Ecosizer – Central Heat Pump Water Heating Sizing Tool

ECOTOPE

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1. INTRODUCTION

Ecosizer is a sizing tool for heat pump water heating (HPWH) equipment and domestic hot water (DWH) storage volume built on best practices for optimizing these variables when designing a split-system for central heat pump water heaters (CHPWH). It provides basic sizing information for any building with a known or estimated consumption of DHW. This tool supports the following CHPWH market development objectives:

- to rapidly increase the adoption of the technology
- to reduce the real and perceived risk of the technology
- to reduce performance and maintenance issues
- to reduce system cost by establishing a simple, standardized approach to system sizing

This manual details Ecosizer's methodology and best practices for sizing CHPWH systems.

Common sizing methodologies for central water heating equipment favor fast temperature recovery over large storage volumes, advantageous for designs with high heating capacity. Reliable, cost-effective gas (and less-often electric resistance) water heating systems can be sized to deliver high heating capacity and fast DHW recovery, but at the expense of efficiency and higher greenhouse gas (GHG) emissions compared to CHPWHs. Because heating capacity is inexpensive in these systems, they are often oversized for a building's DHW requirements. They are designed using rule-of-thumb design approaches to meet and exceed DHW demand in all scenarios – at the expense of efficiency.

CHPWH systems can deliver hot water at 2-5 times the efficiency of gas or electric resistance systems but have several design trade-offs. Because they are more expensive per unit of heating capacity, a CHPWH sized like a gas or electric system would result in costly and sometimes unreliable systems. Ecosizer helps designers utilize larger storage volumes for peak DWH demand periods, compensating for smaller output capacity. This approach can help optimize the cost per unit of heat pump heating capacity, resulting in long DHW recovery periods with heat pump compressors operating up to 16-20 hours per day.

Many CHPWH systems that follow this sizing strategy are used in multifamily buildings today. HPWH system retrofits using this method are becoming common. An illustrative example can be seen in a DHW system retrofit of the Elizabeth James, a 60-unit low-income multifamily building. Ecotope monitored the pre-retrofit electric resistance water heating system and the post-retrofit heat pump water heating system to quantify the CHPWH's functionality. The CHPWH system delivered a 63% reduction in energy required for the DHW system[1].

[1] Banks, A., Grist, C., and J. Heller. 2020. CO2 Heat Pump Water Heater Multifamily Retrofit: Elizabeth James House, Seattle WA. Prepared for Washington State University Energy Program, under contract to Bonneville Power Administration

This case study from the early market development of CHPWHs demonstrated that a small heat pump capacity and a relatively large amount of storage volume can provide reliable DHW for a multifamily building. The system supplied more than sixty occupants with hot water using the equivalent of 20kW heat pump output capacity – one-sixth of the pre-retrofit capacity (120kW). Using Ecosizer resulted in specifying heat pump capacity an order of magnitude lower than that specified using traditional methods for sizing gas or electric resistance water heating equipment. Proper sizing that enables confidence to specify smaller systems to serve DHW loads can help mitigate price concerns as the CHPWH market continues to emerge and mature.

Section 2 describes the reasoning underpinning appropriate CHPWH design. Section 3 details how CHPWH design appropriately accounts for temperature maintenance loads. Section 4 explains the methodology employed in the Ecosizer CHPWH sizing tool for normal operation and load shift scenarios. Section 5 discusses future work for the Ecosizer design tool.

2. EQUIPMENT OVERVIEW

Currently Ecosizer supports sizing of Single-Pass CHPWHs with separated temperature maintenance, including Swing Tank and Parallel Loop Tank system configurations as described in the Northwest Energy Efficiency Alliance (NEEA) Advanced Water Heating Specification (AWHS)[2].

1) Swing tank designs use a loop tank piped in series with the primary storage (Figure 1) and
2) Parallel loop tank design uses a loop tank piped in parallel with the primary storage (Figure 2).

Ecotope is actively looking for funding opportunities to add Multi-Pass Return to Primary and Single-Pass Return to Primary to the Ecosizer web page.

The current configurations with separated temperature maintenance – including swing tank and parallel loop tank – are designed around CHPWHs that use CO_2 as the refrigerant. However, for other refrigerants – such as R290 – Single-Pass Return to Primary is the most efficient. Multi-Pass Return to Primary configurations also have advantages in retrofits, and where recirculation loads are high.

[2] https://neea.org/our-work/advanced-water-heating-specification

3. TEMPERATURE MAINTENANCE SYSTEM OVERVIEW

CO2 HPWHs provide high-efficiency performance when heating cold water. Typically, CO2 HPWHs are less efficient as heating warm water returning from recirculation systems. A temperature maintenance system, separated from the thermally stratified primary storage volume, can overcome this limitation of CO2 HPWHs. The AWHS[2] includes detailed definitions and descriptions for CHPWHs that include temperature maintenance systems. Figures 1 and 2 are excerpted from the AWHS to illustrate the two calculation engines within EcoSizer.

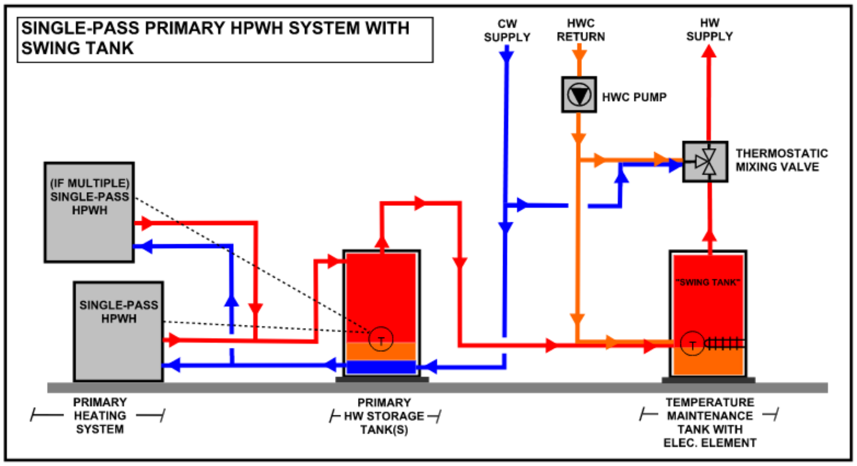

Figure 1. Example of centralized domestic hot water HPWH plant with a swing tank.

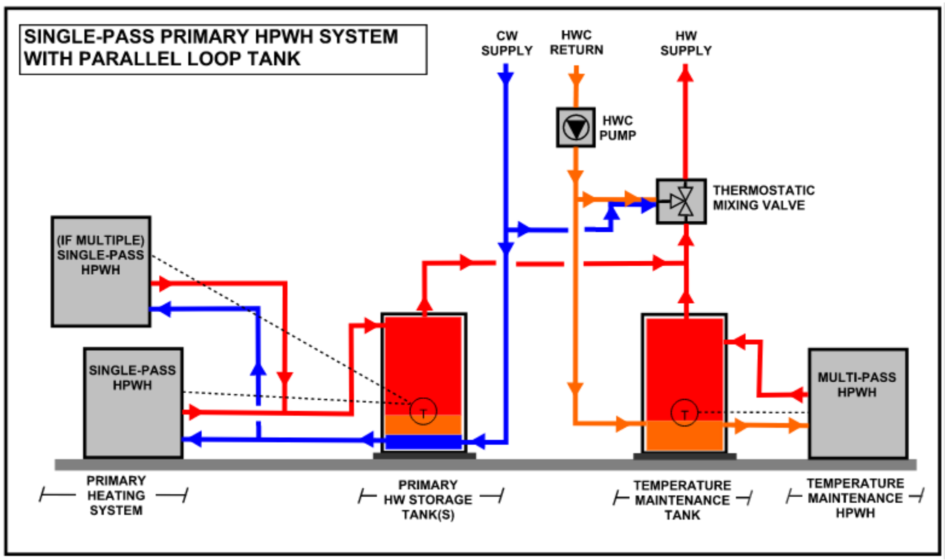

Figure 2. Example of a CHPWH plant with a parallel loop tank.

4. SIZING TOOL METHODOLOGY

The following section covers Ecosizer's methodology for sizing primary systems and temperature maintenance systems for Single-Pass systems.

The daily hot water demand on the design day determines the size of a primary system. For a multifamily building, the tool requires user inputs for *Number of People* (number of occupants in the building), *Number of Apartments* (number of apartments in the building), and *Peak Gallons per Day per Person* (the highest number of gallons used by an occupant of the building per day). Alternatively, the user could provide more detailed input by entering the number of studio apartments, one-bedroom apartments, two-bedroom apartments, etcetera, and using a default or custom *Occupancy Rate* (average number of occupants in an apartment) and *Peak Gallons per Day per Person* for each apartment size. Using these alternative metrics, Ecosizer can calculate *Number of People*, *Number of Apartments*, and *Peak Gallons per Day per Person.* See Table 2 for more information on these occupancy rates.

Sizing for the temperature maintenance system depends on the user input for *Recirculation Loop Heat Loss* (W/Apartment for multifamily buildings or calculated from return temperature and flow rate) in the *Advanced Schematic Options*. Ecosizer and the Temperature Maintenance Sizing section of this manual provide guidance for this load. The data and code for the calculation methods described below are publicly available[3].

Hot Water Demand Calculation

Estimating building hot water demand is the first step in sizing CHPWH plants for multifamily buildings, defined as the daily DHW demand (in gallons) and its load shape. The daily hot water demand $V_{HW,Day}$ is calculated as follows:

$$V_{HW,Day} = N_{people} \cdot V_{gpdpp}$$

Where N_{people} is the total number of people in the building, and V_{gpdpp} is the peak hot water demand in gallons per day per person. Users must specify the expected number of occupants and the peak hot water demand or use estimates defined by ASHRAE or California code standards. More details on assessing the number of people for a multifamily building can be found in the "Magnitude Units and Number of People" section below.

For non-multifamily buildings (See Table 1 for the full list of non-multifamily building types supported by Ecosizer), the approach to finding $V_{HW,Day}$ is similar. In this approach, users are asked to enter a parameter (specific to the building type) to define the magnitude of the building in "magnitude units." For example, when sizing a CHPWH for a motel, Ecosizer requires the number of rooms in the motel (the magnitude unit) for the sizing calculation. When this statistic has been obtained $V_{HW,Day}$ is calculated as follows:

$$V_{HW,Day} = N_{magnitude\ units} \cdot V_{gpd\ per\ magnitude\ unit}$$

Where $N_{magnitude\ units}$ is the total number of magnitude units and $V_{gpd\ per\ magnitude\ unit}$ is the peak hot water demand in gallons per day per magnitude unit. Ecosizer has an internal, publicly available[4] list of magnitude units and their associated $V_{gpd\ per\ magnitude\ unit}$ for a variety of building types. This

[3] https://github.com/EcotopeResearch/EcosizerEngine

[4] https://github.com/EcotopeResearch/EcosizerEngine/blob/main/src/ecoengine/objects/Building.py

information can also be found in Table 1 below. These values were calculated from the maximum daily water use load shape charts from Figure 24 in Chapter 51 of the 2019 ASHRAE Applications Handbook.

Table 1. Magnitude Units for Ecosizer-supported building types

Building Type	Magnitude Units	$V_{gpd\ per\ magnitude\ unit}$
Men's Dorm	Number of Students	23.6
Women's Dorm	Number of Students	19.6
Motel	Number of Rooms	21.4
Nursing Homes	Number of Beds	23.4
Full-Meal Restaurants	Maximum Meals per Hour	11.032
Drive-ins, Snack Shops	Maximum Meals per Hour	6.44
Elementary Schools	Number of Students	1.24
Junior High Schools	Number of Students	3.75
Senior High Schools	Number of Students	3.26
Office Buildings	Number of People	2.1
Multifamily Building	Number of People	User input or calculated GPDPP

Magnitude Units and Number of People

When sizing for a non-multifamily building, the number of magnitude units are taken directly as a user input, the Ecosizer webpage working dynamically to provide the appropriate input field for the selected building type. However, for multifamily buildings, there are a few more options to calculate magnitude units (Number of People). To estimate the number of people (occupants) in a multifamily building, Ecosizer employs two input method options:

1. Enter the number of expected occupants directly
2. Enter occupancy estimates based on the number of bedrooms and the occupancy rate (number of people per unit by the number of bedrooms).

