Ecosizer – Central Heat Pump Water Heating Sizing Tool

Draft Report

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

July 30, 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 multi-family 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 multi-family 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 between 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 multi-family 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 multi-family 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 multi-family 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

[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

when sizing gas or resistance water heating equipment. The building was previously served by 120kW of 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 110-118°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 MAINTENCE SYSTEM OVERVIEW

A key innovation that can be implemented with single-pass HPWHs is use of a thermally stratified primary storage volume and a separate temperature maintenance system. The temperature maintenance system is assumed to consist of a recirculation pump, a storage tank (the “loop tank”) and a temperature maintenance heat source (multi-pass HPWH or electric resistance). There are two characteristically different systems presented here: a “swing tank” piped in series with the primary storage (Figure 1) and a parallel loop tank piped in parallel with the primary storage (Figure 2).

Important design commonalities between the two systems are:

- Multiple Storage Tanks in Series: The primary storage volume may be provided with one large vertical storage tank or multiple smaller tanks. If multiple storage tanks are used to achieve a larger storage volume, those primary storage tanks shall be plumbed in series. The series plumbing arrangement enables a high degree of temperature stratification throughout the system, with the hottest water at the delivery end of the primary storage system.

- 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 bacteria and associated 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 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 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. 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 DHW delivery temperature.

During a DHW draw event, water is supplied from the swing tank to the thermostatic mixing valve, but the volume removed from the swing tank is replaced by hot water from the primary system (~135-160°F). This water mixes with warm return water from the building distribution system, effectively using the primary DHW system to heat the temperature maintenance system. The temperature in the tank then "swings" from about 120°F to about 150°F (depending on heat loss in the distribution system) to supply a consistent 120°F water to the building with a low need for additional heating input from the resistance element.

Piping the primary storage to the bottom of the swing tank is important to ensure complete mixing. When the swing tank is mixed, the outlet temperature of the tank will be lower than if it was stratified. When mixed, the average hot water draws 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 relatively efficient 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.

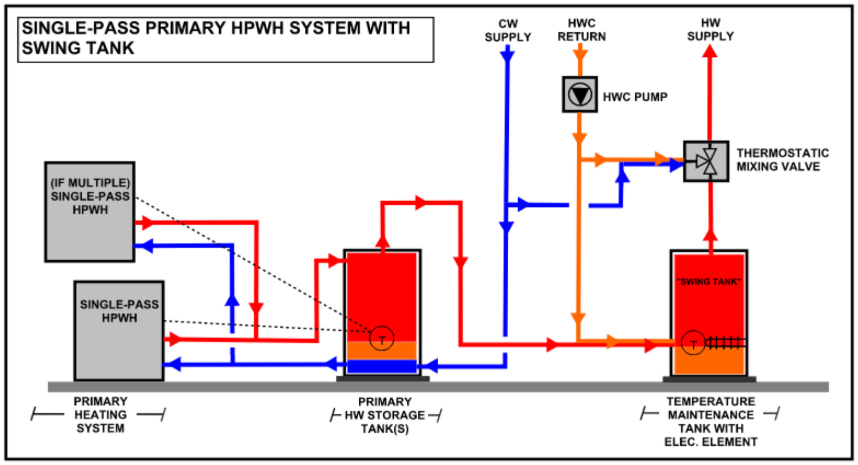

Figure 1. Example of centralized domestic hot water HPWH plant with a swing tank.

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 hot water circulation (HWC) 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. Contrary to the swing tank design, the goal of the parallel loop tank is to maintain as much thermal stratification as possible for optimal operation of the multi-pass HPWH that heats the tank. During operation, the multi-pass HPWH raises the tank temperature 5-10°F to account for the temperature maintenance load.

This parallel piping arrangement for the loop tank is recommended in buildings with relatively higher 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.

