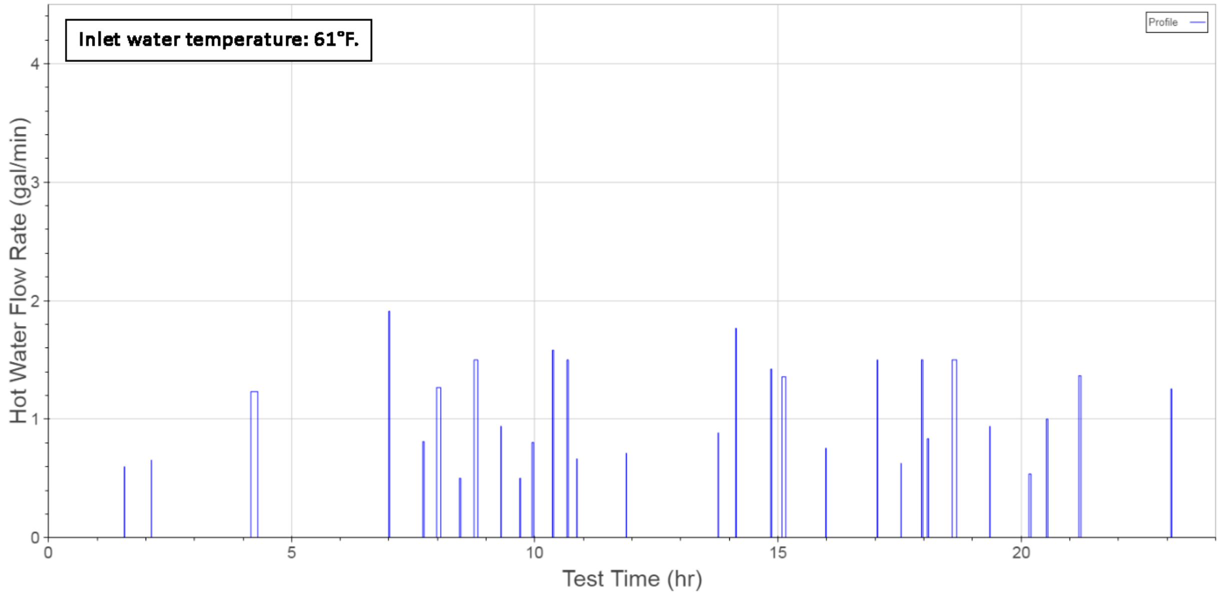


Figure 16: Hot Water Flow Rate for a two-bedroom house in Climate Zone 3 on August 31st

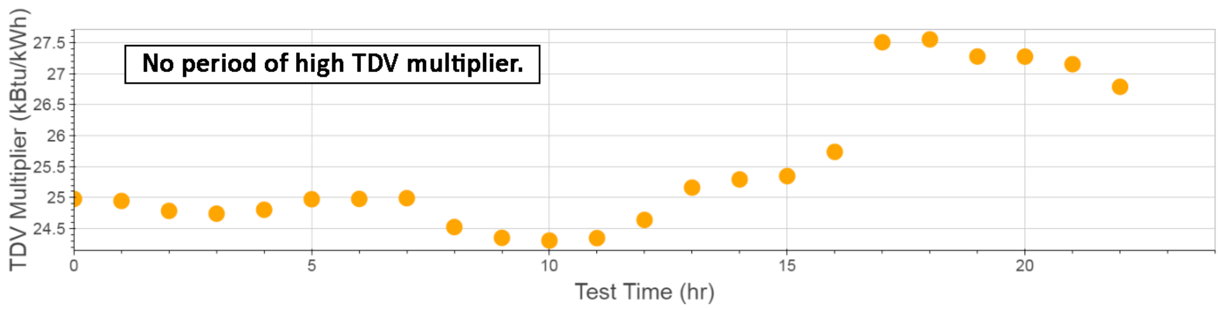


Figure 17: Hourly TDV Multiplier on August 3 in Climate Zone 3

Table 5 presents some of the characteristics of the selected draw profiles. All three draw profiles represent portions of the annual CBECC-Res draw profile for a 2100 ft^2, two-bedroom house. The first row presents the day of the year from which the draw profile was selected. The second row states the climate zone (CZ) used for the draw profile, and the third row shows the associated inlet water temperature. The fourth row states important characteristics of the draw profile. Both the Highest TDV Penalty and Peak Summer draw profiles included a 40 minute shower at 7:28 PM, as those draw profiles are intended to stress the HPWH during the peak period. The Low Challenge draw profile did not include a large draw during the peak period, as it was intended to be a case where it's much easier to shift the load. The final row presents the maximum TDV multiplier in each of these cases. The Highest TDV Penalty day has a maximum TDV multiplier of 363 kBtu/kWh, the Peak Summer day has a maximum TDV multiplier of 2,751 kBtu/kWh, and the Low Challenge day has a maximum TDV multiplier of 27 kBtu/kWh. The Highest TDV Penalty day has a higher total TDV penalty despite the lower maximum multiplier because of the lower inlet water temperature. Meeting the high demands in the peak period with the 40 °F inlet water temperature often, depending on the HPWH selected, requires use of the electric heating element for several hours during the peak period. The Peak Summer Day has a higher inlet water temperature, and that same afternoon draw can often be meet without using the resistance element.

Table 5: Characteristics of the Selected Draw Profiles

	Highest TDV Penalty Day	**Summer Peak Day**	**Low Challenge Day**
Day	March 6	July 10	August 31
Location	Bishop (CZ16)	Sacramento (CZ12)	San Francisco (CZ3)
Inlet Water Temp	40 °F	68 °F	61 °F
Draw Profile Characteristics	Largest peak draw: 40' shower at 7:28 PM	Largest peak draw: 40' shower at 7:28 PM	Largest peak draw: 2.16 gallon faucet at 8:09 PM
Maximum TDV Multiplier	363 kBtu/kWh	2751 kBtu/kWh	27 kBtu/kWh
Total Mixed Water Volume	114 gal	114 gal	95 gal

These draw profiles were originally entered into the experimental control system exactly as they appear in CBECC-Res. However, some of the draws in the draw profiles overlapped which caused issues with the control program. When a second draw began, LabVIEW would automatically cancel the original draw and only complete the second draw. To overcome this limitation, many draws were combined into larger, single draws. The draws were not combined with a specific method; instead, an iterative process was used to alter the draw profiles such that the total volume of water, and energy content required were held the same while also preserving the general structure of the draw profile.

Draw Profile Test Results

As described in Methods - CBECC-Res Draw Profiles, each HPWH/draw profile scenario was tested twice. One test used a “static” setpoint temperature, referred to as the Static test, and once using a “dynamic” setpoint temperature, referred to as the Dynamic test. The Static setpoint represented current practice, with the HPWH set to 125 °F at all times. The Dynamic test used a changing setpoint to the manufacturer’s maximum from 9 AM to 5 PM as described in the Methods - CBECC-Res Draw Profiles section.