Ecosizer provides four options for determining the number of people per apartment size/type (Table 2).

Table 2. Occupants per bedroom for four different Multi-family data sets.

Apartment Size	Occupants/Bedroom			
	CBECC-Res	CTCAC	ASHRAE Market Rate	ASHRAE Low Income
Studio	1.37	1	1.49	1.69
1 BR	1.74	1.5	1.93	2.26
2 BR	2.57	3	2.39	2.83
3 BR	3.11	4.5	2.84	3.40
4 BR	4.23	6	3.29	3.97
5+ BR	3.77	7.5	3.74	4.54

The California ratios used in CBECC-Res are based on the 2009 Residential Appliance Saturation Study[5]. For low-income groups in California, ratios are sourced from the CA Tax Credit Allocation Committee (CTCAC)[6]. An ASHRAE publication[7] provides two sets of national data for multi-family and low-income multi-family buildings developed from the 2009 Residential Energy Consumption Survey. The ASHRAE low-income multifamily occupancy ratios are higher than the ASHRAE market rate multifamily occupancy ratios.

Peak Demand Per Person in Multifamily Buildings

The sizing tool provides several options to estimate the peak hot water demand per person when sizing for a multifamily building. First, the tool provides estimates for V_{gpdpp} from 2015 ASHRAE HVAC Applications handbook pages 50.15 - 50.16. These options are ASHRAE Low at 20 gallons per day per person (gpdpp) at 120°F and ASHRAE Medium at 49 gpdpp at 120°F. Due to the outdated data, the ASHRAE Medium number is likely an overestimate of any modern multifamily building.

To provide a modern[8] estimate, Ecotope evaluated hot water usage in three market-rate multi-family buildings with low-flow fixtures in Seattle, WA. From a design perspective, one building stands out from the others as having higher hot water use and a higher peaking load. The 118-unit building is in a family-oriented neighborhood, while the others are in more night-life-oriented neighborhoods. Data for the building was collected between January 2014 and November 2018.

The studies used the 98th percentile of daily hot water demand to find the design peak hot water use. The empirical cumulative density function (ECDF) is given in Figure 3, which evaluates to 25 gpdpp[9].

[5] Palmgren, C., N. Stevens, M. Goldberg, R. Bames, and K. Rothkin (2010). 2009 California Residential Appliance Saturation Survey. Technical report, KEEMA, Inc., Oakland, California.

[6] California Tax Credit Allocation Committee (CTCAC) (June 2020). Compliance Online Reference Manual Low Income Housing Tax Credit Program (LIHTC). Part 3.3 B. https://www.treasurer.ca.gov/CTCAC/compliance/manual/manual.pdf

[7] Florida Solar Energy Center. *Estimating Daily Domestic Hot-Water Use in North American Homes.* FSEC-PF-464-15. June 30, 2015. www.fsec.ucf.edu/en/publications/pdf/FSEC-PF-464-15.pdf

[8] Note that Ecotope's recent hot water usage data was evaluated before the COVID-19 pandemic. Average water usage increased in monitored Seattle buildings by 20% during the stay-at-home orders. It is not clear how that may have impacted the peak daily use.

[9] We find the best-fit distribution to the ECDF is a normal distribution. Therefore, the normal distribution is used to scale the user input for a percentage of days load shifted in the load shift section of the report.

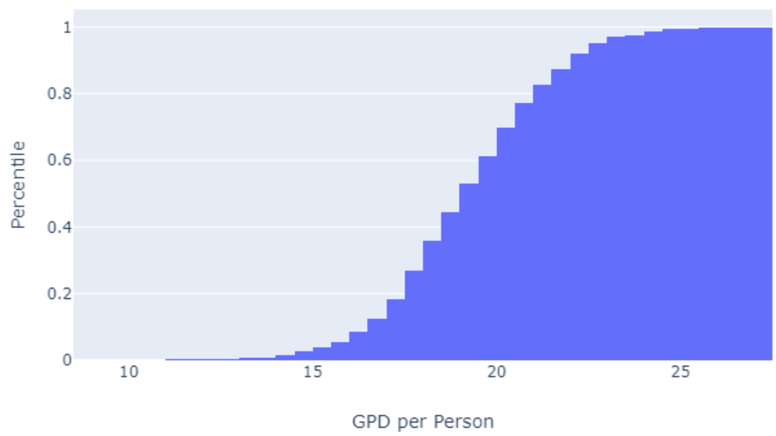

Figure 3. The empirical cumulative density function for the design building.

California Demand Per Person

The Ecosizer tool also provides an option for hot water demand derived from CBECC-Res 2019, a software used to show compliance with California energy code[10]. The software includes hot water use profiles divided into ten distinct profiles for studios, 1-bedroom units, 2-bedroom units, 3-bedroom units, 4-bedroom units, and 5-bedroom units[11]. When a CBECC-Res user constructs a multi-family building in the software, the software uses the appropriate number of units of each size. If there are more than ten units in the building of a bedroom size, the CBECC-Res will repeat hot water draw profiles.

To adapt this data to the Ecosizer, one-minute timestep output was captured for the HPWH system in a 10-unit building of just one-bedroom size. The resulting hot water draws were aggregated to the daily level and divided by the number of people in the building to get an expected value of DHW in gallons per day per person for each unit size for each day of the year. The results of this process are shown in Figure 4 for each unit size for hot water supplied at 120°F. The dashed red lines represent the 98th percentile days. The dashed blue line represents the median daily use. By sourcing this data directly from CBECC-Res 2019, the data captures assumed hot water waste associated with distribution piping in the unit and with waiting for the hot water to heat up. For details on the losses, see Kruis et al. (2019)[11] .

To maintain the variation present in the daily DHW demand, the methodology in the Ecosizer multiplies the daily expected values for each unit size by the user input for number of apartments of a given size to get an expected value in the building for each unit size. The expected values by unit size are summed together to build a yearly DHW profile for the building. The Ecosizer finds the 98th percentile DHW day from the yearly profile to calculate the peak demand.

[10] http://www.bwilcox.com/BEES/cbecc2019.html

[11] Kruis, N, Wilcox, B., Lutz, J. and Banaby, C. (2019) Development of Realistic Water Draw Profiles for California Residential Water Heating Energy Estimation – Revised (March, 2019). http://www.bwilcox.com/BEES/docs/dhw-profiles-revised3.pdf

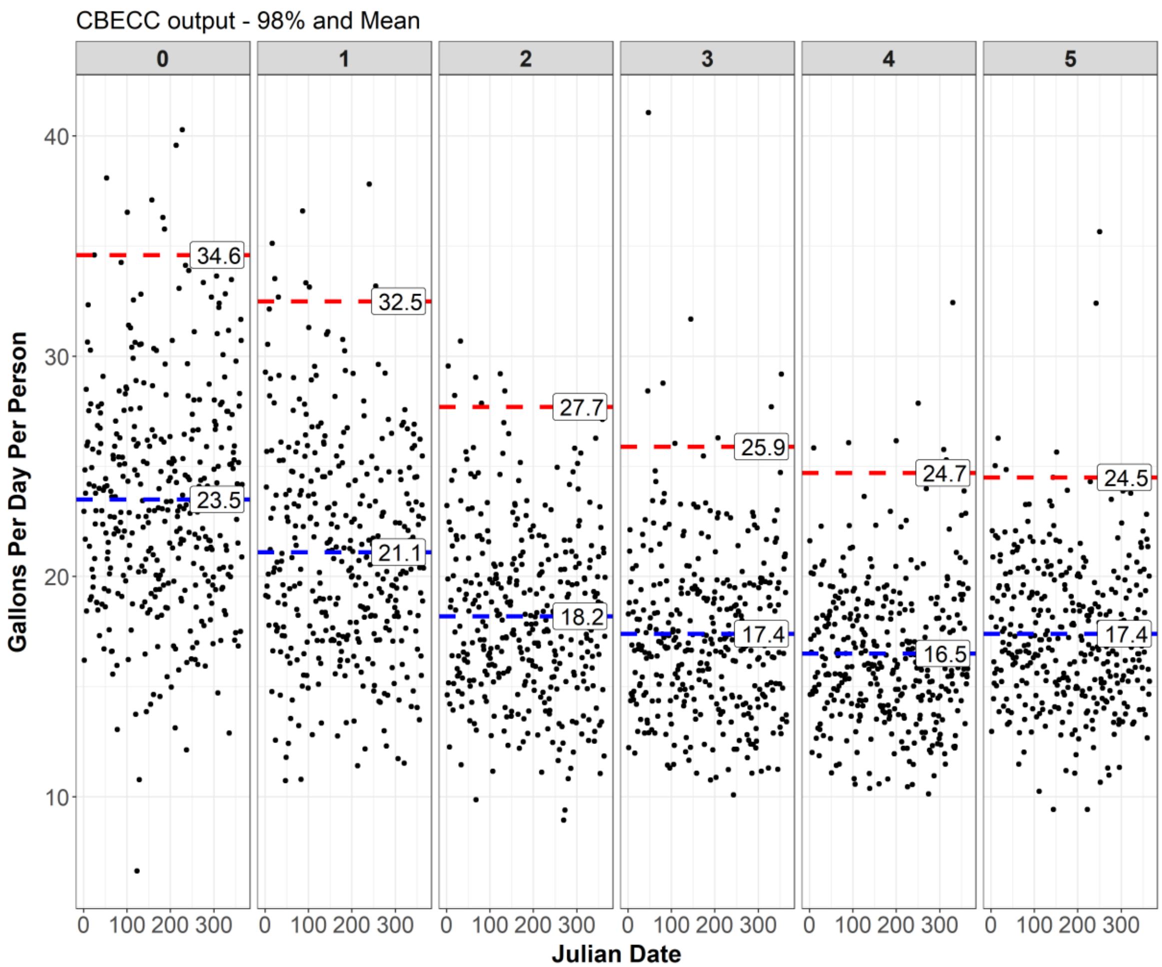

Figure 4. Expected daily DHW per person for each of the CBECC-Res apartment types.

Load Shape

For multifamily buildings, the load shape is found from an analysis of the hourly demand for each day in the dataset for the 118-unit multifamily building. A selection of potential days is chosen between the 98th and 95th percentile of daily hot water use and in the upper percentile of 3- and 4-hour peak loads. Most days satisfying the first criteria also satisfy criteria for a high peak load, indicating a correlation between the volume of hot water used during the day and the peak hot water use during the same day. The design day chosen is one that maximizes the cross-correlation between itself and the average day, both shown in Figure 5. This means the design day has a similar use pattern to the average day load shape but has the peaking hot water loads that are important for sizing a HPWH system and are useful for predicting the timing of peaking loads in a load-shifting scenario.

The peak design day load shape represents a likely worst-case multifamily load shape with a very high morning peak driven by morning showers and cooking, very low mid-day usage which indicates most occupants at work or school, and a second slightly smaller evening peak representing after work showers and dinner prep. Building occupancy types with fewer workforce occupants (i.e. senior or supportive housing) will likely exhibit a somewhat flatter curve with hot water usage spread out more even over the day. Those load shapes will not need as much storage volume to get through the peak periods. Note that this worst-case load shape assumes some diversity of occupants in a multifamily building with some high users and some low users distributing their demand over the day. Usage patterns could align to produce higher peaks or higher total demand in small multifamily buildings with less diversity. Therefore, care should be taken when using the Ecosizer for buildings with fewer than 20-30 occupants.