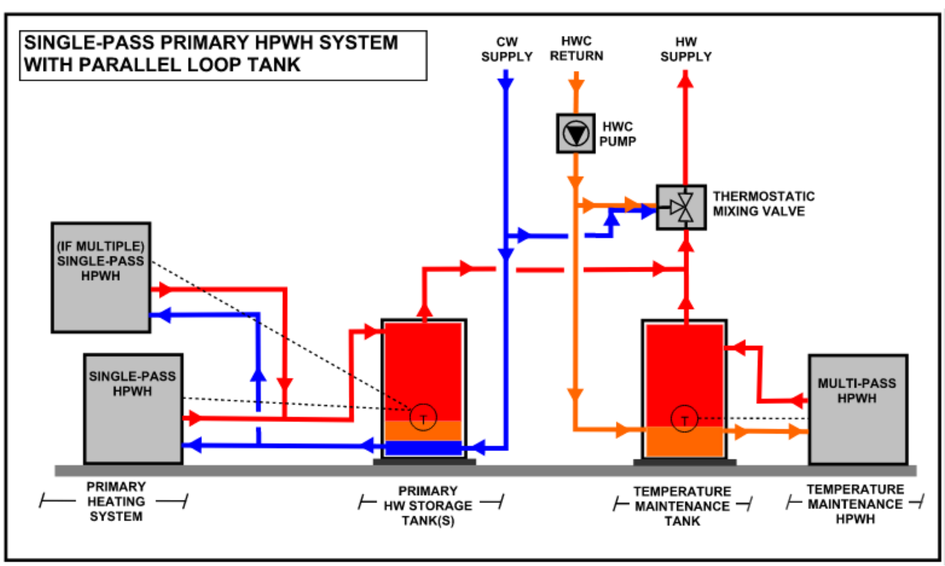

Figure 2. Example of a CHPWH plant with a parallel loop tank.

4. SIZING TOOL METHODOLOGY

This section covers the methodology used in the Ecosizer CHPWH sizing tool for the primary HPWH plant and the temperature maintenance plant. The first steps in sizing the primary system is determining the total daily DHW load or demand on the design day. This is dependent on the number of people in the building and how many gallons per day they are expected to use. Sizing for the temperature maintenance load depends on the user input for the temperature maintenance load. Guidance for this load is provided in the Temperature Maintenance Sizing methodology section of this report and in the Ecosizer. The data and code that performs the calculations below is publicly available[2].

Demand Calculation

The first step in sizing CHPWH plants is estimating the hot water demand in the building. This can be summarized as the total number of people and the volume of water each person uses per day at the supply temperature on the peak day. The total daily hot water demand, $V_{HW,Day}$, can then be summarized by:

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

Where N_{people} is the total number of people and V_{gpdpp} is the peak hot water demand at 120°F in gallons per day per person. In the sizing tool users must directly input the number of people and the peak hot water demand or use estimates defined by ASHRAE or the California standard.

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 provided by the 2009 Residential Appliance Saturation Study[3]. The ASHRAE published data[4] provides two sets of data for multi-family and low-income multi-family buildings developed from the 2009 Residential Energy Consumption Survey. The ASHRAE low-income multi-family occupancy ratios are higher than the ASHRAE market rate multi-family occupancy ratios.

[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] 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

Table 1. Occupants per bedroom for two different Multi-family (MF) data sets.

Apartment Size	Occupants/Bedroom		
	CBECC-Res	ASHRAE MF	ASHRAE Low Income MF
Studio	1.37	1.49	1.69
1 BR	1.74	1.93	2.26
2 BR	2.57	2.39	2.83
3 BR	3.11	2.84	3.40
4 BR	4.23	3.29	3.97
5+ BR	3.77	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 multi-family building due to the outdated data used, from 1991 – 1999. To provide a modern[5] 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 building is in a family-oriented neighborhood, while the others are in more night-life oriented neighborhoods. Data for the 118-unit 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 (ECDF) is given in Figure 3, which evaluates to 25 gpdpp[6].

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

[5] 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.

[6] 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.

California Demand per Person

The Ecosizer tool also provides an option for hot water demand derived from CBECC-Res 2019[7]. 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[8]. 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, 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 day. By sourcing this data directly from CBECC-Res, the data captures assumed losses associated with distribution piping in the unit and losses associated with waiting for the hot water to heat up. For details on the losses see Kruis et al. (2019)[8] .

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 and sums all these DHW use profiles together to build the profile for DHW use during the year. In the Ecosizer, the design day hot water demand is the 98th percentile day of the sum of profiles and is adjusted for the user input supply temperature.