Each of the different draw profiles provide different insights into the performance of HPWH in response to this control strategy.

Highest TDV Penalty Day

Figures 18 and 19 show the measured temperatures during tests with static and dynamic controls in a 50-gallon rated HPWH (#3). Both plots show the temperature data, both measurements and calculated average, with Temperature_1 representing the measurement at the top of the tank and Temperature_12 showing the measurement at the bottom. The sequential location of each thermocouple is also expressed with a temperature gradient. Temperatures higher in the tank are expected to be warmer and are shown with lighter shades of blue. Temperatures lower in the tank are expected to be colder and are shown with darker shades of blue. There are four main points to notice in these two plots:

1. First, the high rate of temperature increase at 9 AM in Figure 19 indicates that the HPWH used the resistance element. This is not ideal for this control strategy, as the intent is to use the compressor for an extended period to gradually use energy at a high COP instead of rapidly at a low COP. Application of this control strategy may require careful control and communication to avoid HPWHs making this choice.
2. The outlet temperature in the static case dropped to a low of 83 °F during the evening shower. In the Dynamic case, the minimum recorded outlet temperature during that draw was 161 °F. This indicates that HPWHs using this control strategy will provide much more hot water to occupants than with a standard control, as is expected due to the higher stored energy content.
3. In both cases, the resistance element engaged during the peak period. This result is disappointing as the intent is to use the elevated day time temperature to avoid that result. However, this result may be caused by the combination of: a) This test was performed using the most challenging draw profile in CBECC-Res, and b) This HPWH has the lowest storage volume (50 rated gallons) of all tested HPWHs. While the dynamic controls didn’t prevent resistance element operation during the peak period, they did delay the resistance element use by 40 minutes resulting in significantly less total electricity consumption during the peak.

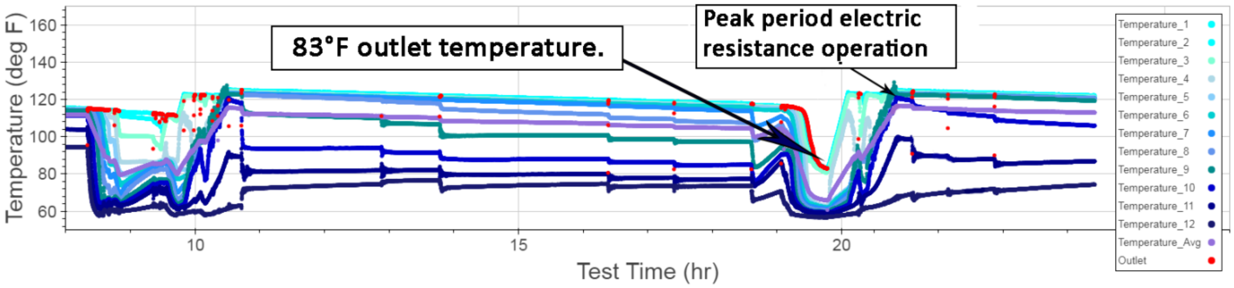


Figure 18: Measured Temperatures During the Static Test With a 50 Gallon Rated Storage HPWH (#3)

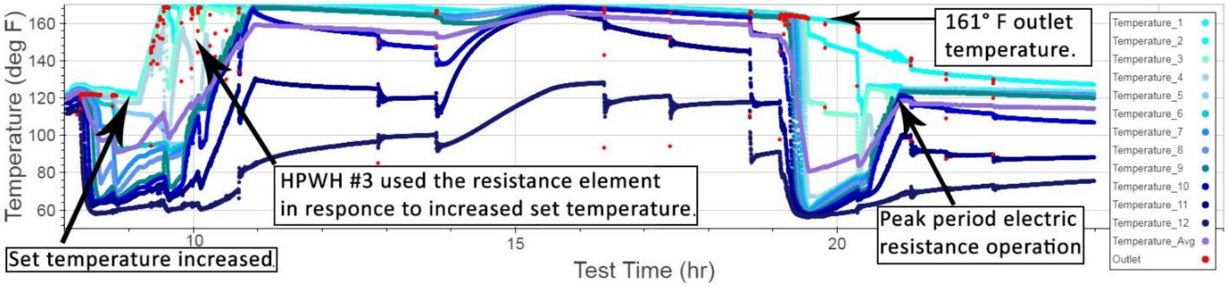


Figure 19: Measured Temperatures During a Dynamic Control Test with a 50 Gallon Rated HPWH (#3)

Figures 20 and 21 present the TDV penalty paid by the 50-gallon rated HPWH during this draw profile with the static and dynamic controls respectively. As the figures show, the Static control case used significantly more electricity during the peak period and pays a significantly larger TDV penalty. In the Static case, the compressor engaged at 6:39 PM and the resistance element at 7:32 PM. In the Dynamic case, compressor usage was delayed until 7:33 PM and resistance element usage until 8:20 PM. These improvements yield a daily TDV reduction from 2,764 kBtu to 1,563 kBtu, a 43% reduction. It's worth noting that the increase in set temperature during the mid-day period, from continuously operating the compressor at lower COPs caused by the higher water temperatures, did increase TDV penalty during the time of day. However, the low TDV multiplier at those times, as shown in Figure 13, mean that this TDV increase in negligible compared to the TDV savings during the peak period.

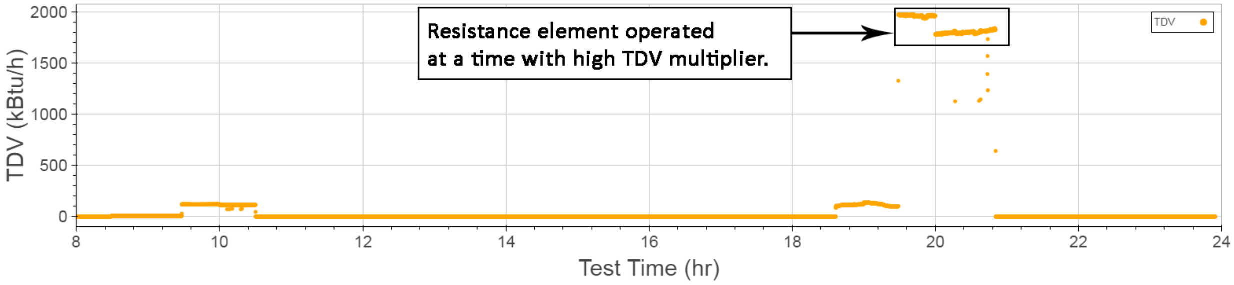


Figure 20: TDV Penalty During a Static Control Test with a 50 Gallon Rated HPWH (#3)