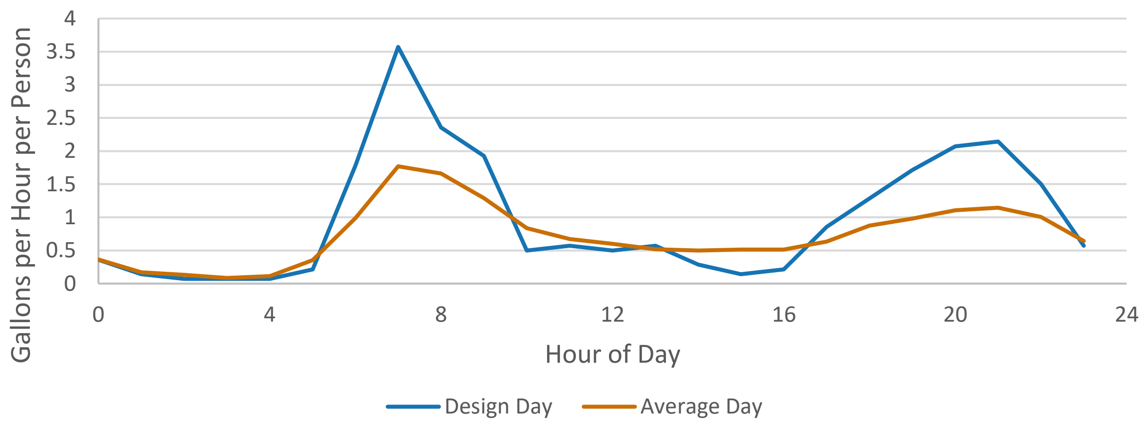

Figure 5. Measured Load Shapes from Ecotope Buildings.

In the sizing tool, the load shape is used for any input of N_{people} or V_{gpdpp}. The design day load shape in Figure 5 is normalized by the total daily use per person such that each hour represents a fraction of the daily use. For use in the sizing tool, the load shape is scaled by the total daily hot water demand for a user's specific case.

For non-multifamily buildings, the load shape is the maximum hourly use load shape for the specified building type from Figure 24 in Chapter 51 of the 2019 ASHRAE Applications Handbook. This load shape is normalized and multiplied against the $V_{HW,Day}$ defined in the "Hot Water Demand Calculation" section to get our final loadshape.

Sizing Methodology for Primary Plant

This section discusses the sizing of the primary plant when using no recirculation loop or a parallel loop tank. The method is altered when using a swing tank design as the primary plant must provide a portion of the heating capacity to support temperature maintenance of the distribution system, as discussed in the next section on sizing for swing tank systems. The sizing method presented in this section is the next logical step forward from the "More Accurate Method" referred to in the 2015 ASHRAE HVAC Applications handbook, pages 50.15 - 50.16. Here, it is modified to better represent lower-capacity systems producing hot water during occupant use. We call this method the Ecosizer Method.

Sizing the primary plant of a CHPWH system is done to meet the peak hot water usage period (when HPWHs cannot generate enough hot water to keep up with demand) on the design day. This ensures that hot water will be continuously supplied year-round. The sizing of the system depends on the design and operation of the storage volume. The design of storage volume is summarized into one idealized storage tank shown below in **Error! Reference source not found.**, which represents storage tanks in p arallel or series. The user input for the aquastat fraction is the percentage of hot water volume removed from the tank before the HPWHs turn on due to cold water at the sensor.

The recommended minimum sizing options are found by:

1. The minimum capacity for the water heater is determined first based on the user input value for "maximum daily runtime for the HPWH compressor", $h_{max,hr}$., which is recommended and defaulted to 16 hours. However, designer must consult with product venders as some products required sizing for 12 hours or less to meet warranty requirements. The corresponding hot water generation rate, $\dot{G}(t)$, is calculated following:
$$\dot{G}(t) = \frac{V_{HW,Day}}{h_{max,hr}}$$
Where $V_{HW,Day}$ is the total hot water used on the design day. This calculation gives a first order estimate of the gallons per hour that need to be heated over the course of 1 day.

2. Storage volume is found by considering the worst-case scenario: entering a peak hot water usage period when the HPWH has not heated up the whole volume of the tank and the HW level is below the aquastat. A peak hot water usage period (peak period) is defined as any period where the hot water draw rate exceeds the hot water generation rate, i.e. $\dot{V}_{HW}(t) > \dot{G}(t)$ where $\dot{V}_{HW}(t)$ is the full load shape of hot water usage for the design day. The full load shape is calculated as
$$\dot{V}_{HW}(t) = V_{HW,Day} * \dot{V}_{HW,Norm}(t)$$
where $\dot{V}_{HW,Norm}(t)$ is the normalized hot water load shape for the building, either inferred from the ASHRAE standard load shapes for the building type or uploaded by the Ecosizer user as a custom load shape. The storage volume that remains at the start of a peak period is the running volume, shown in Figure 7. This must be equal to the volume of hot water used during the peak period and subsequent peak events greater than the volume of hot water the HPWH can generate until the conclusion of those periods. To find this volume, the running integral of the difference between the hot water draws and generation rate is found by:
$$V^i_{supply}(t) = \max\left(\int_{t^i_{peak}}^{t} \left(\dot{V}_{HW}(t') - \dot{G}(t')\right) dt'\right)$$
Where $V^i_{supply}(t)$ is the running difference , t^i_{peak} is the start of the i^{th} peak period in the design day, and $t \in \{ t^i_{peak}, t^i_{peak} + 1, \dots, 48\}$. The design day could have multiple peak periods, each is used to evaluate a running volume and only the max running volume is used for sizing. The maximum running difference will occur at the end of a peak period, but might not occur at the end of the first peak period (t^1_{peak}). To make sure the sizing accounts for any running difference that happens overnight, the integral range is calculated for 48 hours (two subsequent design days). By taking the maximum of the running integral and the maximum of $V^i_{supply}(t)$ calculated starting at each peak period, the sizing methodology ensures there will be enough storage. The running volume required for the system to be adequately sized is the absolute maximum of the all the $V^i_{supply}(t)$ values.
$$V_{running} = \max\left(V^i_{supply}(t)\right).$$
To visualize this algorithm, please see Figure 6. Although the algorithm assesses the max integral over a 48-hour period, the figure shows a 24-hour period for simplicity. The top two graphs in the figure show the logic to get the maximum volume for the first peak. In this particular case,

taking the integral of just the first peak is greater than taking the integral from the first peak to the end of the load shape period so the maximum volume is determined to be the integral of only the first peak. Similarly, the maximum volume needed for the second peak is assessed on the bottom two graphs. In the case of this scenario, the volume needed for the first peak is greater than the volume needed for the second peak, thus $V_{running} = V^1_{supply}(t)$.

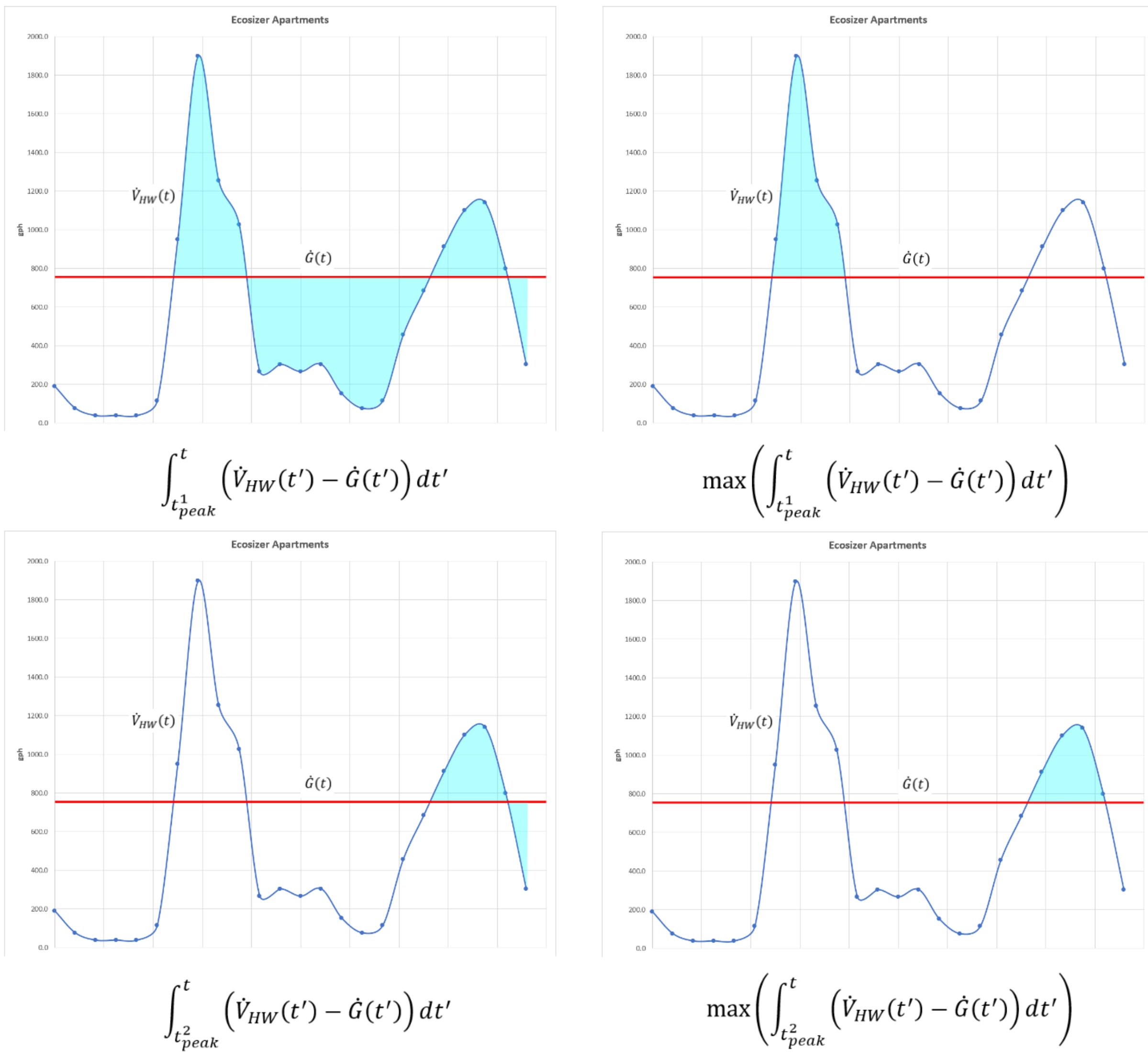

Figure 6. An illustration of the sizing methodology for running storage volume.

3. Since the running volume is just what is above the aquastat, the total storage for DHW at the supply temperature is then found by the user input for the aquastat fraction (AF) defined as the ratio between the total storage volume and the usable fraction of storage (the red section in Figure 7), referred to as the “drawdown” in Ecosizer.

$$V_{total,T_{supply}} = \frac{V_{running}}{(1 - AF)}$$

4. Ecosizer checks that the cycling volume, the primary storage volume between the aquastat and the bottom of the effective storage volume (drawdown), has a large enough volume that the primary HPWHs can run for at least ten minutes in the absence of hot water draws, per manufacturer recommendation. If the minimum cycling volume is larger than the cycling volume calculated with the user defined aquastat and drawdown, an error is returned

$$V_{cycling,min} = 10 \text{ minutes} * \dot{G}(t)$$

$$V_{cycling,min} \leq V_{total,T_{storage}} * \left(AF - (1 - drawdown)\right)$$

5. Lastly, offsets are used for the differences in the user inputs for storage temperature and supply temperature.

$$V_{total,T_{storage}} = \frac{T_{supply} - T_{CW}}{T_{storage} - T_{CW}} V_{total,T_{supply}}$$

6. The sizing curve (storage vs. capacity) is created by varying $h_{max,hr}$ from 24 hours to the minimum value defined as $\frac{1}{h_{max,hr}} > \max\left(\dot{V}_{HW}(t)\right)$, which would lead to a scenario where the hot water generation rate is greater the DHW usage.

