Ecosizer – Central Heat Pump Water Heating Sizing Tool

ECOTOPE

Manual

Prepared for:

Charles Kim, Southern California Edison

Alex Chase, 2050 Partners

Yanda Zhang, ZYD Energy

Brett Korven, Sacramento Municipal Utility District

Prepared by:

Ecotope: Paul Kintner, Adria Banks, Scott Spielman, Colin Grist, Jonathan Heller

October 1, 2020

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1. INTRODUCTION

This report details the need and methodology for a best-practice sizing tool for central heat pump water heater systems (CHPWH) in multifamily buildings. This will be a generic sizing tool that gives basic sizing information for any piece of equipment with a known heating output capacity. The tool is called the Ecosizer.

Overall, the Ecosizer will assist designers to optimize the selection of heat pump water heating (HPWH) equipment and hot water storage volume for multifamily buildings. This tool is intended to support the market for CHPWHs and the following goals:

- to rapidly increase the adoption of this technology
- to reduce the perceived risk of this new technology
- to reduce maintenance issues
- and to reduce system cost by standardizing and simplifying the approach

Existing common water heater sizing methodologies for central water heating equipment tend to be very conservative and favor quick recovery capacity over large storage volumes. These approaches can deliver reliable and cost-effective gas water heating systems, but if CHPWH systems are sized in the same way they often result in very expensive, and sometimes unreliable, systems. In general, sizing for CHPWHs should take a different approach, which utilizes large storage volumes to provide for peak hot water demand periods and smaller output capacity, which results in long, slow recovery periods with compressors operating up to 16-20 hours per day. These systems will be the most cost effective and result in fewer maintenance issues.

CHPWH systems following this sizing strategy to minimize heating capacity are already in use in multifamily buildings. In 2018 Ecotope completed the design of a central Sanden CO2 HPWH system as a retrofit DHW system in a 60-unit low income multifamily building. Both the existing electric resistance water heating system and the retrofit heat pump water heating system were monitored to quantify how well the heat pump water heating system functioned. That retrofit resulted in a 63% reduction in energy needed for the domestic hot water system[1].

The case study also demonstrated that an extremely small amount of heat pump capacity, coupled with a relatively large amount of storage volume, can provide reliable hot water for a multifamily building. At the case study noted above, 60 people were supplied with hot water with only the equivalent of 20kW of heat pump capacity. This is much less capacity than has traditionally been provided in the marketplace when sizing gas or resistance water heating equipment. The building was previously served by 120kW of

[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

electric resistance heating capacity. Therefore, to drive the price of these systems down to make them cost effective, the marketplace needs support in the form of a sizing tool that will enable confident sizing of smaller systems to serve the load.

This report is laid out as follows: Section 2 provides brief insight into HPWH and why HPWH systems need specialized design. Section 3 details how the specialized design of HPWH systems accounts for the temperature maintenance load. Section 4 provides 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

The heat pump equipment currently directly addressed by this tool employ “Single-Pass” heat exchangers, as opposed to the “Multi-Pass” approach employed in most hydronic space heating applications. This means that the flow of water through the heat pump is regulated to maintain a constant target output temperature. Most single-pass heat pumps can output hot water at the target setpoint of 135-160°F with incoming water temperatures ranging from 40-110°F. The advantage of the “Single Pass” arrangement is that a usable water temperature is always delivered to the top of the storage reservoir.

Most refrigeration cycles used in HPWHs do not operate well at warm incoming water temperatures (above approximately 110°F). Building hot water circulation pumps provide hot water throughout the distribution system, with typical supply water at 120-125°F and return water at 105-115°F. In DHW systems based around fossil gas or electric resistance, this warm water can go directly back to the primary storage tanks or primary heaters. A critical design feature of CHPWH systems with hot water circulation systems is to separate these two distinct building DHW loads: primary water heating and temperature maintenance. In doing so the DHW system design can prioritize delivering cool water to the HPWHs for peak performance while maintaining thermal stratification in the primary tanks. This results in optimal equipment efficiency, less cycling of the heating equipment, and better reliability of the system.

3. TEMPERATURE MAINTENANCE SYSTEM OVERVIEW

Single-pass HPWHs provide high-efficiency performance but cannot be used to heat warm water returning from recirculation systems. A key innovation that can be implemented to overcome this limitation of single-pass HPWHs is to use a temperature maintenance system separated from the thermally stratified primary storage volume. A temperature maintenance system consists of a recirculation pump, a storage tank (the “loop tank”), and a temperature maintenance heat source. (The Ecosizer considers two characteristically different types of temperature maintenance systems: “swing tank” design uses a loop tank piped in series with the primary storage (**Figure 1**) and parallel loop tank design uses a loop tank piped in parallel with the primary storage (**Figure 2**).

Important design commonalities between the two types of temperature maintenance system are:

- Multiple Storage Tanks: The primary storage volume may be provided with one large vertical storage tank or multiple smaller tanks.

- High Primary Storage Tank Temperature: HPWHs can heat water to a relatively high temperature (135-160°F). Doing so increases the effective stored hot water volume of the plant and mitigates legionella related risks. It also supports the ability of the primary heat pump plant to offset temperature maintenance heat losses.
- Thermostatic Mixing Valve: To prevent scalding, outgoing water shall be tempered with recirculation return water and incoming city water down to approximately 120°F before delivery to the occupants. A high-quality electronic mixing valve is recommended. The distribution system return water should be piped to the mixing valve and the temperature maintenance tank.

Swing Tank

In the swing tank approach, the primary system uses a temperature setting in the range of 140-160°F, which is higher than the water temperature supplied to occupants. The temperature maintenance system is in series with the primary storage such that the high temperature water from the primary system is supplied to the bottom of the temperature maintenance tank, or swing tank. A backup electric water heater is necessary in the temperature maintenance tank to account for the temperature maintenance load during periods of low DHW demand. The backup electric heater is controlled to keep the temperature maintenance tank from dropping below the supply water temperature.