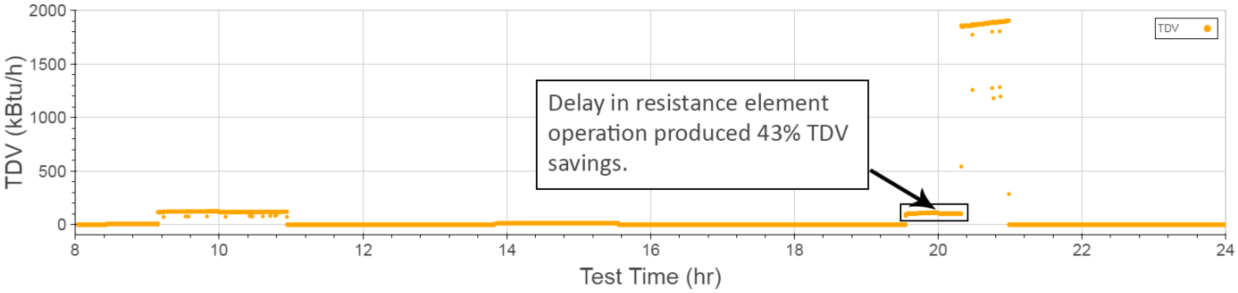


Figure 21: TDV Penalty During a Dynamic Control Test with a 50 Gallon Rated HPWH (#3)

While the results with the 50-gallon rated HPWH showed significant savings, they also showed that the load shifting strategy did not preclude resistance element operation during the peak period. This result is not surprising, as the 50-gallon rated HPWH has the least storage of the HPWHs tested in the project, and storage capacity is fundamental to the success of this approach. Higher storage volumes should yield higher performance in this strategy. Figures 22 and 23 show the measured temperatures during the same test with a 66-gallon rated HPWH. As before, Temperature_1 is at the top of the tank while Temperature_12 is at the bottom.

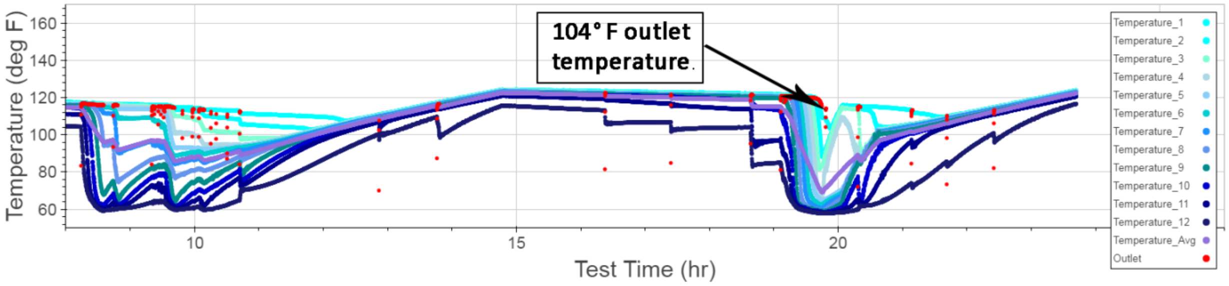


Figure 22: Measured Temperatures During the Static Test With a 66 Gallon Rated Storage HPWH (#1)

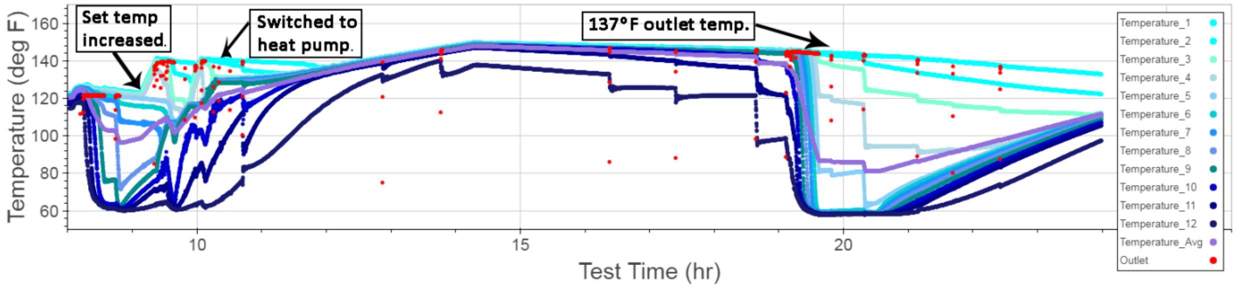


Figure 23: Measured Temperatures During the Dynamic Test With a 66 Gallon Rated Storage HPWH (#1)

In this case, the HPWH again used the resistance element to reach the new set temperature in the Dynamic control case. However, it only used the resistance element until the top of the tank reached the set temperature, then switched to the compressor. The 50-gallon rated HPWH used the resistance element until most of the water in the tank reached the new set temperature.

The Static controls again failed to meet the hot water demand during the peak period. With the 66-gallon rated HPWH the outlet temperature dropped to 104 °F, which is 21 °F higher than the 50-gallon rated HPWH but still cooler than occupants expect. Also, like in the 50-gallon rated case, the resistance element engaged to avoid delivering low temperature water.

The Dynamic case performed far better. The lowest outlet temperature at the end of any draw with Dynamic controls was 137 °F, both indicating that the occupants would receive adequate hot water and that the tank was still storing significant amounts of heat. Additionally, the resistance element did not engage in the test with Dynamic controls. Instead, the compressor activated to reheat the water stored in the tank to 125 ^{o}F.

Figures 24 and 25 present the TDV penalties paid by the 66-gallon rated HPWH with the Static and Dynamic control strategies. In the Static control case the compressor engaged at 7:21 PM, and the resistance element at 7:41 PM. In the Dynamic control case the compressor engaged at 8:30 PM, and the resistance element never engaged. This performance improvement yielded a TDV penalty reduction from 1,902 kBtu to 304 kBtu, or 84%.

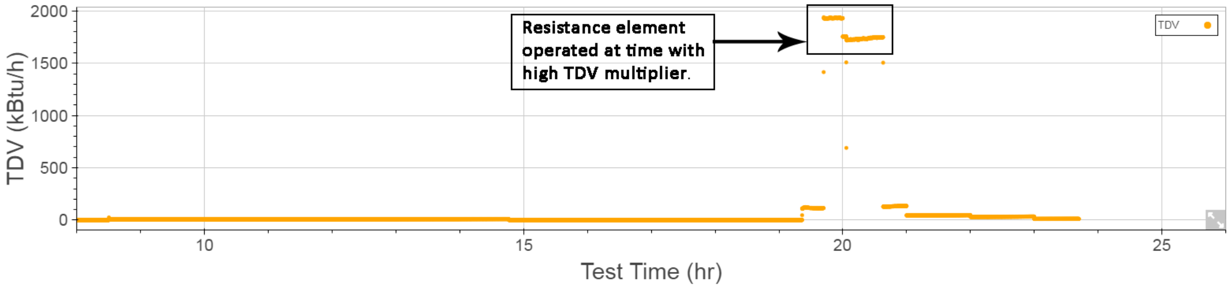


Figure 24: TDV Penalty During a Static Control Test with a 66-Gallon Rated HPWH (#1)