Given the methodology, the load shape chosen will have a large effect on the recommended sizing. Load shapes with higher peaking loads will require more storage than load shapes with a more distributed hot water load. This is the reason careful consideration for the peaking hot water load was given in the load shape section.

Lastly, the required heating capacity, $\dot{Q}_{primary}$, on the design day can be found from:

$$\dot{Q}_{primary} = \rho c_p \frac{V_{HW,Day}}{h_{max,hr} * D}\left(T_{supply} - T_{CW}\right)$$

where ρ is the density of water, c_p is the heat capacity of water, and D is the defrost factor.

An example of this is worked through in Figure 8 and Figure 9, for a building using 2000 gallons of DHW per day and a maximum daily runtime for the compressor of 16 hours. In Figure 8, the blue bars represent the daily hot water load shape, $V_{HW,Day} * \dot{V}_{HW}(t)$, and the hot water generation rate is shown in green.

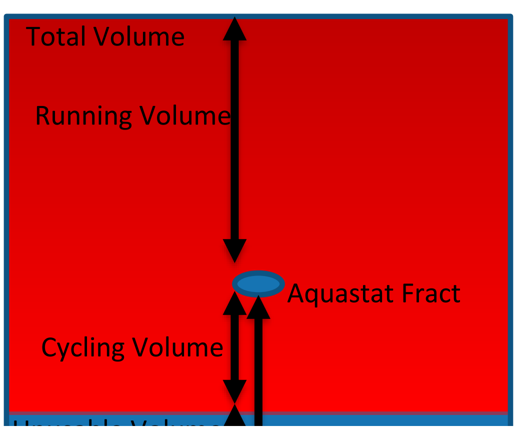

Figure 7. An illustration of the parts of the storage volume

The difference between the hot water use and the hot water running difference is shown in orange. In this case, there are two instances of peak period, t_{peak} starting at 06:00 and at 19:00.

The cumulative difference between DHW generation and DHW use starting at the beginning of each peak period is shown in Figure 9. The minimum value of both curves represents the running volume. In this instance the running volume is 270 gallons. If the aquastat fraction is 0.4, then the total storage volume is 450 gallons (V=270/(1-0.4)=450).

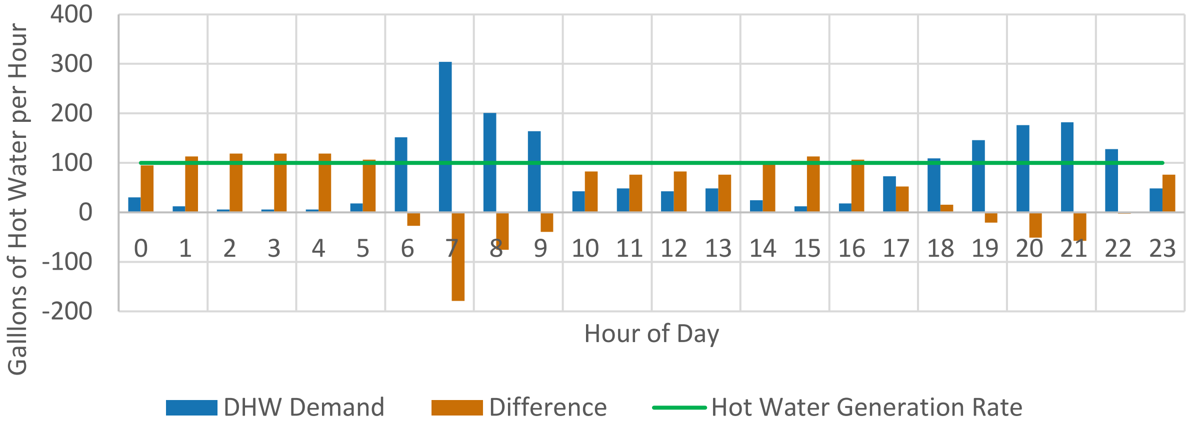

Figure 8. Hot water (HW) use, heating rate and difference throughout the day.

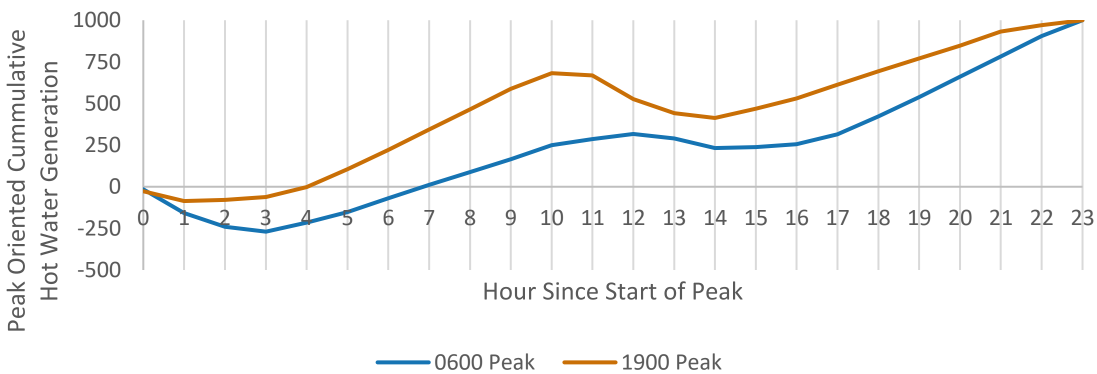

Figure 9. Cumulative supply after peak event.

On occasion, HPWHs can run all day, much longer than the design minimum runtime. This creates a built-in safety factor for days when the total GPDPP may be greater than the max used in the sizing tool. However, this safety factor does not increase the heating rate and does not provide safety against a greater-than-predicted peak. For an increase in the peak event, the aquastat fraction serves as a safety factor. It will typically be unusual for the storage volume to be sitting at just the running volume at the start of the peak draw period. Therefore, the extra heat within the cycling volume provides an increase in the total available storage.

To give an idea about the storage and the heating capacity, a simple model is run for the primary heat pump water heater plant on the design day and plotted in the Ecosizer. More information on the simulation is available in Appendix A.

Temperature Maintenance Sizing

The temperature maintenance module will size the temperature maintenance storage and heat capacity using the inputs for the time-dependent load shape, primary storage temperature, and supply temperature to the occupants from the primary sizing tool. Additionally, the optimization of the temperature maintenance tank will depend on user input for the number of apartments and temperature maintenance heat loss rate.

Based on the schematic chosen, the temperature maintenance system will either be designed as a parallel loop tank or as a swing tank. A parallel loop tank has an electric resistance element or a multi-pass HPWH that is piped in parallel with the primary system. On the other hand, the swing tank has an electric resistance element and is designed to use the hot water from the primary HPWH to account for the majority of the distribution losses.

Calculation of the Temperature Maintenance Load

Sizing for temperature maintenance is difficult because the recirculation load is unknown a priori. This load is unknown for new construction and relatively hard for the designer to predict as it is determined by many factors that may be outside of their control, including the pipe sizing, the length of circulated piping, the insulation levels, the quality of the insulation and thermal bridging at pipe supports, and the location of the piping inside or outside of the heated envelope of the building.

The temperature maintenance load has a user input value for the recirculation loop loss. For advising and setting a default for what this should be, we can only base our assumptions of this load on data from previously studied buildings. These data show a median of ~100 watts per apartment (W/apt), with a 25th percentile of ~66 W/apt and a 75th percentile of ~175 W/apt[12]. This upper bound of 175% of the median value is recommended for sizing the heating elements in the temperature maintenance systems for new construction.

In a retrofit, a measurement of the recirculation loop heat loss rate is possible and highly recommended. This is a poorly researched load and it will ultimately require the designer to estimate the loss rate and provide back-up heating capacity as a safety factor. An engineer may be more familiar with the recirculation loop-flow rate and return temperature which can be used to find the heat loss rate from:

$$\dot{Q}_{loop} = \rho c_p f_{loop}(T_{supply} - T_{return})$$

Where $\dot{Q}_{loop}$ is the recirculation loop losses for the building, f_{loop} is the flow rate of the recirculation loop, T_{return} is the recirculation loop return temperature, and T_{supply} is the temperature entering the recirculation loop. Alternatively, for multifamily buildings, the recirculation losses can be calculated via

[12] Kintner P., and Larson, B. (2019). Literature Review of Multifamily Central Domestic Hot Water Distribution Losses. Prepared for NEAA.

$$\dot{Q}_{loop} = N_{apt}\dot{Q}_{apt}$$

Where N_{apt} is the number of apartments, and $\dot{Q}_{apt}$ is the recirculation loop losses per apartment unit. The tool offers users inputs for the recirculation loop losses per unit, or the recirculation loop flow rate and return temperature. Using the later inputs, the tool will calculate the recirculation loop losses per apartment unit based on the inputs for flow rate, return temperature, and supply temperature.

Swing Tank

The swing tank heating capacity is sized to meet the recirculation loop load during periods without hot water input from the primary system. The minimum heating capacity for the swing tank, $\dot{Q}_{TM}$, is:

$$\dot{Q}_{TM} = SF * \dot{Q}_{loop}$$

Where SF is the user input for safety factor applied so that the swing tank heating capacity will exceed the temperature maintenance load. The resistance element in the swing tank is recommended to be sized to meet the 75th percentile of temperature maintenance loads. In a study of 45 multifamily buildings in CA, WA, and NY, the 75th percentile was approximately 1.75 times the expected input for the temperature maintenance load following the available data, which is used to set the default safety factor.

The swing tank gains energy from the primary system during DHW draws to meet a fraction of the temperature maintenance losses. In an ideal situation, the energy gained by the swing tank could coast through long periods of time, i.e. overnight, without using the resistance elements. For typical multifamily buildings with primary storage temperature at 150°F, the primary storage can supply up to 50W/Apt of heat to the swing tank on average. Since the industry has not prioritized reduction of distribution losses, the reality of most systems is that the temperature maintenance losses are greater than the energy gained in the swing tank from hot water draws.

To understand the effects of swing tank storage volume on energy use of the resistance element, we performed a simulation to model just the swing tank in the open-sourced HPWH simulation software used in CBECC-Res, HPWHsim[13]. In this analysis, we assume the primary system always supplies hot water at 150°F and vary the temperature maintenance load and the swing tank volume. More details of the simulation are available in Appendix B. The goal of modeling the systems is to develop simplified recommendations that can be used to size the system. The results of the study suggested that the sizing of the swing tank volume does not effectively reduce energy use at typical temperature maintenance values. If care is taken to reduce the temperature maintenance load below about 50 W/apt, a system can benefit from increased swing tank volume. An increased volume can store energy from peak hot water events for longer periods of time, allowing the swing tank to coast through periods of low hot water draws without using backup electric resistance elements.

CA Title 24 prescriptive sizing requirements for the swing tank volume were developed before this more thorough analysis was completed. Therefore, the Title24 prescriptive sizing requires tank sizes that are likely larger than necessary in most cases with high temperature maintenance loads[14]. In cases where

[13] https://github.com/EcotopeResearch/HPWHsim

[14] This is likely to change following future code development.

meeting the CA prescriptive sizing is not necessary, the sizing recommendations are in Table 3. The sizing of the swing tank was done to minimize the size of the tank and thus the cost of adopting this new technology.

Because the swing tank is in series with the primary system, the swing tank requires the size of the primary system be increased to account for the temperature maintenance load. To find the increase in the volume and heating capacity of the primary system, the swing tank is simulated by tracking changes in the tank temperature due to hot water draws and temperature maintenance losses, according to Appendix A.