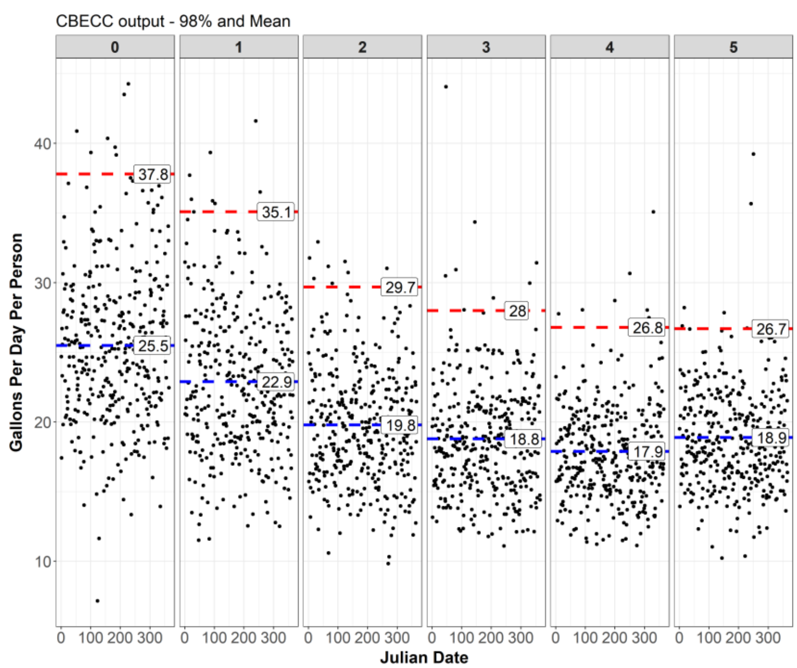

Figure 4. Expected daily DHW per person for each of the CBECC-Res apartment types.

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

[8] 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

Load Shape

The load shape is found using a similar method for the design gallon per day above. From a selection of potential percentile days between the 98th and 95th percentile, 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 load shape to the average day 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.

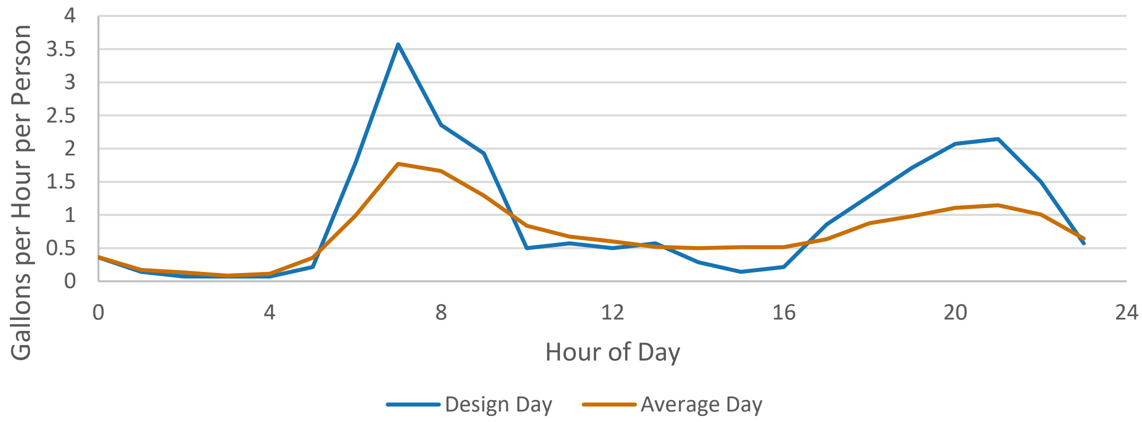

Figure 5. Load Shape Ecotope measured and a CBECC-res prototype.

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 heat the distribution system, details are discussed in the swing tank section below. The method is similar to the "More Accurate Method" referred to in the 2015 ASHRAE HVAC Applications handbook pages 50.15 - 50.16 but modified to better represent lower capacity systems. In lieu of calling the method here the More "More Accurate Method" we call this method the Ecotope Modified ASHRAE method (EMASHRAE).

The recommended minimum results are found by:

1. The minimum capacity for the water heater should first be built around the user input for the maximum daily runtime for the HPWH compressor, $h_{max,hr}$. On the design day, the hot water load should be met in $h_{max,hr}$, this is recommended to be 16-20 hours depending on the equipment selected.
2. This then defines a rate at which we can generate hot water on the design cold weather day, the hot water generation rate, $\dot{G}(t)$:

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

3. 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. The storage volume that remains, the running volume in Figure 6, must be equal to the minimum value of the integrated difference between the hot water draws and the generation rate over the next 24 hours. This is written as
$$V_{running} = \min\left(\sum_{t_{peak}}^{t_{peak}+24hrs} V_{HW,Day} * \dot{V}_{HW}(t) - \dot{G}(t)\right)$$
Where $V_{running}$ is the running volume, $\dot{V}_{HW}(t)$ is the normalized load shape, and t_{peak} is the start of the peak hot water usage period, 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 design day could have multiple t_{peak}s, each is used to evaluate a running volume and only the max running volume should be used for sizing.
4. Total storage for DHW at 120°F is then found by the user input for the aquastat fraction, AF, and the running volume,
$$V_{total,120°\mathrm{F}} = \frac{V_{running}}{1 - AF}$$
The aquastat fraction, shown in Figure 6 is the fraction of the tank that is cold before the signal for heating is sent to the HPWH.
5. Lastly, offsets are used for the differences in the user inputs for storage temperature and supply temperature.
$$V_{total,storage} = \frac{T_{supply} - T_{CW}}{T_{storage} - T_{CW}}$$
6. To create sizing curves (storage vs. capacity) the $h_{max,hr}$ is varied from the user input value 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:

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

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

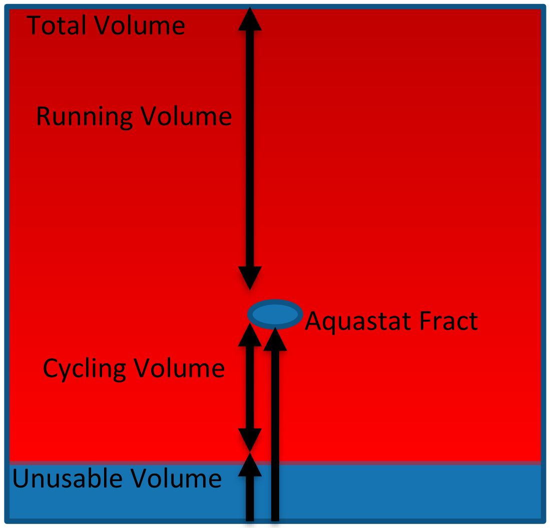

Figure 6. An illustration of the parts of the storage volume.

An example of this is worked through in Figures EX1 and EX2, 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).

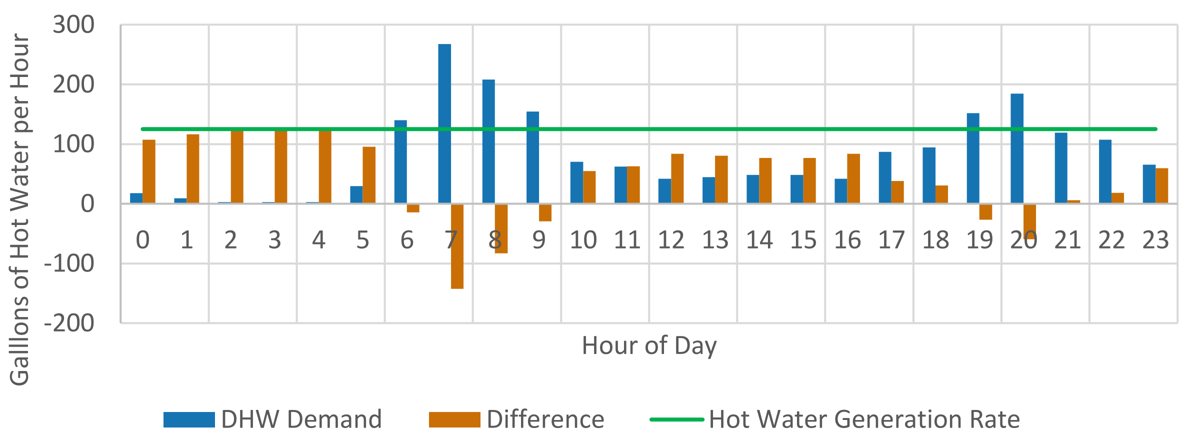

Figure 7. **Hot water (HW) use, heating rate and difference throughout the day.**