During a DHW draw event, water is supplied from the swing tank to the thermostatic mixing valve to mix with warm return water from the hot water distribution system. The water volume removed from the swing tank is replaced by hot water from the primary system, effectively using the primary DHW system to heat the temperature maintenance system. The temperature in the temperature maintenance tank then "swings" between the supply water temperature and the setpoint of the primary HPWHs to reduce the use of the resistance element.

Piping the output of the primary storage to the bottom of the swing tank is to ensure complete mixing of the swing tank. When the swing tank is fully mixed, the outlet temperature of the tank will be lower than if it was stratified. When mixed, any given hot water draw at the taps removes a greater volume from the swing tank and more energy is added to the swing tank from the primary system, making the swing tank concept more effective. This swing tank approach works well in buildings with efficient distribution piping designs and well-insulated distribution systems that keep temperature maintenance losses low, and in buildings that utilize CHPWH equipment which is able to produce relatively high temperature water (>150°F) at relatively high efficiencies, such as CO_2 HPWH equipment.

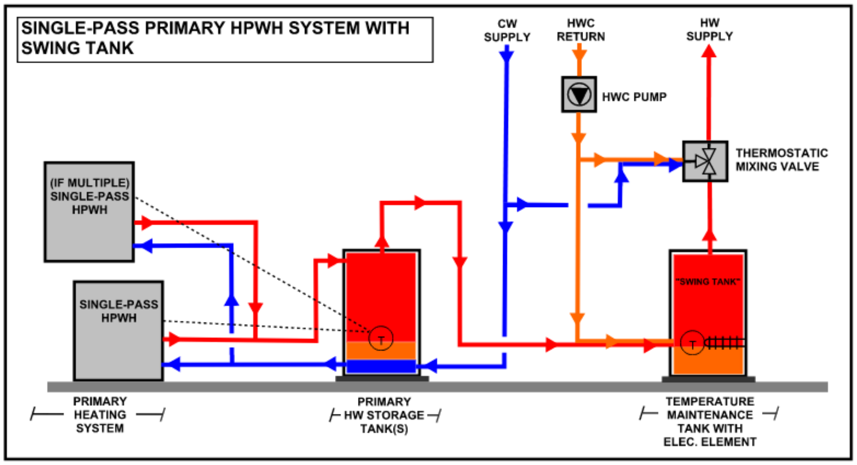

Figure 1. Example of centralized domestic hot water HPWH plant with a swing tank.

Parallel Loop Tank

The parallel loop tank approach completely removes the temperature maintenance load from the primary system by piping the primary system directly to the mixing valve and bringing the recirculation return to the bottom of the temperature maintenance tank, which is plumbed in parallel with the primary storage. This parallel loop tank is then heated with an electric resistance element, or ideally with a separate multi-pass HPWH. For optimal multi-pass HPWH operation, the parallel loop tank should be maintained to have as much thermal stratification as possible. During operation, the multi-pass HPWH raises the tank temperature 5-10°F to account for the temperature maintenance load.

This parallel loop tank using a multi-pass HPWH approach is recommended in buildings with relatively high distribution losses due to long inefficient or poorly insulated distribution system, resulting in relatively high temperature maintenance losses. This system will also work well with systems designed to use lower primary water storage temperatures.

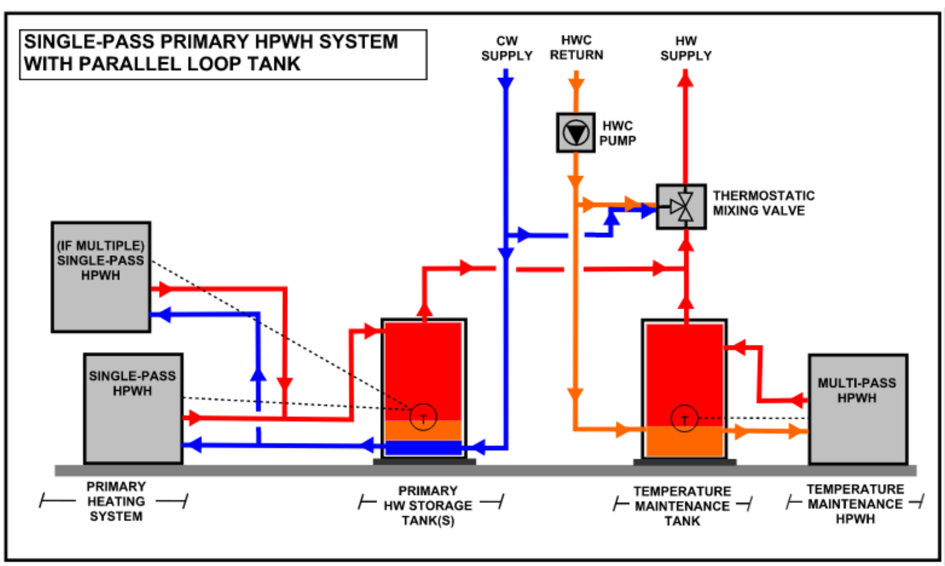

Figure 2. Example of a CHPWH plant with a parallel loop tank.

4. SIZING TOOL METHODOLOGY

This section covers the methodology used in the Ecosizer CHPWH sizing tool for the primary system and the temperature maintenance system. The size of the primary system is determined by the daily hot water demand on the design day, which is calculated based on the user input for Input Method, Number of People, Number of Apartments, and Peak Gallons per Day per Person. Sizing for the temperature maintenance system depends on the user input for Recirculation Loop Heat Loss (W/Apartment), in the Advanced Schematic Options. Guidance for this load is provided in the Temperature Maintenance Sizing section of this report and in the Ecosizer. The data and code for the calculation methods described below is publicly available[2].