In the simulation the resistance element is sized based on the user inputs for the recirculation loop losses and the temperature maintenance safety factor. The swing tank volume in the simulation is sized at the upper bounds of the recommended values. This represents a safety factor as the higher volume swing tank will have a smaller temperature change during the peak hot water draws and result in a greater daily hot water load on the primary system. Lastly, the simulation assumes the resistance element turns on at the supply temperature and has an 8°F dead band, which is typical of resistance hot water tanks.

Table 3. Recommend Swing Tank Volume for Multifamily Buildings following Ecosizer and CA Title 24

	Swing Tank Volume (Gallons)	
Number of Apartments	Ecosizer	Title 24
0 - 12	80	80
13 - 24	80	96
24 - 48	80	168
49 - 96	120 - 300	288
> 96	120 - 300	480

The simulation for the swing tank is run assuming a worst-case scenario, where the swing tank temperature is the coldest possible before the resistance elements turn on, which is when the largest demand on the primary system will occur. In this scenario, the swing tank is marginally above the supply temperature at the start of the peak hot water usage period, defined in the primary plant sizing section.

Example results of the swing tank simulation are shown in **Error! Reference source not found.**, for an e xample with 2000 gallons of hot water used per day, 6 kW of temperature maintenance losses, a supply temperature of 120°F, and a storage temperature of 150 °F. The blue bars are the hot water demand at the supply temperature which is the same curve as Figure 9; this is what occupants are using at the taps. The grey bars are the volume of hot water drawn from the swing tank and primary system at the swing tank temperature, calculated using a mixing ratio. The greater the swing tank temperature, the greater the percent difference is between the two bars.

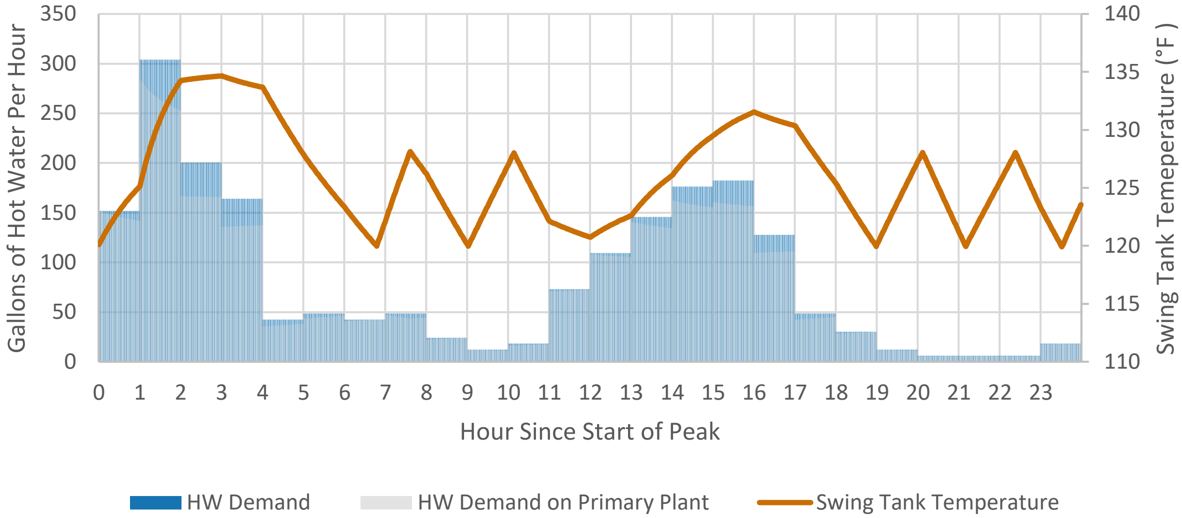

Figure 10. Swing tank simulation plot.

Cumulatively, for the 24 hours after the peak period, the HW demand on the primary plant is 86% of the total volume of daily hot water demand. This is relatively invariant, ±1%, to the initial conditions and reasonable changes to the volume of the swing tank.

Importantly for sizing the primary plant, the volume of hot water drawn from the primary plant to the swing tank is at the storage temperature, not the supply temperature. The sizing methodology for the primary plant with a swing tank factors this in by using the hot water demand on the primary plant in Figure 10 as the hot water load. The ratio between the total daily hot water demand, $V_{HW,Day}$, and the total daily hot water demand on the primary plant from the swing tank, $V_{HW,Swing}$, is found from:

$$f_{swing} = \frac{V_{HW,Swing}}{V_{HW,Day}}$$

This represents the average mixing ratio of hot water supplied by the swing tank for the peak day. The daily hot water demand on the primary plant is the volume of hot water that the primary plant must supply at the storage temperature to the swing tank.

Beyond the change in load calculation there are two important changes for sizing the primary plant:

1. This method accounts for the mixing of hot water down to the supply temperature. Thus, the storage volume is already sized at the storage temperature, so step 5 in the primary plant methodology is skipped.
2. The primary heating capacity is adjusted to meet the demand on the primary plant, $V_{HW,Swing}$ at the storage temperature:

$$\dot{Q}_{primary} = \rho c_p \frac{V_{HW,Swing}}{h_{max,hr}} (T_{storage} - T_{CW})$$

Parallel Loop Tank

A parallel loop tank sees only the constant temperature maintenance load. The design of a parallel loop tank system must balance the expected load with the volume of the loop tank and the capacity of the temperature maintenance heating system. Too little capacity will lead to cold water being circulated. Too large of a capacity could lead to short-cycling of equipment.

The first control on sizing the parallel loop tank is the minimum time the HPWH is expected to be off, t_{off}. This controls the loop tank volume, which is designed to cool off from the setpoint of the temperature maintenance HPWH to the minimum temperature in t_{off}. This is represented graphically for an example case in Figure 11, where, during the first time period t_{off} the tank loses energy equal to $N_{apt}\dot{Q}_{loop}t_{off}$. When the temperature change in the tank is known, the tank volume, V_{TM}, can be found from

$$V_{TM} = \frac{\dot{Q}_{loop}}{\rho c_p} * \frac{t_{off}}{T_{setpointTM} - T_{turnOn}}$$

Where ρ is the density of water, c_p is the heat capacity of water, $T_{setpointTM}$ is the temperature maintenance multi-pass HPWH setpoint, and T_{turnOn} is the temperature at which the multi-pass HPWH turns on.

The sizing of the heating capacity for a parallel loop tank follows that of the swing tank heating capacity, in that the heating capacity is designed to exceed the recirculation loop losses using the user input for the temperature maintenance safety factor. Again, the default temperature maintenance safety factor is 1.75.

$$\dot{Q}_{TM} = SF * \dot{Q}_{loop}$$

The expected runtime of the temperature maintenance multi-pass heat pump can be found from the volume and the heating capacity to ensure the system does not short cycle. The tool compares the expected runtime to a threshold of 20 minutes. The heat capacity for the temperature maintenance heat pump is equal to the energy that is added to the tank over the expected runtime, t_{run}, plus the continuous temperature maintenance load. This is shown graphically in **Error! Reference source not found.**, and can b e written as

$$\dot{Q}_{TM} = \frac{\rho c_p V_{TM}}{t_{run}}\left(T_{setpointTM} - T_{turnOn}\right) + \dot{Q}_{loop}$$

Then substituting in the equation for V_{TM} and $\dot{Q}_{TM}$:

$$SF * \dot{Q}_{loop} = \dot{Q}_{loop}\left(1 + \frac{t_{off}}{t_{run}}\right)$$

Lastly solving for t_{run}:

$$t_{run} = t_{off}/(SF - 1)$$

The Ecosizer checks that t_{run} meets a minimum runtime of 20 minutes to prevent short cycling the multi-pass HPWH.

Error! Reference source not found. gives an example operation where the temperature maintenance tank h as a setpoint of 135°F and a 10°F temperature lift. A typical operation for the temperature maintenance HPWH will run for 20 minutes then turn off for 20 minutes, and cycle repeatedly.

Note that due to the uncertainty in the distribution loss rate, it will often be advisable to size the temperature maintenance HPWH to cover a typical loss rate of about 100 Watts per apartment and then to include some electric resistance as back-up in case of higher than normal losses.

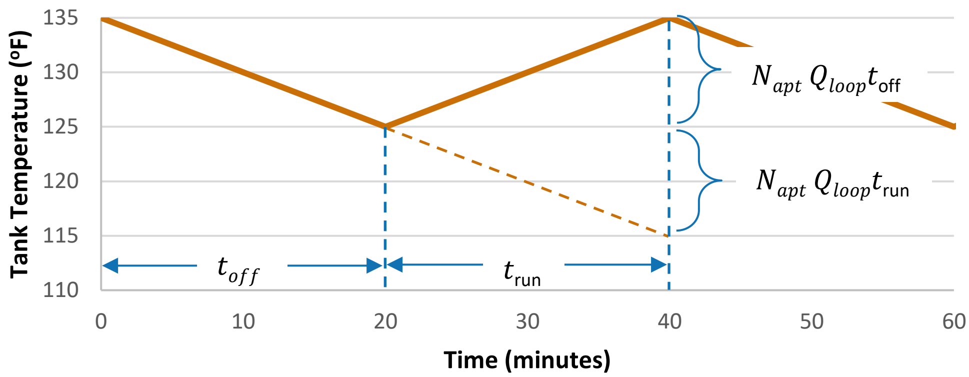

Figure 11. Parallel loop tank average temperature over time in orange.

Load Shift Sizing

The load shift module allows users to block out part of the day when the HPWHs may be prevented from running as a response to utility signals or to avoid peak electricity pricing periods. The storage volume and heating capacity necessary to meet the load may need to be increased depending on the time and extent of these peak power periods. The sizing methodology for load shift differs from non-load shift sizing in that the size of the system's storage volume is calculated as the hot water storage needed to avoid heating during the first shed period (the first period the HPWH is prevented from running) plus the storage needed to maintain DHW through subsequent usage peaks rather than sizing based on peak DHW usage. The storage needed to avoid heating during the first shed period, $V^0_{shed}(t)$, is given by

$$V^0_{shed}(t) = \int_{t_{shed\ start}}^{t_{shed\ end}} \dot{V}_{HW}(t')\,dt'$$

where $t_{shed\ start}$ is the start of the first shed period and $t_{shed\ end}$ is the end of the first shed period. One may notice that this equation is similar to the equation for finding $V^i_{supply}(t)$ in non-load shifting sizing scenarios detailed previously in *Sizing Methodology for Primary Plant*, however it does not account for the system's generation rate, $\dot{G}(t')$. This is because, during a shed period, the generation rate is assumed to be zero due to the fact the HPWH is prevented from running.

Sizing for load shifting can result significant increases in storage volume and/or heating capacity. To avoid overcompensating for days with abnormal load shapes, we employ a modifier for the percent of load shift captured. The user input for percent of load shift captured calculates a derated gallons per person per day according to a normal function fitted to the empirical cumulative density function given in Figure 3. Once $V^0_{shed}(t)$ has been found, the running volume is found as

$$V_{running,load\ shift} = CDF(P) * \left(V^0_{shed}(t) + \max\left(\int_{t_{shed\ end}}^{t} \left(\dot{V}_{HW}(t') - \dot{G}(t')\right) dt'\right)\right)$$

where CDF is the cumulative density function of the user defined percent of load shift covered, P, and $t \in \{ t_{shed\ end} + 1,\ t_{shed\ end} + 2, \ldots, 48\}$ to encompass any residual DHW deficit at the end of a day by extending the load shape $\dot{V}_{HW}(t')$ to a two-day period. The cumulative density function outputs a factor to represent the percentile of days that the system will successfully be able to load shift. For example, setting the parameter P in this equation equal to 0.8 means that the system will be able to load shift completely on an 80th percentile day and will perform a partial shed on days with higher demand.