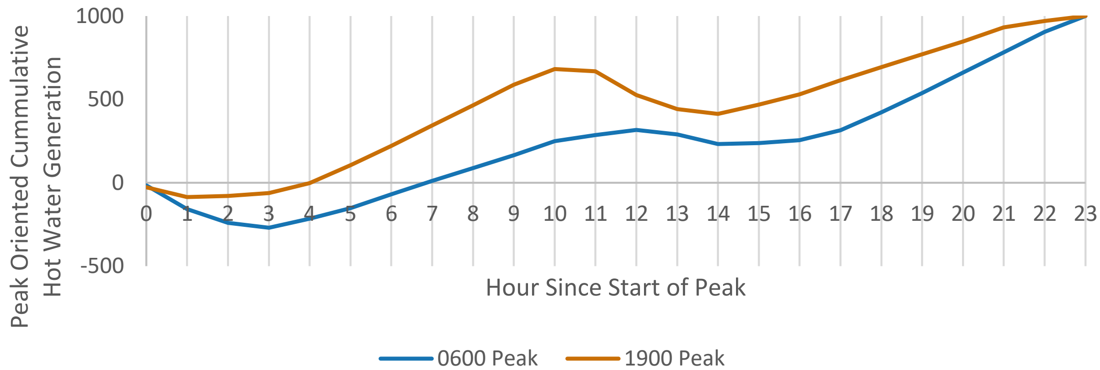

Figure 8. Cumulative supply after peak event.

HPWH's 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.

For comparison, in the Ecosizer sizing tool outputs, the primary curve using the EMASHRAE method is plotted alongside the published ASHRAE "More Accurate Method."

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 some of the distribution losses.

Calculation of the Temperature Maintenance Load

Sizing for temperature maintenance is difficult because the recirculation load is unknown a priori. 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[9]. This upper bound of 175% of the median value is recommended for sizing the heating elements in the temperature maintenance systems.

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 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.

Swing Tank

The swing tank heating capacity is sized to meet the recirculation loop load without hot water input from the primary system, as it must maintain the supply temperature to occupants even during periods of low DHW use. The resistance element in the swing tank is recommended to be sized to meet the 75th percentile of temperature maintenance loads, this is assumed to be 1.75 times the expected input for the temperature maintenance load following the available data. The minimum heating capacity for the swing tank, $\dot{Q}_{TM}$, is:

$$\dot{Q}_{TM} = 1.75 * \; N_{apt}\, \dot{Q}_{loop}$$

The design of 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. Since the industry has not prioritized reduction of distribution losses, the reality of most systems is 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[10]. 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 A.

The goal of modeling the systems is to develop simplified recommendations that can be used to size the system. The results are synthesized into 3 points:

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

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

1. Sizing of the swing tank volume is mostly irrelevant at predictable temperature maintenance values. If care is taken to reduce the temperature maintenance load below 50 W/apt, a system can benefit from increased swing tank volume.

2. Because the primary system accounts for some of the temperature maintenance losses, it must include increased capacity to handle a fraction of the losses. The DHW load for the primary system is increased to account for the temperature maintenance losses at 50 W/apt.

3. The swing tank also requires an increase in sizing for the primary system, since the hot water drawn from the primary system does not benefit from the mix down at the primary storage temperature but is instead dependent on the swing tank temperature. In a worst-case scenario, the swing tank will not heat up significantly above the supply temperature during a peak draw event, so the volume of the primary system must include the volume at the supply temperature not at the storage temperature.

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. In cases where meeting the CA prescriptive sizing is not necessary, the swing tank volume is sized just to separate the temperature maintenance system from the primary system, the sizing recommendations are in Table 2.

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
> 96	120 - 300	480

Parallel Loop Tank

A parallel loop tank sees only the constant temperature maintenance load. This load is unknown for new construction and relatively hard for the designer to predict as it is determined by many factors outside of their control, including the pipe sizing, the length of circulated piping, the insulation levels, the quality of the insulation and pipe supports, and the location of the piping. 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 9, 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.

For sizing the heating capacity, the control input is the expected runtime to heat the temperature maintenance tank from T_{turnOn} to $T_{setpointTM}$. The heat capacity needed for the temperature maintenance heat pump, $\dot{Q}_{TM}$, is then equal to the energy that needs to be added to the tank over the expected runtime, t_{run}, plus the continuous temperature maintenance load. This is shown graphically in Figure 9, and can be written as

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

Or substituting in the equation for V_{TM}:

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

Figure 9 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.

The Ecosizer checks that the sized heating capacity is greater than the 75th percentile range of temperature maintenance losses expected. If the user changes the input for the expected temperature maintenance losses, the 75th percentile range changes to be 1.75 times the expected losses, maintaining the same scale of the distribution of losses. This enforces a safety factor of 1.75 in the sizer.

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 or to increase the heating capacity of the HPWH.