Hot Water Demand Calculation

The first step in sizing CHPWH plants is estimating the hot water demand in the building. Hot water demand is specified by daily hot water demand (in gallons) and load shape. The daily hot water demand, $V_{HW,Day}$, is calculated as:

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

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. In the sizing tool users must specify the number of people and the peak hot water demand or use estimates defined by ASHRAE or California code standards.

Number of People

To estimate people, the sizing tool needs inputs for the number of people and/or number of apartments. There are two input methods for these:

1. If the designer knows how many people will occupy the building they can simply enter the number of people into the tool.
2. If the designer does not know how many people will occupy the building, there is an option to use available data sources for occupancy estimates. This will be based on the number of bedrooms and the occupancy rate (number of people per unit by the number of bedrooms).

For the later input method, the tool provides three options for the number of people per apartment size/type, presented in Table 1. The California ratios used in CBECC-Res are based on the 2009 Residential Appliance Saturation Study[3]. For California low income groups ratios are sources from the CA Tax Credit Allocation Committee (CTCAC)[4]. An ASHRAE publication[5] provides two sets of national data for multi-family and low-income multi-family buildings developed from the 2009 Residential Energy Consumption

[2] https://github.com/EcotopeResearch/HPWHulator

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

[4] 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

[5] 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

Survey. The ASHRAE low-income multifamily occupancy ratios are higher than the ASHRAE market rate multifamily occupancy ratios.

Table 1. Occupants per bedroom for three 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

Peak Demand Per Person

To estimate the peak hot water demand per person, the sizing tool provides a few options. 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. The ASHRAE Medium number is likely an overestimate of any modern multifamily building due to the outdated data used. To provide a modern[6] estimate, we evaluated hot water usage in three market-rate multi-family buildings with low flow fixtures in Seattle, WA, to determine peak hot water usage.

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.

To find the design peak hot water use we use the 98th percentile of daily hot water demand, the empirical cumulative density function is given in **Figure 3**, which evaluates to 25 gpdpp[7].

[6] Note that our modern hot water usage data is pre-COVID. We have found that 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.

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

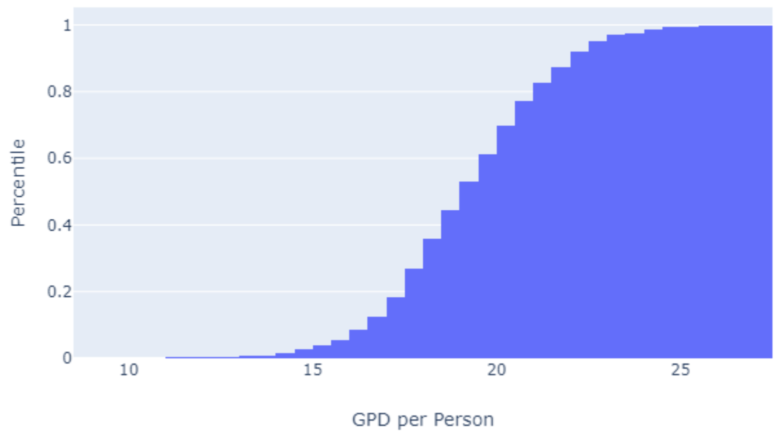

Figure 3. The empirical cumulative density function for the design building.

California Demand Per Person

The Ecosizer tool also provides an option for hot water demand derived from CBECC-Res 2019[8]. The hot water use profiles are divided into ten distinct profiles for studios, 1-bedroom units, 2-bedroom units, 3-bedroom units, 4-bedroom units, and 5-bedroom units[9]. When a CBECC-Res user constructs a multi-family building in the software, the software uses the appropriate number 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, 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)[9] .

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.