When sizing a load shifted CHPWH plant the system is sized against both the load shift and the non-load shift scenarios, to ensure that the load shift scenario is the more conservative design compared to the non-load shift scenario. Once this and the running volume from a non-load shifting scenario for the system have been calculated, $V_{running,non\ load\ shift}$, the final system running volume is given as

$$V_{running} = \max\left(V_{running,non\ load\ shift}, V_{running,load\ shift}\right)$$

The load shape used for a load shifting scenario corresponds to the average load shape in Figure 5, resulting in a less conservative sizing estimate than the design day load shape used in the non load shifting scenario. For more of an explanation on this differing use of load shapes, see Appendix C.

For example, in a situation similar to the example worked in **Error! Reference source not found.** and **Error! Reference source not found.**, if a user sets the shed period to be between 5PM and 8PM, the assumption is that hot water generation rate goes to 0 during this time period, shown as the yellow line in **Error! Reference source not found.**.

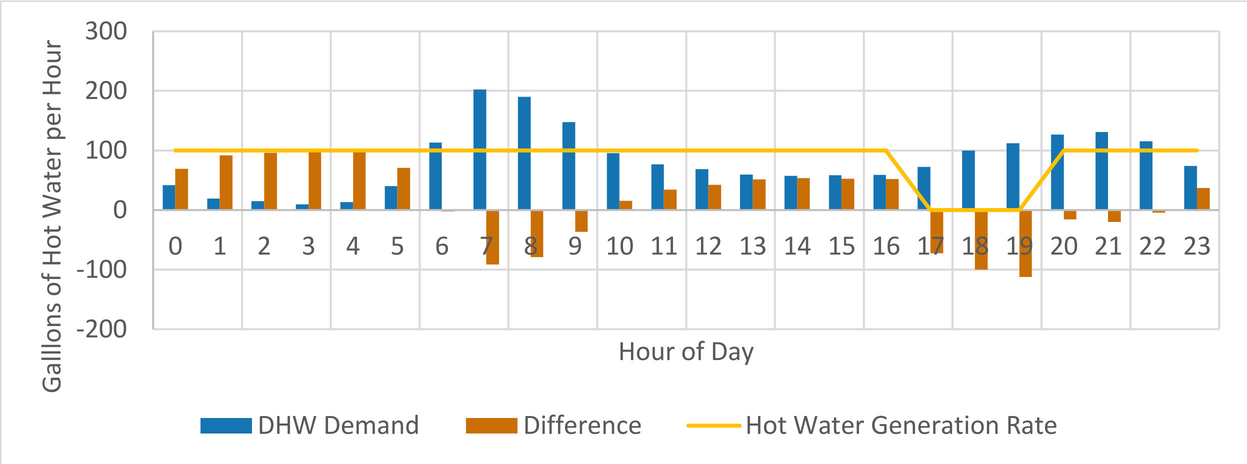

Figure 12. A load shift scenario where the systems is HPWH is excluded from 1700 to 2000.

Thereby, the running volume calculation for the load shifting scenario would be

$$V_{running,load\ shift} = CDF(P) * \left(\left(\int_{17}^{20} \left(\dot{V}_{HW}(t')\right) dt'\right) + \max\left(\int_{20}^{t} \left(\dot{V}_{HW}(t') - \dot{G}(t')\right) dt'\right)\right)$$

where $t \in \{21,22, \ldots ,47,48\}$. In this instance the load shift scenario needs a greater volume of storage than the non-load shifting scenario, which is sized by the 06:00 peak in Figure 12. However, cases with shorter load shifting periods may size the system smaller than the non-load shifting scenario. The methodology used here is to check both scenarios and return the larger running volume.

There are scenarios where increasing the hot water generation rate can reduce the primary storage volume. For example, in **Error! Reference source not found.**, if the hot water generation rate is increased t o 200 gallons of hot water per hour, the required load shifted storage volume would decrease because the DHW demand at 20:00 can be met. But the running volume during this load shift scenario cannot be less than the volume of DHW demand during the hours from 17:00 – 20:00.

A similar scenario occurs if two load shift periods were used. If the hot water generation rate were not large enough to fully recover the storage volume between the two periods, the running volume would have to store the storage volume from the first load shift period and some from the second. Again, increasing the hot water generation rate to a point where the tank could fully recover would decrease the storage volume.

When designing for load shift with a single default aquastat fraction of 0.40, the storage volume required for load shift will be unnecessarily large. Therefore, Ecosizer requires users to fill out the load shift controls tables which simulates changing aquastat fractions and setpoints. To optimize sizing when load shifting, multiple aquastat fractions must be employed; one for normal periods, one for shed periods, and one for load up periods (the hours leading up to a shed period, with the user specifying the number). When load shifting, users will input aquastat fractions for each of these phases. It's crucial to position the shed aquastat fraction higher in the tank than the normal aquastat fraction and the load up aquastat fraction lower in the tank than the normal aquastat fraction. This lower load up aquastat fraction ensures that the CHPWH system will frequently activate heating during a load up period to ensure the tank is full at the start of a shed period. As a result of the higher shed aquastat fraction, the tank will not begin heating until its hot water supply is nearly depleted.

For most cases, sizing for load shift will require an increase in primary storage volume over a non-load shift scenario. This is true even in cases with an increased storage temperature. The tool will not directly tell users what temperature to increase their storage volume to for load shifting through their input periods, but users can increase the storage temperature to see the decrease in storage volume for their load shift scenario. Additionally, users may specify a temperature setpoint for the stored water to be higher to during a load up period. However, not all HPWHs are capable of setpoint adjustments and designers should confirm with venders the products capabilities. The default for the load up setpoint is the normal/standard setpoint plus 10 degrees Fahrenheit, however, it can be set higher or lower at the user's discretion. Users should note that not all HPWH systems, accommodate such increases in setpoint, so it is necessary to consult your HPWH specifications before proceeding with elevated load up temperatures.

If users are interested in finding out how much load shift can be achieved with a non-load shift sized system and an increased primary storage temperature setting, users will have to first find out how big their storage volume is for the non-load shift scenario with a low storage temperature. Noting the primary system size for the non-load shift case, users can set their load shift hours and elevated storage temperature, then iteratively adjust the user input for percent of load shift captured to find the effectiveness of their non-load shifted system.

Temperature Maintenance Load Shift

The Ecosizer tool allows for load shifting of the parallel loop tank, but the swing tank design is inherently load shift capable during periods of high DHW demand compared to the temperature maintenance load. See the swing tank temperatures in **Error! Reference source not found.**. In practice, to accomplish load s hift of the swing tank, it should be heated above setpoint by the electrical resistance elements prior to the load shift period.

Users interested in load shifting a parallel loop tank can increase the number of hours the multi-pass HPWH is turned off. The results will end up increasing the required volume and the heating capacity. The expected run time could be set to the expected time between a load shifting signal and the load shifted period.

Electric Resistance Trade-Off Sizing

Due to the cost of CHPWH capacity, especially in cold temperature climates where wintertime system efficiencies are lower, it may be cost-effective to use a CHPWH that is undersized for a building and supplement the system with an electric resistance (ER) swing tank with additional capacity to compensate for when the CHPWH cannot provide the DHW demand on its own. For designers who choose to use this type of system, we have developed an ER trade-off sizing method.

To determine the amount of electric resistance needed to supplement a system, it is assumed that we know the storage volume at storage temperature, $V_{total,T_{storage}}$, and heating capacity of the undersized primary CHPWH (in BTU/hr), $\dot{Q}_{primary}$, as well as the volume (in Gallons), V_{TM}, and capacity (in BTU/hr), $\dot{Q}_{TM}$, of the swing tank that has already been sized adequately for the recirculation losses in the building but not for compensating for the CHPWH. Once these parameters have been provided, we can calculate the ER heating capacity required for the swing tank to compensate for the undersized CHPWH.

To start, we run two simulations, detailed in the Swing Tank section in Appendix A, of the undersized CHPWH system for a 2-day period. The first simulation assumes the storage tank full of storage temperature; the other simulation assumes the storage tank is full of cold water. The two simultaneous simulations, with a full and empty storage tank, ensure both extreme cases are covered.

The simulations use a one-minute time interval, t, and calculate the hot water draw from the swing tank, $\dot{V}_{draw,T_{swing}}(t)$, such that it depletes the stored gallons of storage temperature water in the primary storage tank, $V_{primary,T_{storage}}(t)$, and pulls in a mixture of storage temperature ($T_{storage}$) and cold (T_{CW}) water that lowers the swing tank temperature below the building's supply temperature (T_{supply}). From there, we calculate the temperature deficit, $T_{deficit}(t)$, or amount the temperature of water delivered to the building dips below supply temperature at time t as

$$T_{deficit}(t) = T_{supply} - \frac{\left(T_{swing}(t) * \left(V_{TM} - \dot{V}_{draw,T_{swing}}(t)\right) + T_{entering}\left(\dot{V}_{draw,T_{swing}}(t)\right)\right)}{V_{TM}}$$

Negative values of $T_{deficit}$ indicate that the primary system is meeting the building demand; positive values of $T_{deficit}$ are used to add to the ER swing tank size. In the equation above, the temperature of water entering the swing tank from the primary system is

$$T_{entering} = \frac{T_{storage} * \left(V_{available,T_{storage}}(t)\right) + T_{CW} * \left(V_{primary}(t) - \dot{V}_{available,T_{storage}}(t)\right)}{V_{primary}(t)}$$

$T_{TM}(t)$ is the temperature of the swing tank after accounting for swing tank heating and recirculation loss in the time interval, $V_{HW}(t)$ is the DHW demand at supply temperature, $V_{available,T_{storage}}(t)$ is the volume of available storage temperature water in the primary system at the time interval, and T_{supply} and T_{CW} are the supply and coldest city water temperatures respectively. We then find the electric resistance capacity for the swing tank required to compensate for the undersized HPWH as

$$\dot{Q}_{TM,new} = \dot{Q}_{TM} + 60minutes * max\left(T_{deficit}(t)\right) * \rho c_p * V_{TM} * SF_{TM}$$

Where t is any one-minute time step where $V_{available,T_{storage}}(t) < \dot{V}_{draw,T_{swing}}(t)$ and SF_{TM} is the user input safety factor for additional electric resistance sizing. The $\dot{Q}_{TM,new}$ is the maximum calculated from both simulations.

5. FUTURE MODULES

The Ecosizer CHPWH sizing tool is needed to support designers to incorporate CHPWHs in a way that helps ensure optimally sized systems. To help the industry in this transition, this sizing tool should be combined with an annual performance model so that designers can see the energy use impacts of the range of possible design choices. The annual performance model would be based around typical use conditions as opposed to the peak design conditions used in the sizing tool. The tool would use the premier open-sourced HPWH simulation software used in CBECC-Res, HPWHsim[15], and would be based on:

- Location-based weather from TMY3 files, including a model for predicting entering water temperature.
- Equipment specific sizing for specific manufacturers (i.e. 15-ton stages), using performance maps for specific equipment to calculate design temperature minimum output capacity. These performance maps have been collected for a wide range of CHPWH equipment by the CEC for use in the CBECC-Res software.
- Adding Multi-Pass Return to Primary and Single-Pass Return to Primary to the Ecosizer web page.

[15] https://github.com/EcotopeResearch/HPWHsim

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APPENDIX A – SIMPLIFIED SIMULATION

The simulation plots used in the Ecosizer tool were provided to instill confidence in the method and help users understand the methodology. The simulation is run for three days, with minute timesteps, to initialize the CHPWH system but only the last day is provided for the user in the Ecosizer.