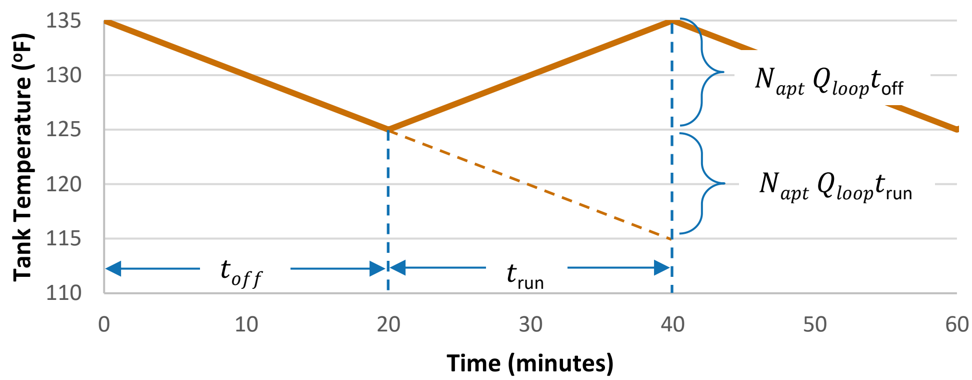

Figure 9. Parallel loop tank average temperature over time in orange.

Load Shift Sizing

The load shift module allows users to block out part of the day when the HPWH's 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.

For example, in a situation similar to the example worked in Figure 7 and Figure 8, if a user sets the load shift period from 1700 to 2000, the assumption is that hot water generation rate goes to 0 during this time period, shown as the yellow line in Figure 10. This also shifts the start of the 2nd peak period to 1700 from 1900 in Figure 7.

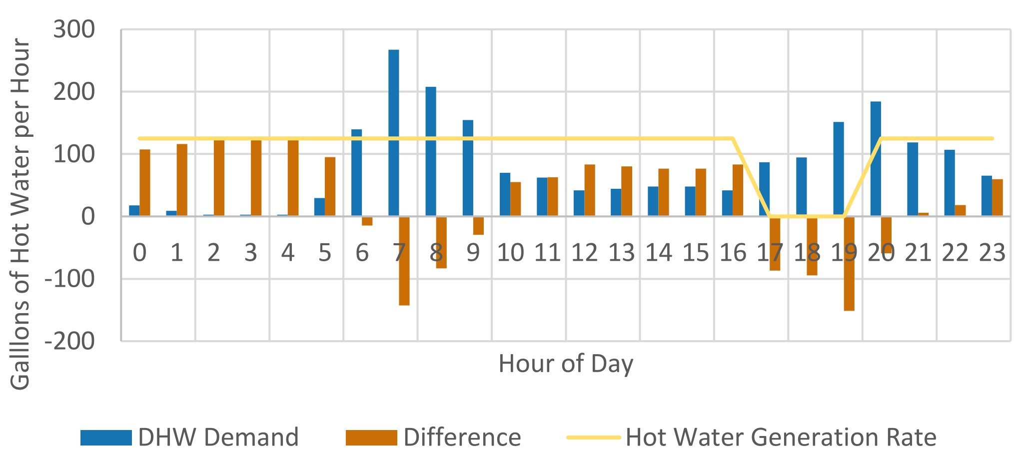

Figure 10. A load shift scenario where the systems is HPWH is excluded from 1700 to 2000.

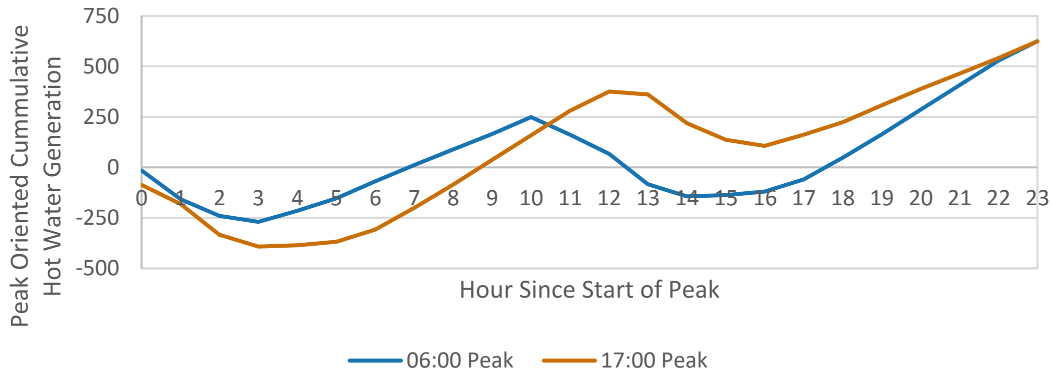

Figure 11. The cumulative supply after peak events for a load shift scenario.