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

[9] 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

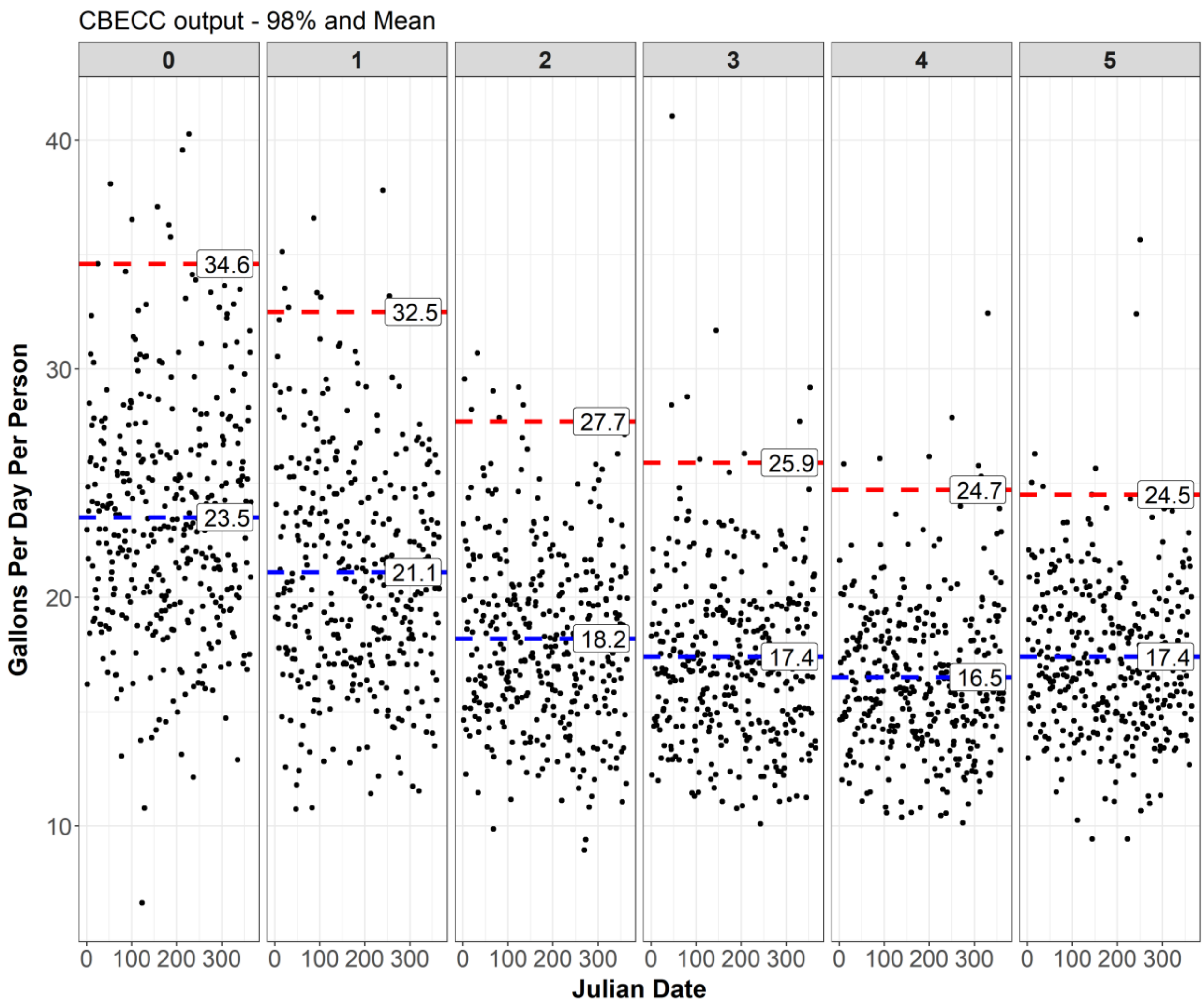

Figure 4. Expected daily DHW per person for each of the CBECC-Res apartment types.

Load Shape

The load shape is found from an analysis on the hourly demand for each day in the dataset for the 118-unit multifamily building. A selection of potential days is chosen from days that are in 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 is 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 (ie. 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. It is possible in small multifamily buildings with less diversity that usage patterns could align in ways that produce higher peaks or higher total demand. Care should therefore be taken when using the Ecosizer for buildings with fewer than about 20-30 occupants.

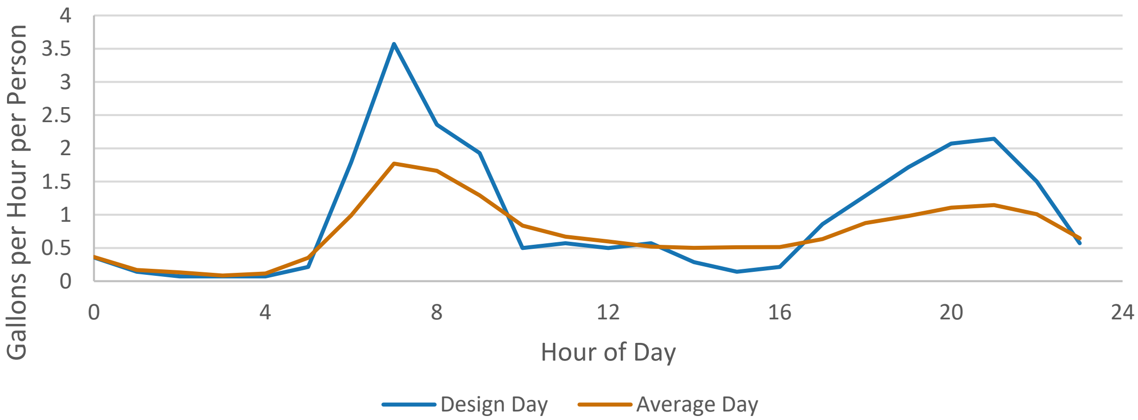

Figure 5. Measured Load Shapes from Ecotope Buildings.

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.

Sizing Methodology for Primary Plant

This section discusses 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. In lieu of calling the method here the More "More Accurate Method" 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. Sizing of the systems depends on the design and operation of the storage volume. The design of storage volume is summarized into one idealized storage tank in Figure 6, which represents storage tanks in parallel or series. The user input for the aquastat fraction is the percentage of hot water volume removed from the tank before the HPWH's turn on due to cold water at the sensor. The user input for storage efficiency represents what percentage of the total hot water storage volume is at the storage temperature when full, the red section in Figure 6, since the storage volume can be degraded by mixing and that HPWH's will turn off when the incoming water is below setpoint.

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. The corresponding hot water generation rate, $\dot{G}(t)$, is calculated following:

$$\dot{G}(t) = \frac{V_{HW,Day}}{h_{max,hr}}$$

2. Storage volume is found by considering the worst-case scenario, when entering a peak hot water usage period the HPWH has not heated up the whole volume of the tank and the HW level is just below the aquastat. A peak hot water usage period is defined as any period where the hot water draw rate exceeds the hot water generation rate, i.e. $\dot{V}_{HW}(t) > \dot{G}(t)$. The storage volume that remains at the start of the peak hot water usage is the running volume, shown in Figure 6. This must be equal to the volume of hot water used during the peak event that the HPWH cannot generate. To find this volume the running integral of the difference between the hot water draws and generation rate is found by:

$$V_{supply}^{i}(t) = \int_{t_{peak}^{i}}^{t} \left(V_{HW,Day} * \dot{V}_{HW}(t') - \dot{G}(t')\right) dt'$$

   Where $V_{supply}^{i}(t)$is the running difference, $\dot{V}_{HW}(t)$ is the normalized load shape, and t_{peak}^{i} is the start of the i^{th} peak hot water usage period. The design day could have multiple peak periods, each is used to evaluate a running volume and only the max running volume should be used for sizing. The running volume is the absolute minimum of the all the supply values $V_{running} = \min\left(V_{supply}^{i}(t)\right)$.