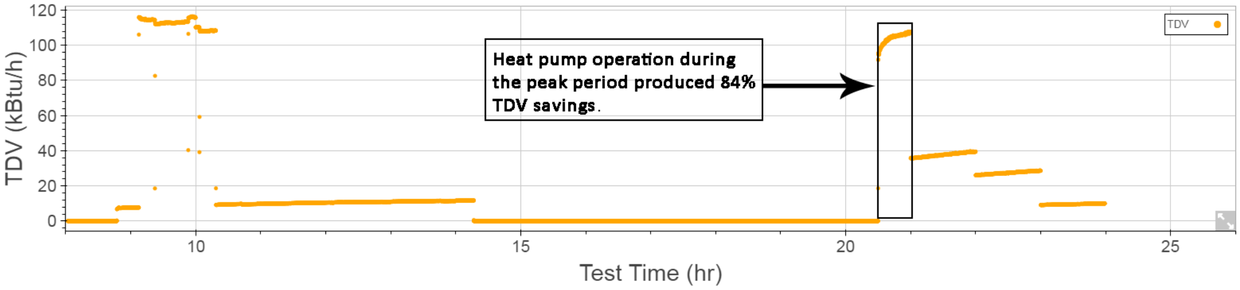
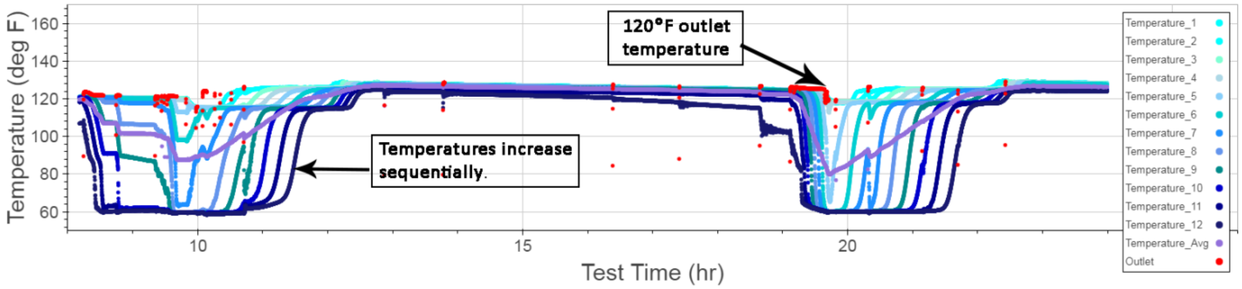


Figure 25: TDV Penalty During a Static Control Test with a 66-Gallon Rated HPWH (#1)

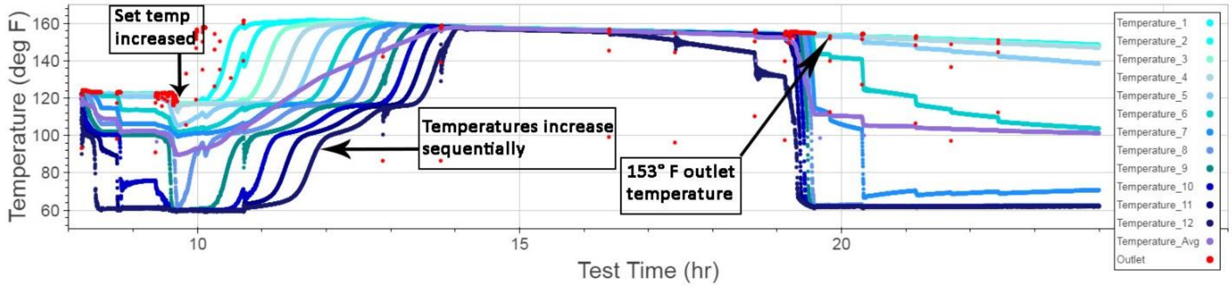
The highest performing unit was HPWH #4, with 80 gallons of rated storage, CO_2 as a refrigerant, and a split system configuration. As was previously mentioned, high storage volume means proportionately higher energy storage. The increased energy storage makes it possible to coast through peak periods with higher hot water draw loads without adding heat to the water. The fact that this HPWH uses a split system means that the condenser circulates cool water from the bottom of the tank, heats it and returns the water to the top of the storage tank. This is in contrast to integrated HPWHs that have an immersed heat exchanger, typically in the bottom 1/3 - 1/2 of the storage tank, meaning that the heat is not added to the top of the tank. This change means that a similar sized compressor will do a better job of maintaining outlet temperature in a split system than an integrated system. Finally, HPWH #4 employed a 1 kW compressor, instead of the ~450W of the other units. The increased compressor capacity enables this HPWH to meet demand without having a resistance element.

Figures 26 and 27 show the measured temperatures in this HPWH during the same test with both Static and Dynamic controls. Note how, during heating cycles, the temperatures increase sequentially with higher temperature measurements rising to the set temperature before the next lower measurement. This is a unique result, caused by the split system design. Also note the stability of the outlet water temperature. In the Static case, the outlet temperature never fell below 120 °F, and in the Dynamic case it never fell below 153 °F. In both cases, this HPWH delivered satisfactory hot water to the occupants even in the most challenging draw profile in CBECC-Res.


120°F outlet temperature

Temperatures increase sequentially.

Figure 26: Measured Temperatures During the Static Test With 80 Gallon Rated Storage, Split System HPWH (#4)


Set temp increased

Temperatures increase sequentially

153° F outlet temperature

Figure 27: Measured Temperatures During the Dynamic Test With 80 Gallon Rated Storage, Split System HPWH (#4)

Figures 28 and 29 show the TDV penalty paid for using this HPWH in this draw profile with both Static and Dynamic controls. In the Static test, the compressor engages during the peak period; however, since it draws ~1 kw instead of the 4-5 kW of the resistance elements in other HPWHs, it pays a TDV penalty of ~300 kBtu/hr instead of the ~2000 kBtu/hr of other units. In the Dynamic control case, the compressor did not need to engage during the peak period to meet the load. This presents a case where the load was completely shifted, despite performing the test on the most challenging draw profile. The daily TDV in both cases was quite low because HPWH #4 has no resistance element to operate. In the Static case the daily TDV was 622 and in the Dynamic case it was 117, resulting in an 81% TDV savings.