In Figure 10, 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 20:00, the heating rate is not enough to accommodate the total hot water load during that hour, and this is factored into the sizing of the running volume.

The peak oriented cumulative supply curves are given in Figure 11 for both peak events. The absolute minimum of both curves in Figure 11 is the running volume. In this case the load shifted peak period starting at 17:00 provides the larger running volume at 390 gallons.

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 10. 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 load shifted volume. For example, in Figure 10, 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 – 20.

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. (Note: if it is turned down too low the user is notified of the minimum value to use).

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.

To do load shifting with increased storage temperatures, a user can easily input a higher storage temperature for the primary HPWH system. The Ecosizer will account for increased heating capacity due to a higher temperature lift and decreased storage volume due to storing water at a higher energy density. Users should, however, check that their load shift scenario with increased storage temperature does not have a lower storage volume than the system sized without load shift.

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. In practice, to accomplish load shift the swing tank should sometimes be heated above setpoint by the electrical resistance elements.

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. It is recommended users also increase the expected run time for the multi-pass HPWH to decrease 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 shift to 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 design calculation will use the premier open-sourced HPWH simulation software used in CBECC-Res, HPWHsim[11], and will 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.

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

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 – SWING TANK SIMULATION

To develop rules around the appropriate storage volume for a swing tank, we performed a simplified model of a swing tank in the open-sourced HPWH simulation software used in CBECC-Res, HPWHsim[12]. The simulation uses minute-long timesteps to track temperatures with a HPWH or electrical resistance tank and energy introduced by the heating mechanisms. For this study, we 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 is mixed with the cold-water temperature and 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 12, 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

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

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.

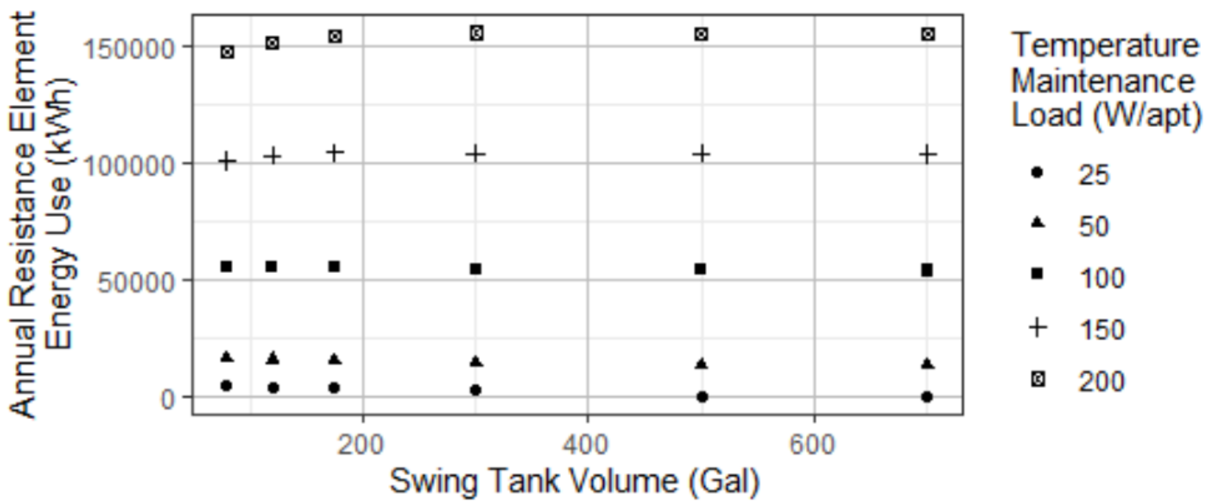

Figure 12. Annual energy use in the swing tank with swing tank volume for different temperature maintenance loads.

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:

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

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

The data shown in Figure 5 suggests this only occurs for 1 hour of the day during the morning peak on average. However, that is an overestimate as Figure 5 plots hot water draws at 120°F but the f_{draw} is calculated at the time dependent swing tank temperature, which is hotter than 120°F. Therefore, the mixed down draw will be less than depicted in Figure 5. 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. 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.