3. 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 useable fraction of storage, the red section in Figure 6.

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

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

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

5. 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 large effects for the recommend 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:

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

where ρ is the density of water, c_p is the heat capacity of water.

The Ecosizer also checks that the cycling volume, Figure 6, the primary storage volume between the aquastat and the bottom of the effective storage volume, 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. The cycling volume found from user inputs is compared to a minimum cycling volume:

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

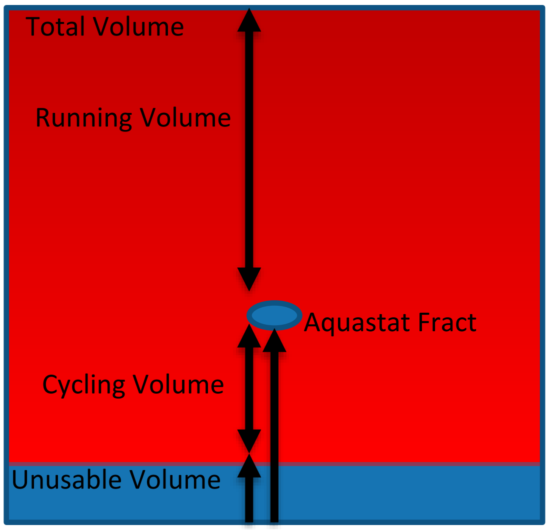

Figure 6. An illustration of the parts of the storage volume.

An example of this is worked through in Figure 7 and Figure 8, for a building using 2000 gallons of DHW per day and a maximum daily runtime for the compressor of 16 hours. In Figure 7, 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. The difference between the hot water use and the hot water generation rate is shown in orange. In this case, there are two instances of peak hot water use, t_{peak} at 0600 and 1900.

The cumulative difference between DHW generation and DHW use starting at the beginning of peak events is shown in Figure 8, 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).

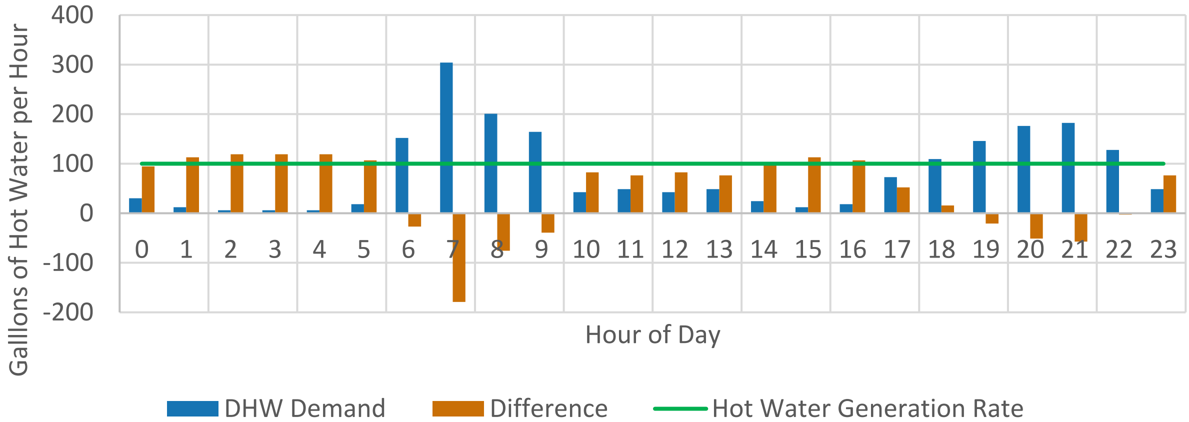

Figure 7. **Hot water (HW) use, heating rate and difference throughout the day.**

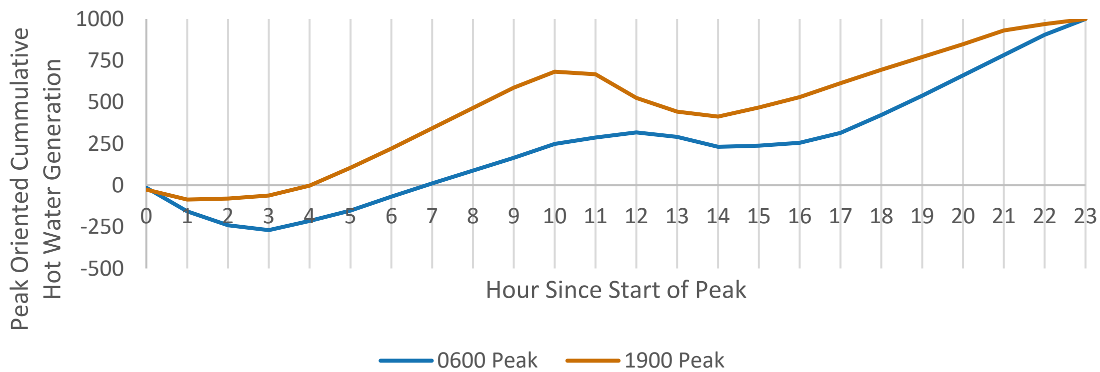

Figure 8. **Cumulative supply after peak event.**

HPWHs can run longer than the design minimum runtime on occasion, for example all day, and this creates a built-in safety factor for days where 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, this extra typical fraction of 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[10]. 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:

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

Where N_{apt} is the number of apartments, $\dot{Q}_{loop}$ is the recirculation loop losses per apartment unit, f_{loop} is the flow rate of the recirculation loop, T_{return} is the recirculation loop return temperature, and T_{supply} is the supply temperature to the occupants or the temperature entering the recirculation loop. 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:

$$\dot{Q}_{TM} = SF \;\; N_{apt} \; \dot{Q}_{loop}$$

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

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[11]. 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[12]. In cases where meeting the CA prescriptive sizing is not necessary, the sizing recommendations are in Table 2. The sizing of the swing tank was done to minimize the size of the tank and thus the cost of adopting this new technology.