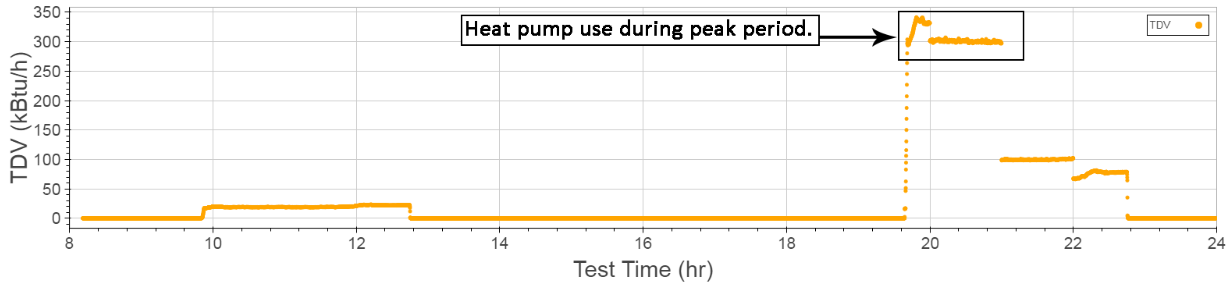


Figure 28: TDV Penalty During a Static Control Test with an 80-Gallon Nominal, Split System HPWH (#4)

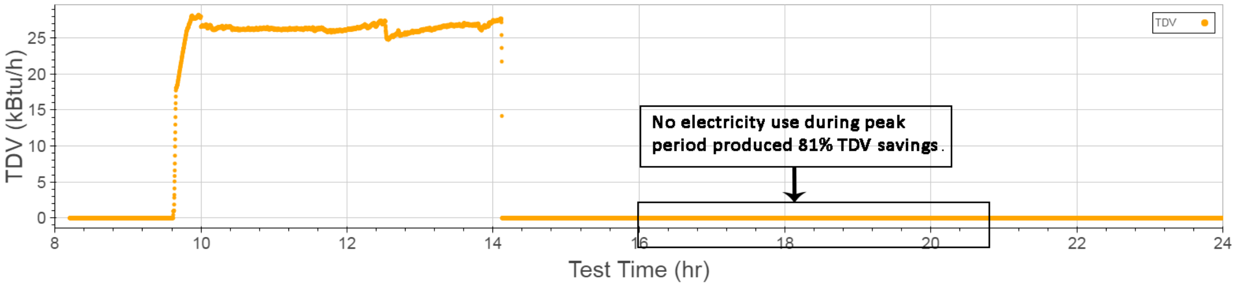


Figure 29: TDV Penalty During a Static Control Test with an 80 Rated Gallon, Split System HPWH (#4)

Table 6 presents the primary performance metrics for all tests using the Highest TDV Penalty Day draw profile. The results show that, for all four HPWHs, the Dynamic controls provided a significant reduction in builder TDV penalty and thus total electric load during the peak period. However, only two HPWHs (#1 and #4) coasted through the peak period without engaging the resistance element. In the case of #4 the cause is obvious since HPWH #4 does not have a resistance element[15]. HPWH #1 not using the resistance element is likely caused by a pro-compressor control strategy; that unit only has a rating of 66 gallons of storage, whereas HPWH #2 has a rating of 80 gallons and did use the resistance element. HPWH #3 was expected to use the resistance element during the peak period, as it only has a rating of 50 gallons, and the reduced capacity impedes the ability to shift the load.

Table 6: Peak Demand and Daily TDV in All Highest TDV Penalty Day Test Cases

		Static		Dynamic	
HPWH	Rated Storage Volume (gal)	Peak Demand (kW)	Daily TDV (kBtu)	Peak Demand (kW)	Daily TDV (kBtu)
1	66	4.85	1,902	0.3	304
2	80	4.51	2,354	4.16	1,447
3	50	5.08	2,757	5.25	1,561
4	80	0.85	622	0	117

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[15] In this case, avoiding use of the compressor is considered a valuable result.

Summer Peak Day

Table 7 presents the same figures for all test cases using the Summer Peak Day in Climate Zone 12 draw profile. These results show that the load shifting control strategy did not work when used in this Climate Zone; in many cases, the peak demand and daily TDV increased when using the Dynamic controls instead of the Static controls. This occurred because the load shifting strategy employed did not match the TDV profile for this case. As documented in Table 2, the control strategy assumed that the peak period began at 5 PM; however, as is shown in Figure 15, the peak period in the Summer Peak Day began at 4 PM. These results serve to add emphasis the need for optimized load shifting control strategies.

As was shown in Table 2, the peak period was defined as 5 PM – 9 PM. But, as shown in Figure 15, the high TDV period in this draw profile began at 4 PM. This mismatch yields some of the odd results, such as how HPWH #1 shows 0 kW peak demand yet still increased TDV. The increased TDV is because the compressor was operating during the high TDV period from 4 – 5 PM, but disengaged at the start of the peak period defined as 5 – 9 PM.

Table 7: Peak Demand and Daily TDV in All Summer Peak Day Test Cases

		Static		Dynamic	
HPWH	**Rated Storage Volume (gal)**	**Peak Demand (kW)**	**Daily TDV (kBtu)**	**Peak Demand (kW)**	**Daily TDV (kBtu)**
1	66	0.33	378	0	862
2	80	0.34	401	0.51	1,341
3	50	5.1	4,281	0	1,186
4	80	0	115	1.18	4,162

Figures 30 and 31 show the measured temperatures recorded in the 66-gallon rated capacity HPWH (HPWH #1) when tested to the Summer Peak Day with the Static and Dynamic control strategies. The recorded temperatures make the cause of the TDV increase quite clear. In the Static case, the water reaches the set temperature of 125 °F and disengages just after noon. In the Dynamic case, the compressor continues heating the water until just before 5 PM. This means that the Dynamic controls resulted in compressor heating during the high TDV period, but not the Static controls.

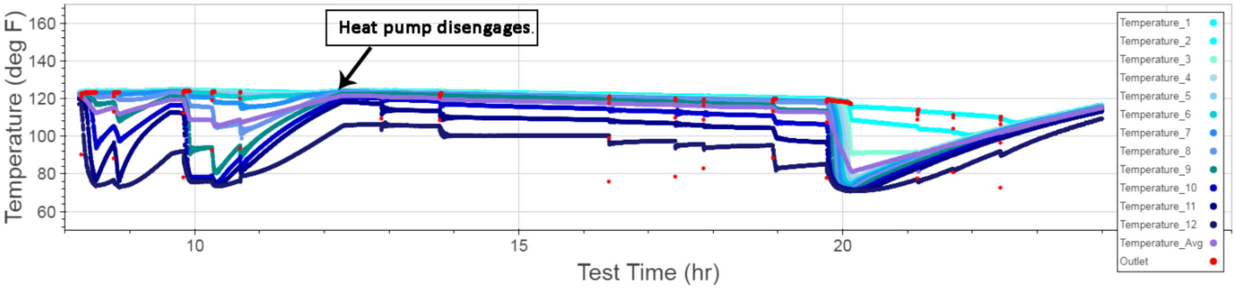

Figure 30: Measured Temperatures During the Static Test With a 66 Gallon Rated Storage HPWH (#1)