Primary Plant

The simulation of the primary system works by tracking the volume of hot water remaining in the primary system. This assumes the system is perfectly stratified and all the hot water above the cold temperature line is at the storage temperature, this also ignores thermal losses to the environment. The simulation balances the hot water demand according to the hot water load shape and the volume added according to the calculated hot water generation rate from the recommend compressor runtime of 16 hours a day. This is:

$$V_{primary,T_{storage}}(t+1) - V_{primary,T_{storage}}(t) = \Delta t \left(\dot{G}_{T_{storage}}(t) - \dot{V}_{draw,T_{storage}}(t) \right)$$

Where $V_{primary,T_{storage}}$ is the effective storage volume, Δt is the time step of one minute, $\dot{G}_{T_{storage}}(t)$ is the time variant hot water generation rate for water at the storage temperature, and $\dot{V}_{draw,T_{storage}}$ is the hot water demand rate at the storage temperature. The hot water demand rate is assumed to be constant across every hour, an assumption that is acceptable for demonstration purposes but not for evaluating an annual energy estimate where real hot water draws are necessary. The demand on the primary system is mixed down from the storage temperature to the supply temperature.

During each time step of one minute, the simulation evaluates if the system is heating or should be heating based on the user input for the aquastat fraction. If it is, the hot water level is adjusted by the difference between the hot water generation rate and the hot water demand rate. If not, heating the hot water level is decreased by the hot water demand rate. Conveniently, the hot water generation rate is assumed to be constant so the simulation will check if the heating condition happens during in the middle of a minute or if the volume at the end of a timestep exceeds the total storage volume, and adjust the time hot water is generated to a fraction of minute.

Swing Tank

Since the swing tank is in series with the primary system, the temperature needs to be tracked to inform inputs for primary step, unlike the parallel loop tank which is separated from the primary system, see Figure 1 and Figure 2. The simulation on the swing tank tracks the average temperature of the swing tank every minute, assuming the swing tank is well mixed. Any hot water demand from the swing tank is mixed at the swing tank temperature and the volume removed from the swing tank is replaced from hot water from the primary system.

The change in temperature is contributed to by three factors: the recirculation loop losses, the heating of the resistance elements, and the contribution of hot water from the primary system. The change in temperature of the swing tank, $T_{swing}(t)$, from one time t to time $t + \Delta t$, can be found from a sum of these heat sources, $\dot{Q}_i(t)$:

$$T_{swing}(t+\Delta t) - T_{swing}(t) = \frac{\Delta t}{\rho c_p V_{TM}} \sum_i \dot{Q}_i(t)$$

The simulation assumes the recirculation loop losses are a constant wattage loss given the user input; then the change in swing tank temperature from one timestep to the next is also a constant. The total recirculation loop losses can then simply be written by:

$$\dot{Q}_{total\ loop}(t) = N_{apt}\dot{Q}_{loop}$$

The resistance heating element is also a constant heat source if the elements are running. The size of the elements is calculated from:

$$\dot{Q}_{TM}(t) = SFN_{apt}\dot{Q}_{loop}$$

The last source of heat in the swing tank comes from the primary system during hot water draws. During draws, it is assumed the swing tank outlet is mixed with the cold incoming water, and the mixed down draw is replaced with water from the primary system. The change in energy can be described as the difference between the energy in and energy out:

$$\dot{Q}_{Primary}(t) = \rho c_p V_{mixed}(t)\big(T_{storage} - T_{CW}\big) - \rho c_p \dot{V}_{draw,T_{swing}}(t)\big(T_{swing}(t) - T_{CW}\big)$$

$$\dot{Q}_{Primary}(t) = \rho c_p \dot{V}_{draw,T_{swing}}(t)\big(T_{storage} - T_{swing}(t)\big)$$

Where $\dot{V}_{draw,T_{swing}}$ is the hot water draw, $\dot{V}_{draw,T_{supply}}$, mixed down from the supply temperature to the swing tank temperature found from:

$$\dot{V}_{draw,T_{swing}}(t) = \frac{T_{supply} - T_{CW}}{T_{swing}(t) - T_{CW}} \dot{V}_{draw,T_{supply}}(t)$$

The mixed hot water draw is important for finding what the total demand is on the primary system and as such the system sizing.

Each timestep, these three heat sources are summed together to find the swing tank temperature for the next timestep. Like with the primary system simulation, the swing tank simulation also checks if the heating elements should be turned on or off at the sub-minute level.

Electric Resistance Trade-Off Swing Tank

Simulating a swing tank sized for ER trade-off is slightly different than simulating the system normally as described in the section above. The main difference is that, since at some points during the simulation the primary system may be low on or out of hot water, the simulation may rely entirely on the swing tank to deliver DHW to residents of the building. Therefore, it cannot always be assumed that the swing tank is receiving storage temperature water, but rather the swing tank may receive a mixture of storage and city water temperature water when it draws from the primary storage. The temperature of the entering water to the swing tank from the primary CHPWH can be found as

$$T_{entering}(t) = \min\left(\frac{V_{primary,T_{storage}}(t)}{\dot{V}_{draw,T_{swing}}(t)}, 1\right) T_{storage} + \max\left(\frac{\dot{V}_{draw,T_{swing}}(t) - V_{primary,T_{storage}}(t)}{\dot{V}_{draw,T_{swing}}(t)}, 0\right) T_{CW}$$

Where $V_{primary,T_{storage}}(t)$ is the total amount of storage temperature water that can be pumped out of the primary system at time step t.

APPENDIX B – SWING TANK SIMULATION

To develop rules around the appropriate storage volume for a swing tank, we performed a simplified model of a swing tank using the open-sourced HPWH simulation tool, HPWHsim[16], which is used in Title 24 CBECC-Res compliance software. The simulation uses minute-long timesteps to track temperatures and heat flows with a HPWH or electrical resistance tank. The inclusion of HPWHsim for this study, is to simulate a swing tank for a year to make annual estimates of energy use in the swing tank and to determine how much of the temperature maintenance load is covered by the swing tank versus the primary system.

The parameter space for modeling a HPWH system is vast. Here we can only test a limited number of inputs due to computational and time constraints. We reduce the varied input parameters to:

- The temperature maintenance load, ranging from 25 W/apt to 200 W/apt, for a building with 118 apartment units.
- The swing tank electric resistance elements were controlled to be 1.5 times the temperature maintenance load.
- The swing tank storage volume, ranging from 80 Gallons to 700 Gallons.
- The annual hot water draws, which was taken from a year of data from a building with 118 apartment units monitored at 10-minute intervals. We assume the hot water draws are averaged across each 10-minute period. This also included data for the cold incoming water supply.

Input parameters that were kept constant across all model runs are:

- The primary storage temperature, at 150°F, which implies that the primary HPWH system can always meet the load.
- The hot water supply temperature was kept constant at 120°F.
- The recirculation pump flow rate was kept constant, which means the hot water recirculation return temperature was calculated from the recirculation loop losses.
- The air temperature around the tank is assumed to be a constant 70°F, which controls the small UA heat losses from the swing tank.

The mixing valve is an important piece of the model because it controls the volume of water removed from the swing tank. During a hot water draw for recirculation, the water from the swing tank is mixed down with the water from the recirculation loop return. This action mixes hot water from the swing tank with warm water (~115°F). As a result, to reach the supply temperature, only a small fraction of the volume comes from the swing tank. On the other hand, DHW drawn by occupants at the tap introduces cold water to the system. At the mixing valve, DHW draws are mixed with swing tank water and the cold-water temperature and thus requires much larger volume to be taken from the swing tank to meet the supply temperature. This action also draws water from the primary system and heats up the swing tank. During this simulation we also assume the swing tank is well mixed during every time step.

The results of the model runs are shown in **Error! Reference source not found.**, where annual resistance e lement energy use in the swing tank is plotted against swing volume for different temperature

[16] https://github.com/EcotopeResearch/HPWHsim

maintenance loads. As expected, increasing the temperature maintenance load increases the annual resistance energy use. Surprisingly though, increasing swing tank volume has a small effect on the annual energy use at higher (>100 W/apt) temperature maintenance loads. This is attributable to the dominance of the constant temperature maintenance load.

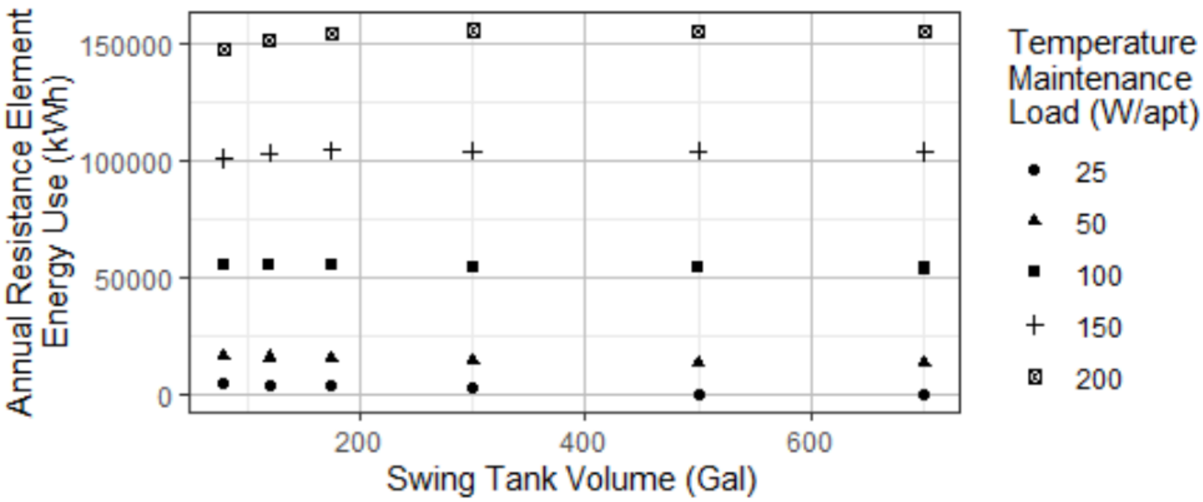

Figure 13. Annual energy use in the swing tank with swing tank volume for different temperature maintenance loads.

For the hot water draws to match the energy lost due to temperature maintenance load at any hour, the hourly hot water draw can be found from:

$$N_{apt}\dot{Q}_{loop} = \rho c_p \, f_{draw}(T_{primary} - T_{supply})$$

$$f_{draw} = \frac{N_{apt}\dot{Q}_{loop}}{\rho c_p(T_{primary} - T_{supply})}$$

For this case, assuming 100 W/apt, we can then calculate the draw per person:

$$f_{draw} = \frac{118[\text{apt}]}{140[people]} * 100\left[\frac{W}{apt}\right] * 3.412\left[\frac{BTU}{hr}\right] / \,(\,8.314\,[\text{lb/gal}]\, * \,1\,[\text{Btu/lb} - {}^\circ\text{F}] \\ * \,(150\,[{}^\circ\text{F}] - \,120\,[{}^\circ\text{F}])$$

$$f_{draw} = 1.15 \text{ gphpp}$$

The data shown in Figure 5 suggests this only occurs for 1 hour of the day during the morning peak on average. For most hours of the year, the temperature maintenance heat losses are dominating the system, meaning the tank rarely has a chance to increase its stored energy and coast through periods of low use and the swing tank serves as a resistance water heater for most of the year. Comparatively, if the system has a reduced temperature maintenance load of 50 W/apt, $f_{draw} = 0.574$ gphpp, which is well below the morning and evening peak on average in Figure 5. Following this logic, buildings that have more diversity of DHW draws may have a higher average draw and see less resistance element use in the swing tank.