Table 2. Recommend swing tank volume following MASHRAE and CA Title 24

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

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

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

> 96	120 - 300	480

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.

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 Figure 9, for an example 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 7; 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.

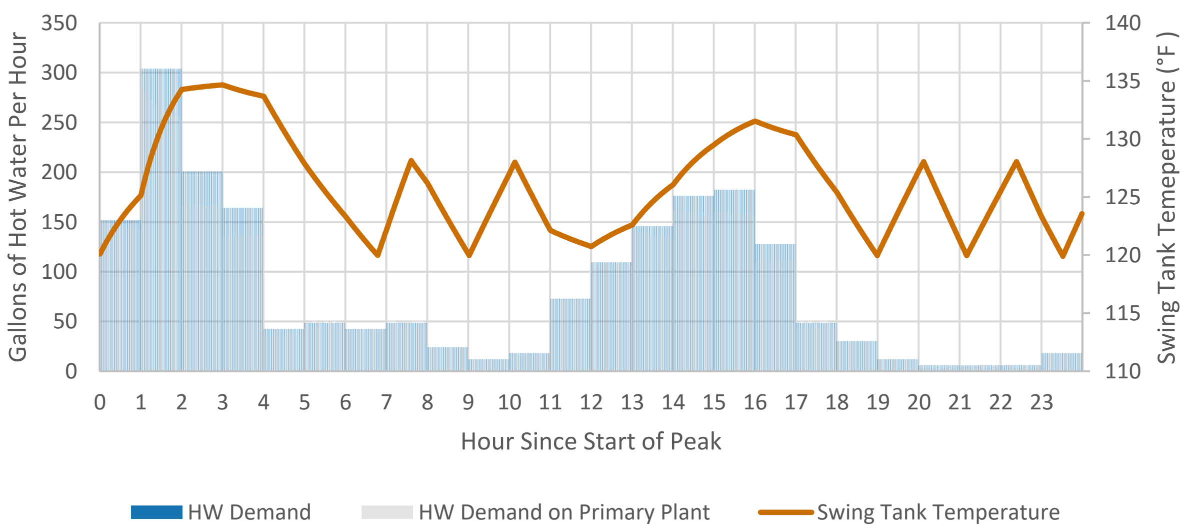

Figure 9. Swing tank simulation plot.

Cumulatively, for the 24 hours after the peak event, 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 9 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:

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

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:

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

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 10, 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

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

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.

$$\dot{Q}_{TM} = SF \;\; N_{apt}\dot{Q}_{loop}$$

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 Figure 10, and can be written as

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

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

$$Saftey \; N_{apt}\dot{Q}_{loop} \; = \; N_{apt}\dot{Q}_{loop}\left(1 + \frac{t_{off}}{t_{run}}\right)$$

Lastly solving for t_{run}:

$$t_{run} \; = \; t_{off}/(Saftey - 1)$$

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

Figure 10 gives an example operation where the temperature maintenance tank has 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.

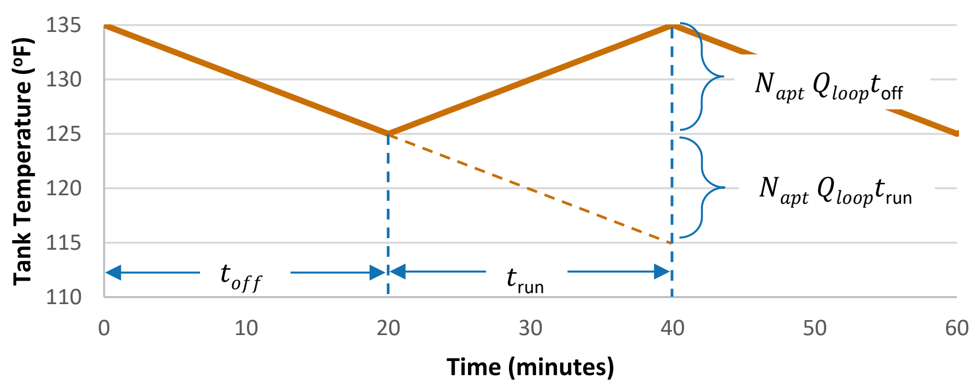

Figure 10. Parallel loop tank average temperature over time in orange.

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 follows the same methodology as the minimum sizing for the primary system, except the time-dependent hot water generation rate, $\dot{G}(t)$, is set to 0 during hours when operation of the HPWH is excluded.

To ensure that a system can achieve load shifting during every peak period of the year would require significant increases in storage volume and/or heating capacity. Therefore, there is also 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.

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 a more conservative design than the non-load shift scenario.

For example, in a situation similar to the example worked in Figure 7 and Figure 8, if a user sets the load shift 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 Figure 11. This also shifts the start of the 2nd peak period to 17:00 from 19:00 in Figure 7.