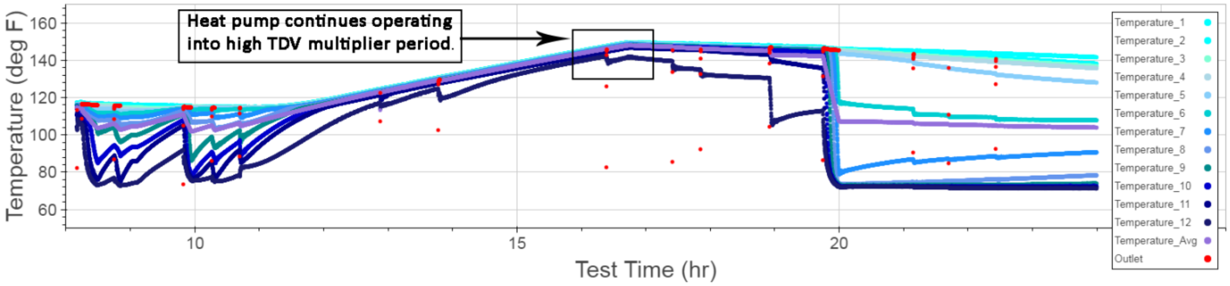

Figure 31: Measured Temperatures During the Dynamic Test With a 66 Gallon Rated Storage HPWH (#1)

Figures 32 and 33 present TDV plots for the same tests. In the Static case, the HPWH uses the compressor to heat the water in the tank from 10:18 AM to 12:10 PM at a very low TDV penalty. The compressor does re-engage from 7:49 PM to 8:58 PM, but this is after the period of highest TDV multipliers has ended. In the Dynamic case, the fact that the compressor operated until 4:42 PM with a high TDV multiplier from 4-5 PM yielded TDV penalty rates in excess of 1000 kBtu/hr.

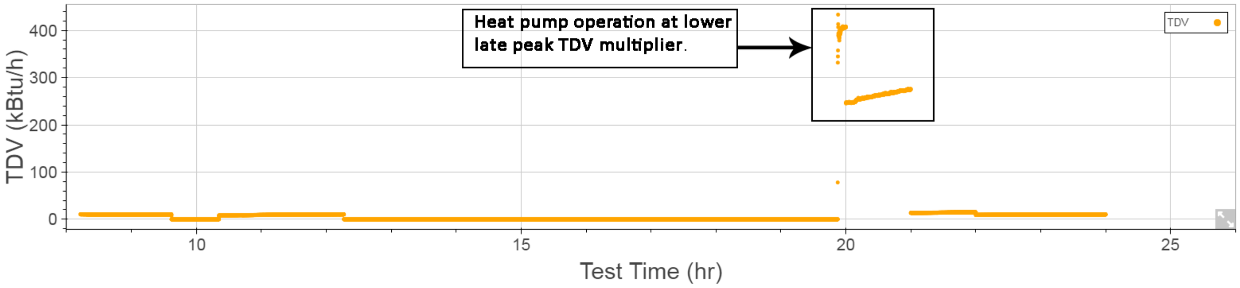

Figure 32: TDV Penalty During a Static Control Test with a 66 Gallon Rated Storage HPWH (#1)

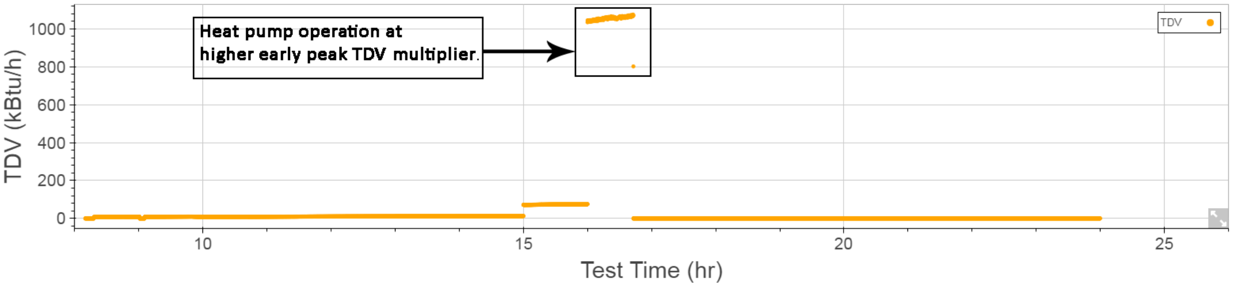

Figure 33: TDV Penalty During a Dynamic Control Test with a 66 Gallon Rated Storage HPWH (#1)

This result shows a problem in the load shifting control strategy as designed for this testing. By assuming that the peak period begins at 5 PM in all cases the control strategy caused compressor use during the high TDV multiplier period and increased the TDV penalty. Considering this is important when designing load shifting control strategies for use in real applications which should consider occupant behavior. From a Title 24, Part 6 compliance point of view, the best strategy would be to make the HPWH control logic sensitive to the TDV profiles used in CBECC-Res. However, that control strategy differs from the best strategy for securing potential cost savings for occupants paying TOU rates. This conflict is one of the remaining research questions on this topic.

Low Challenge Day

Table 8 presents the peak demand and TDV results for the Low Challenge Day test cases for all of the four HPWH. This scenario presents a situation where the control strategy worked well, as is evidenced by the fact that no HPWH Dynamic controls implemented used electricity during the peak period. However, it also presents a case where the control strategy should not have been used. As is clear in Figure 17, there is no TDV spike in this daily draw profile, indicating that there was no peak load problem to be solved. The result is that each HPWH had a higher TDV penalty, despite having no load during the peak period. As noted previously, occupants may save money by using electricity during lower cost TOU times even though there is a simulated increase in TDV kBtu.

Table 8: Peak Demand and Daily TDV in All Low Challenge Day Test Cases

	Static		Dynamic	
HPWH	**Peak Demand (kW)**	**Daily TDV (kBtu)**	**Peak Demand (kW)**	**Daily TDV (kBtu)**
1	0.42	66	0	73
2	0.77	77	0	87
3	0.36	129	0	2,401
4	0	59	0	55

Figures 34 and 35 present the calculated COP of HPWH #4 during the Static and Dynamic control test cases respectively. The plotted COP values are quite noisy, showing the challenge of calculating an instantaneous COP in a device with gradually changing tank temperatures and occasional hot water draws. However, they do show the reason for the increased TDV quite clearly. In the Static control case, the COP of the compressor ranges from approximately 4 down to approximately 3. This decrease in COP is expected and reflects the fact that the average temperature of water in the tank increased during operation. In the Dynamic control case, the compressor brought the water in the tank to higher temperatures, which naturally resulted in lower compressor COPs. This is evident in the plot, as it shows that the COP started at the same value of approximately 4 and gradually decreased to an average value of 2.5. This decrease in COP caused the HPWH to consume more electricity and, absent a TDV spike in this draw profile, pay a higher TDV penalty.