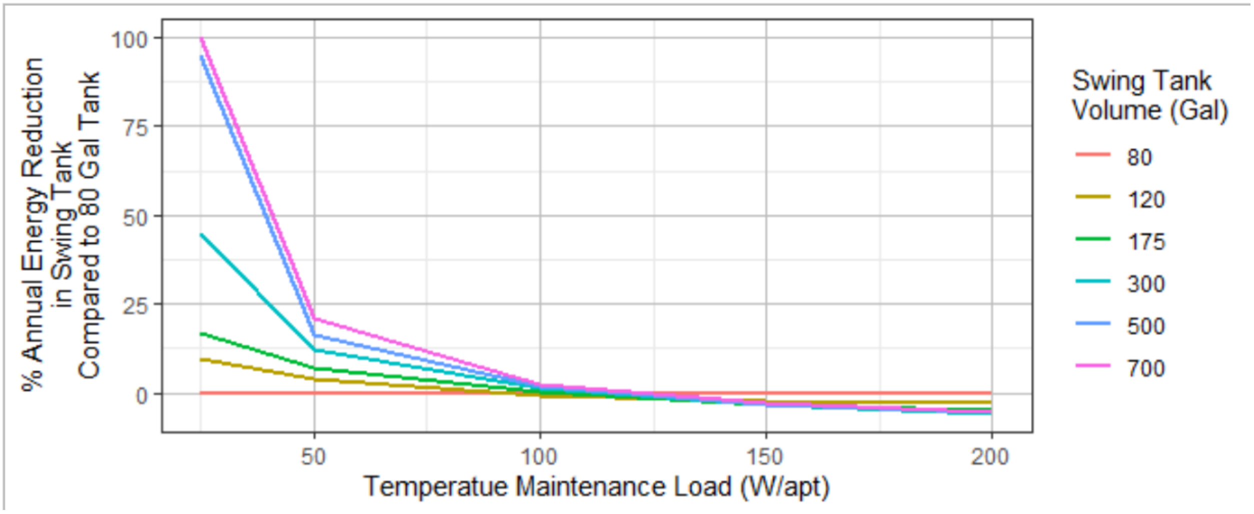

Figure 14. Percent of energy reduction in swing tank from increasing the tank volume above 80 gallons as a function of the temperature maintenance load (For a building with 118 dwelling units).

If the swing tank cannot store hot water to make it through periods of low DHW demand relative to the temperature maintenance load, increases in the swing tank volume cannot save energy. This is shown in **Error! Reference source not found.**, where the annual resistance element energy use is shown as a p ercent savings of an 80-gallon swing tank with varying temperature maintenance loads. At a temperature maintenance load of 100 W/apt, increasing the volume of the swing tank from 80 to 700 gallons only reduces annual energy use 2.6%. However, at a temperature maintenance load of 50 W/apt, this same increase in tank volume sees a 21% energy savings, and at 25 W/apt a 700-gallon tank reduces the annual resistance element energy use to 0 kWh.

A priori, the best estimate for the temperature maintenance load is 100 W/apt, where increases in tank size see a minimal energy savings. Consequently, our recommendation for sizing the swing tank volume would be getting a minimally sized tank that can handle the peak flows. Recommended tank sizes are given in Table 3 by number of apartment units. If designers are able to push for a reduction in recirculation losses through use of insulated pipe hangers or other measures, there are benefits to increasing the swing tank volume. A 300-gallon swing tank could reduce energy use by the resistance elements by 12% over an 80-gallon swing tank.

The swing tank does not cover the entire temperature maintenance load. In an ideal design with a low temperature maintenance load, the primary system will cover the load; but in most use cases the primary system will only cover a fraction. In the simulation we know exactly what the temperature maintenance load is and how much energy is created by the resistance elements to cover this load. The difference between these loads is the energy added by the primary system to cover the temperature maintenance load.

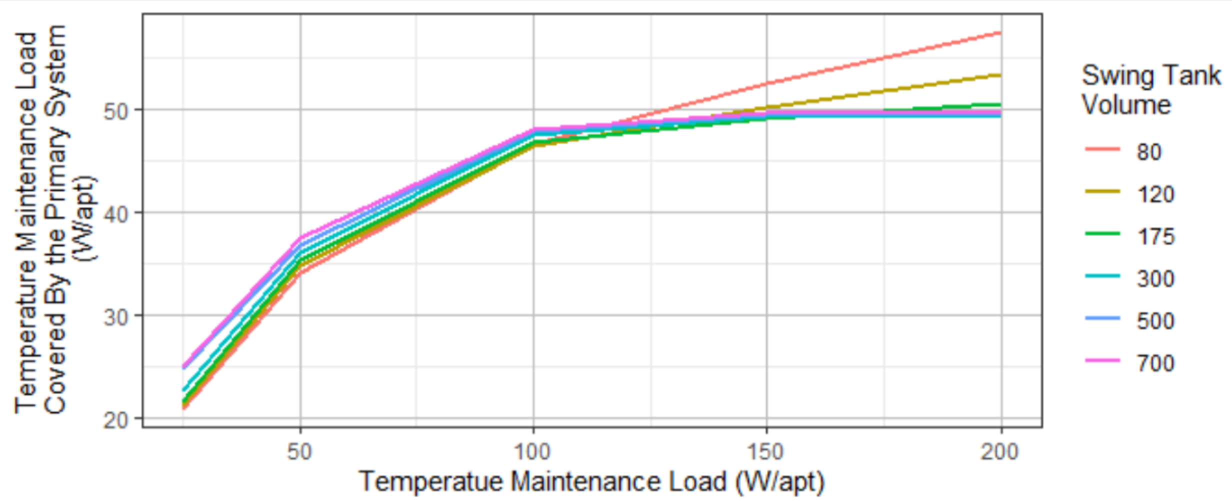

Figure 15. Annual temperature maintenance load covered by the primary system for the modeled temperature maintenance loads.

Error! Reference source not found. shows the annual average of the temperature maintenance load c overed by the primary system in watts per apartment. The figure shows an asymptotic approach towards 50 W/apt; however, the temperature maintenance load covered by the primary system could likely be greater than this for different draw profiles or greater temperature maintenance loads, with the latter being strongly discouraged.

Overall difficulty in sizing the swing tank comes from being able to predict the temperature maintenance load. More research should be done in this field to constrain the problem. More research also needs to be done on sizing of swing tanks, which should include variation in hot water draws, resistance element sizing, and primary setpoint.

APPENDIX C – LOAD SHIFT UPDATE

The Ecosizer originally used overly conservative methods for load shift sizing. The analysis reported in Appendix B used a modified load shape to represent a more typical day instead of a day with unusually heavy use in the mornings and evenings. This resulted in a 400-gallon reduction when providing morning load shifting for 150 apartments corresponding to about a $10,000 cost reduction. Ecotope has determined the new methodology will provide sufficient sizing at a reduced cost.

When sizing a system to ensure tenants will always have hot water, it is important to size conservatively. However, thermal storage can be costly, and having a sizing methodology that is too conservative may lead projects to install unnecessarily large and expensive thermal storage systems. Additionally, the increased size may cause building owners to choose not to design for load shifting or avoid load shifting all together.

In the Ecosizer, two inputs are used to size a system: (1) an hourly load shape and (2) daily total usage in gallons. The hourly load shape is used to account for variation in hot water usage throughout the day. The more peaky the shape, meaning more water used during peak usage hours, the more thermal storage is needed to consistently provide hot water to the building. When sizing a system, to be conservative, the most peaky load shape is used coincidently with the highest volume day. This design point is referred to as the sizing design day.

Originally, the Ecosizer used the sizing design day for sizing load shifting as well. Users are given the option to adjust a slider for "Percent of Load Shift Captured". However, the slider only adjusts for design day water usage volume and does not adjust load shape. Ecotope's analysis of metered data found that there is significant difference between load shapes for the design day and average day. The most peaky and average load shapes are shown in Figure 5.

To reduce oversizing for load shift, the average load shape is used instead of the most peaky load shape. This design point is called the load shift design day.

APPENDIX D – PERFORMANCE MAPS

In some of the tools available on the Ecosizer website, including the "TECH-HPWH Calculator", the input and output heating capacity of the primary system (and additionally the heating capacity of the temperature maintenance system in the case of parallel loop tanks) can be determined by the HPWH make and model along with the outdoor air temperature, inlet water temperature, and storage temperature. Using simulated and lab tested performance maps provided to Ecotope by various HPWH manufacturers, Ecosizer uses the LinearNDInterpolator function from the SciPy library (https://scipy.org/) to create a linear interpolation to map combinations of outdoor air temperature, inlet water temperature, and storage temperature to input and output heating capacities for each model. We then multiply these capacities by the number of heat pumps present in the primary system to get the final input and output capacities for the system at the provided temperatures.

Because of the limitations of the performance maps provided by manufacturers, Ecosizer's tools do have to maintain logic around various edge cases. The edge case logic for performance maps is described in the points below:

- If the outdoor air temperature is lower than the lowest outdoor air temperature in the performance map for the model, it is assumed that the HPWH cannot function at the cold temperature and an electric resistance element is applied to heat the water at this period. The default heating capacity of the electric resistance is equivalent to the required heating capacity for the building as sized by the Ecosizer sizing tool.
- If the outdoor air temperature is higher than the highest outdoor air temperature in the performance map, Ecosizer uses a default input and output heating capacity that is conservatively set to be the input and output heating capacity with the lowest COP value at the highest outdoor air temperature available in the model's performance map.
- In the case that outdoor air temperature is within the range of the model's performance map, yet the inlet water temperature lower than what is available in the performance map, the inlet water temperature is raised to the closest inlet water temperature within the performance map. Since raised inlet water temperatures decrease the performance of the heat pump, this is a conservative estimate. If the inlet water temperature is higher than possible values in the performance map, the highest inlet water temperature in the performance map is used.
- If the storage temperature is higher than the highest available storage temperature for the outdoor air temperature and inlet water temperature in the performance map, the storage temperature will be automatically lowered to the highest storage temperature available. For

the period, the input and output capacity will be adjusted to reflect this lowering of the storage temperature. The adjusted output capacity, $\dot{Q}_{primary,adjusted}$, is detailed below:

$$\dot{Q}_{primary,adjusted} = \dot{Q}_{primary} \frac{T_{storage,user\ input} - T_{storage,performance\ map}}{T_{storage,user\ input} - T_{CW}}$$

Where $\dot{Q}_{primary}$ is the output capacity calculated by the performance map at the input outdoor air temperature, inlet water temperature (T_{CW}), and highest available storage temperature in the performance map at those temperatures ($T_{storage,performance\ map}$). $T_{storage,user\ input}$ is the user input storage temperature the DHW is assumed to be stored at in the Ecosizer calculation. Input capacity is adjusted in the same way should the storage temperature need to be lowered to fit the performance map.

For the TECH-HPWH calculation, an error indicating the need to lower the storage temperature of the system will be returned to the user if the input storage temperature is too high for the fifth percentile outdoor air temperature for the climate zone of the zip code they provided.

APPENDIX E – UTILITY CALCULATION

The Ecosizer Utility Calculation page estimates annual utility costs for the distribution of domestic hot water in a building and compares it to the annual utility cost of using unitary electric resistance water heaters. To calculate utility costs, users will need to input several values regarding their utility billing: on and off-peak demand charges and hours, on and off-peak energy charges and hours, and base utility charges for each billing period of the year. Once all these have been input, an annual simulation is run on the system to determine its energy input at every 15-minute interval of the year, then the utility cost, C_i, for each billing period, i, in the year is estimated as

$$C_i = sum\left(E_{system,input}(t) * C_e(t)\right) + max\left(\dot{Q}_{system,input}(t_p) * C_p + \dot{Q}_{system,input}(t_o) * C_o\right)$$

Where $E_{system,input}(t)$ is the energy use in kWh during the interval t, $C_e(t)$ is the energy cost during that interval, $\dot{Q}_{system,input}(t)$ is the input power of the system in kW during each interval, C_p is the demand charge in a peak period, and C_o is the demand charge in an off-peak period. $t \in \{0, 1, \dots, x-1, x\}$ where x is the last 15-minute interval of the billing period and t_p is all values of t that are in a peak period while t_o is all values of t that are not in a peak period.

Finally, annual utility bills are estimated as $C_{annual} = sum(C_i)$. This estimating tool may help designers with potential trade-offs between various components of a CHPWH system. This module is still in development and should not be relied on to guarantee utility costs for CHPWH system.