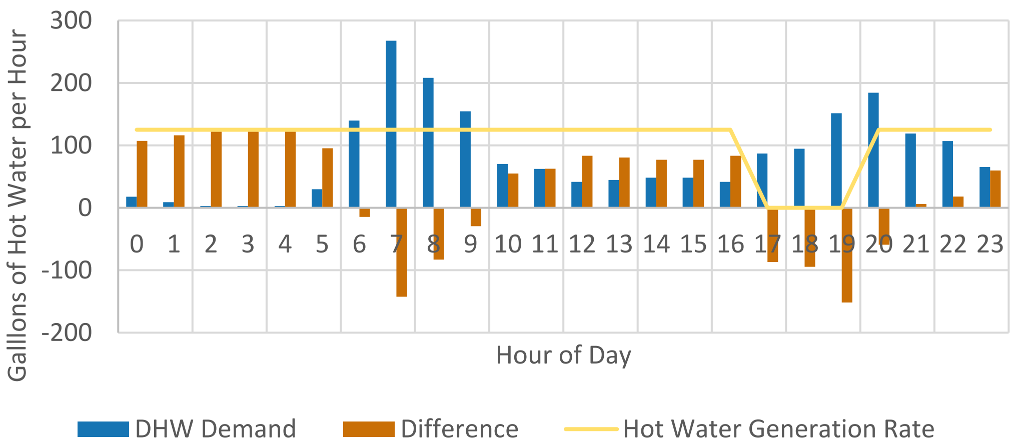

Figure 11. A load shift scenario where the systems is HPWH is excluded from 1700 to 2000.

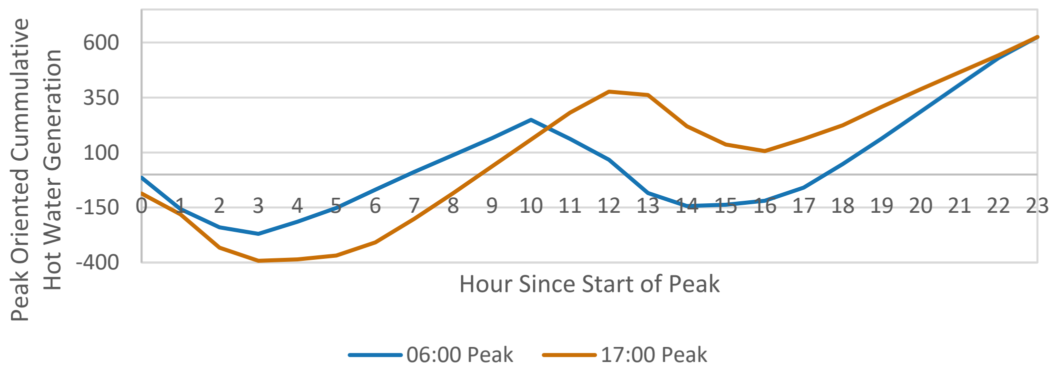

Figure 12. The cumulative supply after peak events for a load shift scenario.

In Figure 11, the load shifted hot water heating rate is given in yellow, noticeably dipping to zero during the hours from 17 – 20, just as an example. The difference between the heating rate in yellow and the hot water load shape is shown in orange. Note that in this case, when heating returns at hour 20:00, the heating rate is lower than the hot water load during that hour. This is factored into the sizing of the running volume in Figure 12 because the method looks at the accumulation of the difference between the generation rate and the demand over the 24 hours after the peak not just the peak period.

The cumulative supply curves after the start of the peak events are shown in Figure 12 for both peak events. The absolute minimum of both curves in Figure 12 is the running volume. In this case the load shifted peak period starting at 17:00 provides a larger running volume than the peak period starting at 06:00.

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 8. 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 Figure 11, if the hot water generation rate is increased to 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 could be envisioned 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, the default aquastat fraction, 0.40, of the storage volume can become pointlessly large. The aquastat fraction provides some safety based on the total storage volume, which can grow quickly when sizing for load shift. When doing load shifting, it is recommended users reduce the aquastat fraction by lowering the aquastat in the primary storage volume to reduce the total stored volume. (Note: if it is turned down too low the user is notified of the minimum value for the aquastat fraction to prevent short cycling). However, this is a parameter of CHPWH plant design, so users should be aware of where the aquastat port is on the storage tanks used in their design and can use the sizing curve and aquastat fraction to match the volume of their designed system to a minimum heating capacity.

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 temperature 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. Users should check that their load shift scenario with increased storage temperature does not have a lower storage volume than the system sized without load shifting with increased storage 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 no 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 Figure 9. In practice, to accomplish load shift 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.

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 could see the energy use impacts of the range of possible design choices. The annual performance model will be based around typical use conditions as opposed to the peak design conditions used in the sizing tool. The energy performance tool will use the premier open-sourced HPWH simulation software used in CBECC-Res, HPWHsim[13], and will be based on:

- Location-based weather from TMY3 files, including a model for predicting entering water temperature.

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

- 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.

ACKNOWLEDGEMENTS

This work is funded by Southern California Edison (Charles Kim) via SCE's contractor 2050 Partners (Alex Chase). There is one separately funded piece under a separate SMUD contract for the add-on load shift module. The methodology has been reviewed by Yanda Zhang of ZYD Energy.

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:

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

The last source of heat in the swing tank comes from the primary system during hot water draws. Where 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:

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

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

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.

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[14], 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.

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

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 Figure 13, where annual resistance element energy use in the swing tank is plotted against swing volume for different temperature 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.