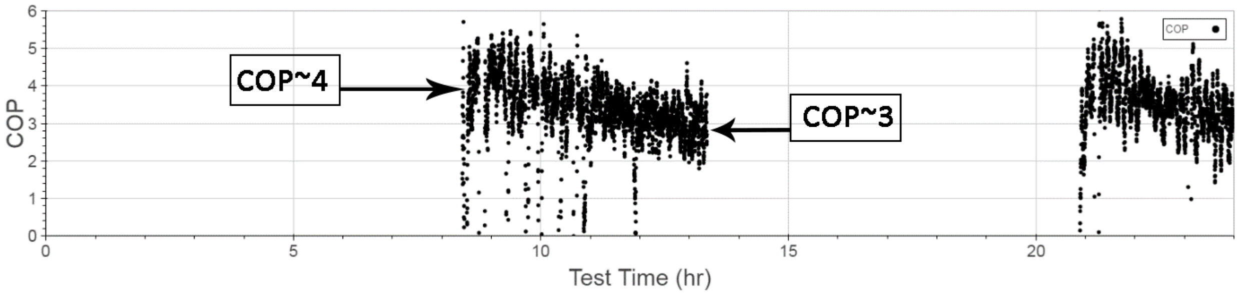

Figure 34: Calculated COP During a Static Control Test in the Low Challenge Day Test Case

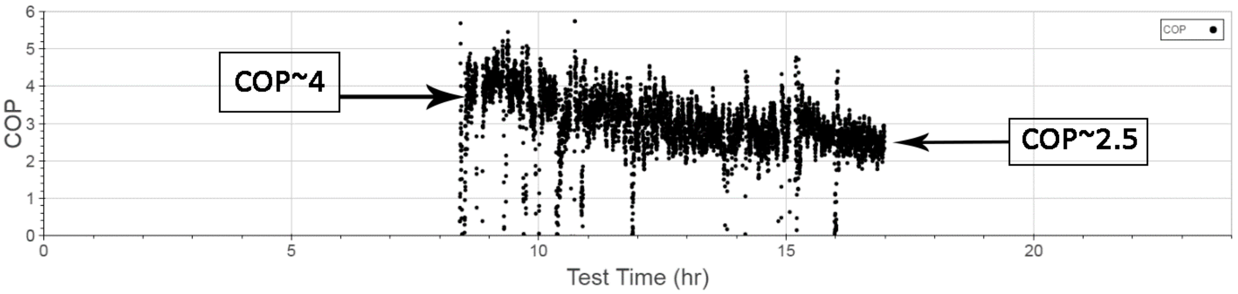

Figure 35: Calculated COP During a Dynamic Control Test in the Low Challenge Day Test Case

This case has demonstrated the need to be careful choosing which days to employ the load shifting strategy. Using this strategy on days when there is not a significant peak load problem will cause HPWHs to use more energy while not solving a problem. The most elegant way to perform load shifting with HPWHs would include communication between the utility and the HPWH, with the utility informing the HPWH of what days it should/should not employ load shifting controls. From a technical point of view, real time rates would encourage occupants to shift load on days when it is beneficial, and not to on days such as this example.

HPWH Performance Comparison

This study tested four different HPWHs with different storage volumes, manufacturer control logic, and heat pump configurations. While this amount of testing with four units is not enough to make definitive statements about optimal HPWH selection, the following conclusions can be drawn:

- Higher Storage Volume Increases Performance: HPWHs with larger storage tanks will perform better in load shifting scenarios. The higher storage volume provides more ability to store thermal energy before the peak period, and reduces the chances of using electricity during the peak period. At the same time, the temperature in the tank will increase less than in units with lower storage volumes, leading to higher COP operation of the heat pump.
- Split Systems Provide Higher COP Operation: The COP of a heat pump only decreases during load shifting when the condenser is exposed to the higher temperature water. In integrated units the condenser is exposed to water in the bottom half of the tank, which gradually heats up during the heating cycle. The COP constantly decreases. In a split system the condenser is only exposed to the coldest water at the bottom of the tank. This yields a stable COP until the entire tank is full of hot water.
- Manufacturer Controls Impact Performance: Some manufacturers employ controls that primarily use the heat pump, while others primarily use the resistance element. Use of the heat pump shifts the load at higher COP than use of the resistance element, and results in lower peak load if additional heating is necessary. On the other hand, the higher capacity of the resistance element allows more load to be shifted, reducing the odds of heating during the peak period. A test method is needed to determine how the HPWH is being controlled.
- Elevated Temperature Tradeoff: Increasing the set temperature during the day causes the heat pump to increase the temperature of water in the tank, increasing the energy stored in the tank and shifting load from the late afternoon/evening peak to the day time. Higher temperatures shift more load. On the other hand, increasing the temperature decreases the COP of the heat

pump. This creates a tradeoff where shifting more load comes at the price of lower COP and higher energy consumption.

Future studies should further investigate the impacts of these conclusions. There are likely optimal storage volumes and control strategies, leading to optimal HPWHs, for any given home and climate zone combination. Simulation studies using HPWHsim and the Title 24, Part 6 TDV profiles would help to identify the optimal way to design and control HPWHs when performing load shifting.

Conclusions

Heat pump water heaters (HPWHs) present an opportunity to address the growing "duck curve" problem in California. By engaging the compressor during the day, HPWHs can consume electricity when PV production is the highest. This can have the effect of heating the water beyond a typical set temperature, and avoiding electricity use during the evening peak period. Because HPWH compressors operate at a COP greater than 1, this is an efficient way to store energy.

This experimental project provided data sets studying the performance of this control strategy with four different HPWHs. The primary goal of the project was to provide datasets to Ecotope for use improving HPWHsim, enabling their simulation study for fine-tuning the anticipated control strategy. To perform that study, Ecotope needed three different data sets: 1) Results showing the COP of each HPWH as the temperature in the tank increased, 2) Data depicting the control logic of each HPWH when exposed to the set temperature changes required for this control strategy, and 3) Data sets showing how each HPWH performs when exposed to 24 draw profiles with this control logic for model validation.

In addition to supplying data to Ecotope, extensive analysis was performed on the data collected in tests studying the performance of the system subjected to 24-hour draw profiles. Testing and analysis were performed on three different draw profiles, representing three different operational conditions in the state of California. One represented the most challenging draw profile in Title 24 compliance software, combining high peak how water use with low inlet water temperatures and a reasonably high peak load problem. A second represented the peak load problem; a hot summer day in the Sacramento region with a serious peak load problem, and high peak period hot water use. The third draw profile represented a non-challenging condition; an October day in San Francisco, with moderate peak period hot water use. The following conclusions were drawn from the analysis of the systems exposed to full draw profiles:

- Performance in the highly challenging draw profile varied from one HPWH to the next. The HPWH with 50 rated gallons of storage was the least able to store energy due to the reduced storage volume and utilized the electric resistance element during the peak period. This HPWH did show a 43% reduction in TDV, and the control strategy improved the performance of the HPWH, but it did not achieve the desired goals. Larger HPWHs, with 66 or 80 rated gallons of storage performed better, either avoiding electric resistance element usage or electricity consumption completely. Another contributing factor was the control logic in the HPWH; some HPWHs engage the resistance element early, while others attempt to use only the compressor. HPWHs favoring the compressor were more likely to obtain significant TDV reductions. This is shown by HPWH #2, which has 80 rated gallons of storage but still used the resistance element during the peak period. It showed a 39% TDV reduction, but a maximum electricity draw of 4.16 kW during the peak period. The best performing HPWHs were #1 and #4 which achieved TDV reductions of 84% and 81%. HPWH #1 used the compressor during the peak period, resulting in a maximum electricity draw of 0.3 kW. HPWH #4 did not heat the water during the peak period and had a maximum peak period draw of 0 kW.