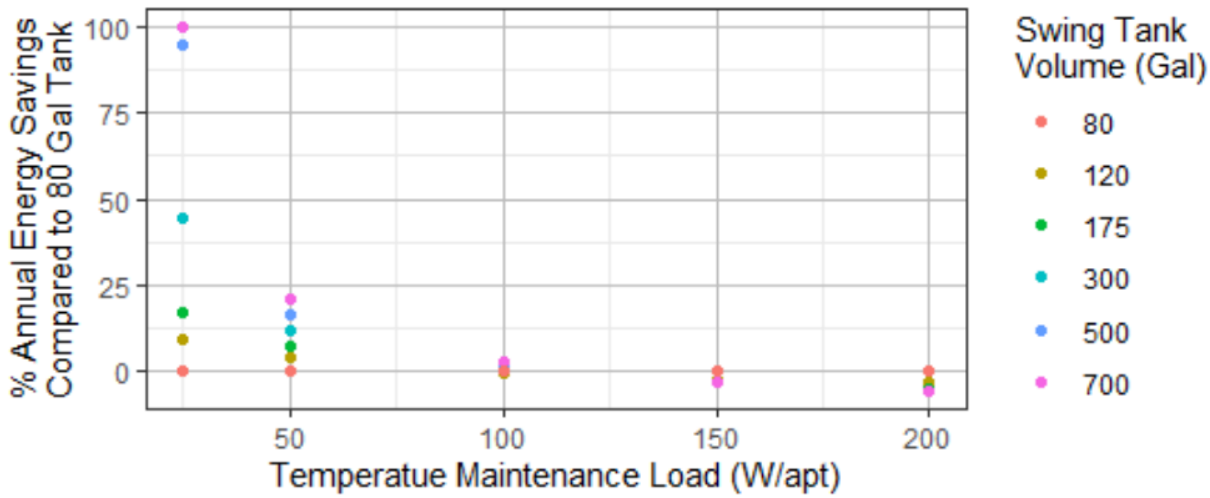

Figure 13. Percent of energy savings from increasing the tank volume above 80 gallons as a function of the temperature maintenance load.

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 13, 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 a proper design, the primary system will cover all the temperature maintenance 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 14 shows the fraction 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 fraction of the load on the primary system could likely be greater than this for different draw profiles or greater temperature maintenance loads, with the latter being strongly discouraged. For sizing purposes, we assume that the worst-case scenario will be that the primary system must be sized to cover an extra 50 W/apt (to cover some of the temperature maintenance load) in a swing tank configuration.

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. And more research needs to be done on sizing of swing tanks, which should include variation in hot water draws, resistance element sizing, and primary setpoint.

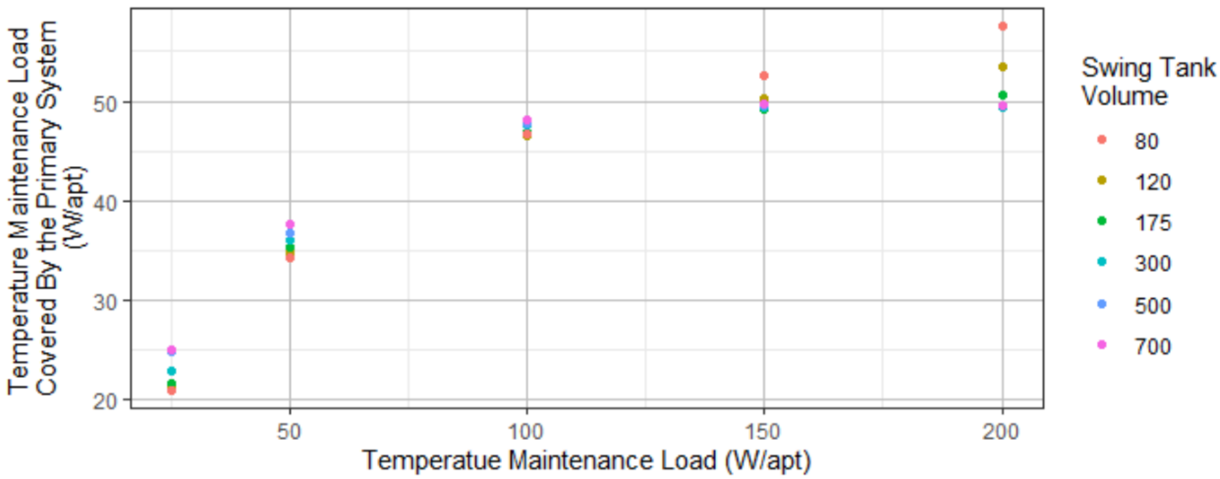

Figure 14. Temperature Maintenance load covered by the primary system for the different modeled temperature maintenance loads.