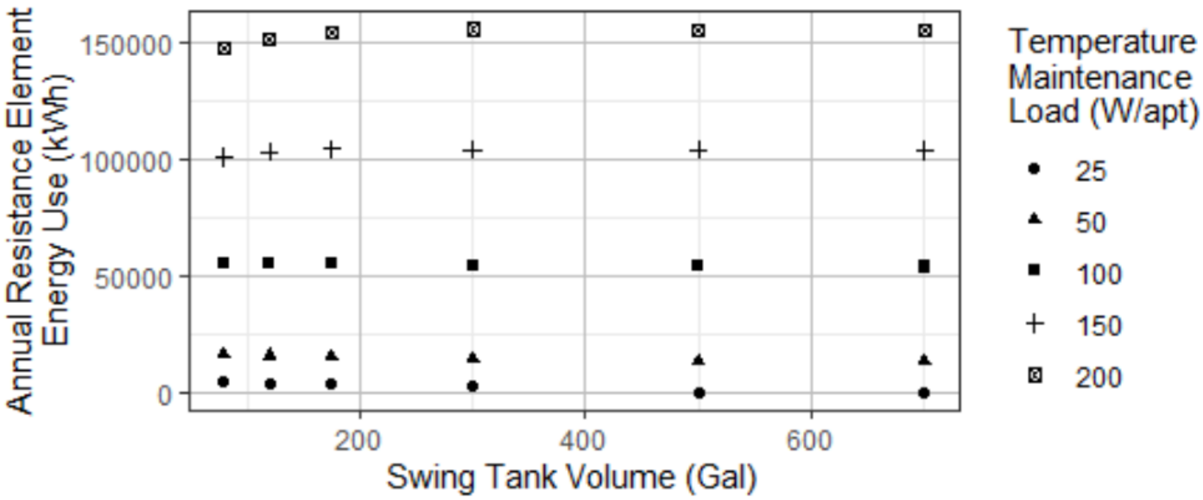

Figure 13. Annual energy use in the swing tank with swing tank volume for different temperature maintenance loads.

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:

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

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

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.

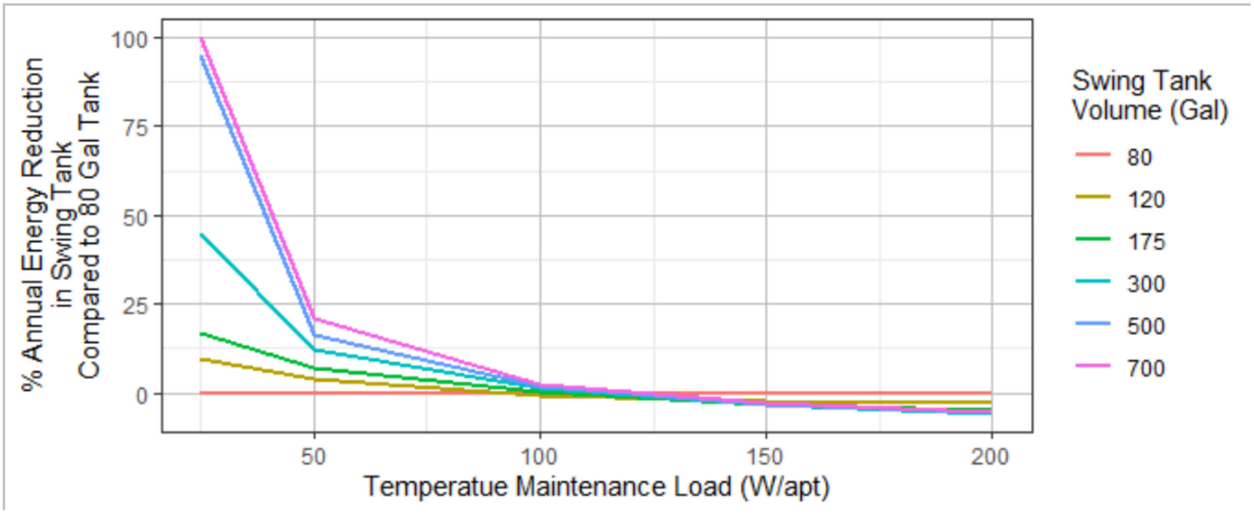

Figure 14. Percent of energy reduction in swing tank from increasing the tank volume above 80 gallons as a function of the temperature maintenance load (For a building with 118 dwelling units).

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 Figure 14, where the annual resistance element energy use is shown as a percent 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 2 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.

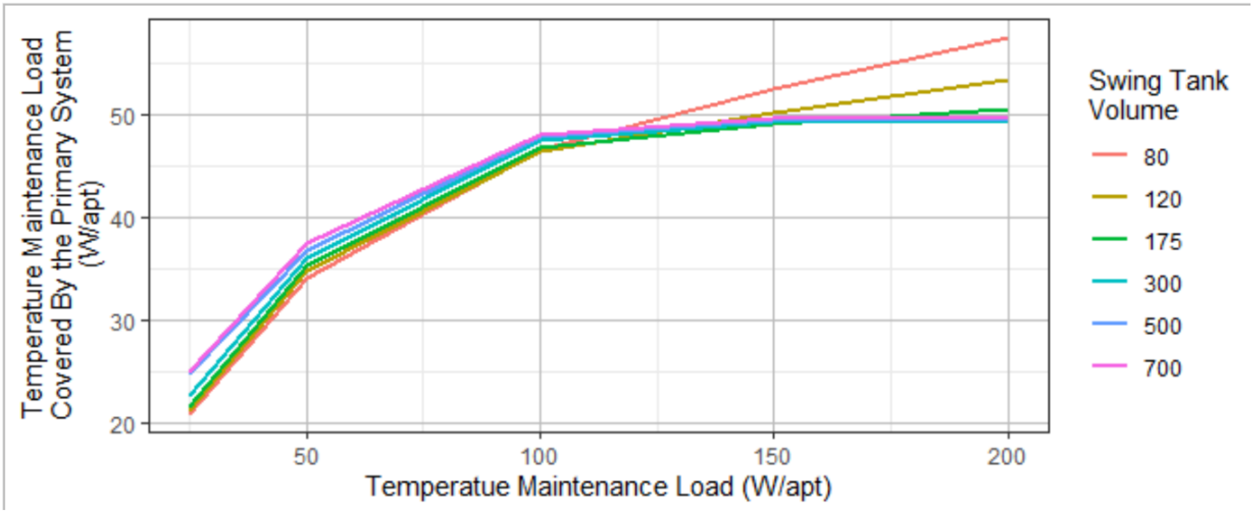

Figure 15. Annual temperature maintenance load covered by the primary system for the modeled temperature maintenance loads.

Figure 15 shows the annual average of the temperature maintenance load covered 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.