- Implementation of the load shifting strategy should also be sensitive to the time of day that utilities are predicting a significant peak load challenge. In this testing, the control logic featured compressor operation from 9AM to 5PM and little or no water heating from 5PM to 9PM. While this worked well in the non-challenging and highly challenging days, it did not work well in the peak load challenge draw profile. In that case, the high TDV period began at 4PM instead of 5PM. The load shifting strategy did an excellent job of avoiding HPWH electricity use from 5PM to 9PM but increased daily TDV because it needed to avoid electricity consumption after 4PM instead of after 5PM. Since TDV is a theoretical representation of grid stress a control strategy designed around it would not make sense. However, this example shows that if the goal of a control strategy is to maximize load shifting capabilities to reduce grid stress, the control strategy should be flexible to anticipated grid loads. Employing a communication strategy where the utility tells the HPWH what time of day will correspond to the afternoon peak period would avoid this problem.
- The load shifting strategy should only be utilized on days when the utilities are anticipating a peak load issue. When testing the non-challenging day profile, which does not simulate a peak load issue or an increase in TDV penalty during the peak, the load shifting strategy decreased the HPWHs COP and increased energy use. Since there was no TDV spike to avoid, it increased daily TDV as well.

Testing revealed some preliminary observations about HPWH characteristics that lead to high performance. Higher storage tank volumes provide the ability to shift more load, reducing the odds of peak period operation, while reducing the tank temperature less, resulting in lower COP degradations and energy consumption. Split systems only expose the condenser to elevated water temperatures when the entire tank is hot, and do not experience the same COP degradation that integrated units do. Manufacturer controls that minimize resistance element use are less likely to engage the resistance element during the peak period, resulting in lower peak demand.

Several research questions remain after performing this exploratory testing. They include:

- <u>Identification of High Performing HPWHs</u>: This study tested four HPWHs across a range of storage volumes, manufacturers, and configurations. Further studies should identify the optimal storage tank volume, manufacturer control logic, and configuration as well as specific models of HPWHs. These answers will likely change across different home sizes and climate zones. To do this thoroughly without prohibitive project costs, it should be performed as a simulation study using HPWHsim and its existing library of validated HPWH models. This study could also analyze the annual energy consumption of the various HPWHs without load shifting controls. Presenting the findings in both scenarios would help consumers choose the HPWH that best fits their needs.
- <u>Derivation of Optimal Control Logic</u>: This study featured control logic where the set temperature was increased from 125 °F to the maximum set temperature at 9 AM and reduced to 125 °F at 5 PM. Since heat pumps operate at lower COP at elevated water temperatures the increased thermal storage comes at a cost of reduced efficiency and increased energy use. Additionally,

some manufacturer control logic used the resistance element to reach the elevated set temperature instead of the heat pump. This had the same effect of providing more load shifting in exchange for reduced efficiency and increased energy consumption. Further studies should perform simulation-based optimizations to identify the optimal control logic in terms of both elevated set temperature and manufacturer preference for resistance element vs heat pump usage.

- Field Study Validation: The potential for load shifting with HPWHs has now been demonstrated in a laboratory setting, and the next step is to test it in the field. This will provide an opportunity to further explore questions such as control logic and communications, reliability of the system, performance of the system in more draw profiles, and occupant satisfaction.
- Balancing Interests: There are three separate parties impacted by load shifting with HPWH. Home builders want a system that gives them the optimal compliance credit, utilities want a strategy that use electricity during times of high PV production, and occupants that choose to implement HPWHs may want an approach that potentially saves them money during the highest cost periods under TOU rates. There currently is not a control strategy that optimizes the impact of these systems for all three parties. Further research should either identify a strategy that’s optimal for all parties or find a way to balance their conflicting interests.
- Communications: Testing showed that assuming a constant peak period, whether it’s 4 PM to 9 PM or 5 PM to 9 PM, will not be appropriate for all days. The period highest net (total demand minus renewables) of peak demand begins at a different times on different days. The most effective and flexible system could be supported by having utilities communicate with HPWH to give controls signals concerning the anticipated peak period for the current day. This will allow HPWH to shift load from the optimal time, and only on days when it is beneficial to both the utility and the occupants.
- Title 24 Compliance Models: There currently is no compliance credit in Title 24, Part 6 for load shifting with HPWH. Adding this option to CBECC-Res would provide builders with an opportunity to earn lower TDV scores by implementing load shifting controls. With HPWHsim and TDV profiles already incorporated, CBECC-Res is well positioned to add a detailed simulation platform for this compliance credit. Adding load shifting control logic to the version of HPWHsim included in CBECC-Res would allow simulations predicting the performance of each HPWH in load shifting scenarios. These simulations would lead to accurate TDV credits for builders, encouraging adoption of load shifting controls.

References

[1] California ISO, "What the duck curve tells us about managing a green grid," Folsom, 2016.

[2] California Energy Commission, "Building Energy Efficiency Program," California, 2018. [Online]. Available: http://www.energy.ca.gov/title24/. [Accessed 28 March 2018].

[3] B. Wilcox, "CBECC-Res Compliance Software Project," 2018. [Online]. Available: http://www.bwilcox.com/BEES/BEES.html. [Accessed 28 March 2018].

[4] N. Carew, B. Larson, L. Piepmeier and M. Logsdon, "Heat Pump Water Heater Electric Load Shifting: A Modeling Study," Ecotope, Inc., Seattle, 2018.

[5] N. Kvaltine, M. Logsdon and B. Larson, "CBECC-Res Compliance Software Project Reference Documents," 15 April 2016. [Online]. Available: http://www.bwilcox.com/BEES/docs/Ecotope%20-%20Guide%20to%20HPWHsim%20v1.docx. [Accessed 28 March 2018].

[6] Northwest Eneergy Efficiency Alliance, "Advanced Water Heater Specification," 10 May 2016. [Online]. Available: http://neea.org/docs/default-source/advanced-water-heater-specification/advanced-water-heater-specification.pdf?sfvrsn=22. [Accessed 29 March 2018].