

Analysis and Opportunities for Load Shift with Central Heat Pump Water Heaters in Multifamily Buildings

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ABSTRACT

Domestic hot water loads in the multifamily sector represent a large portion of building energy use and an opportunity to reduce building peak load impact on grid distribution systems. Commercial heat pump water heating technology can be deployed to achieve significant energy savings in the multifamily sector, while simultaneously reducing peak building loads. Incremental additional components, like expanded storage capacity, further increase the potential for peak load reduction. This paper describes an analysis of multifamily load shape characteristics before and after the deployment of this technology, and describes how the operating and storage characteristics of this equipment can be used to achieve energy savings and peak load reduction.

Introduction

Domestic Hot Water (DHW) loads represent 25-30% of multifamily building end use. (Heller et al. 2009) The magnitude of this energy use is driven by several factors, including building configuration, occupant density, occupant income, and local energy codes, which impact ratio of energy use among different energy end uses depending on stringency and impact. Due to the prevalence in the market of inefficient conventional electric resistance or gas-fired DHW systems, there is significant opportunity for energy savings in the multifamily sector with the adoption of central heat pump water heating (CHPWH) systems in these buildings.

Nationally, the multifamily sector accounts for nearly 30% of all energy use for domestic water heating, as shown in Figure 1. This is the largest single sector with respect to DHW loads (not including single family residential buildings). Over 75% of all commercial energy use for domestic hot water in the US is from four building types; multifamily, food service, grocery, and lodging. (EIA-CBECS 2003, NEEA CBSA 2014) Addressing DHW energy use in the multifamily sector represents an opportunity for an outsize impact on overall energy use.

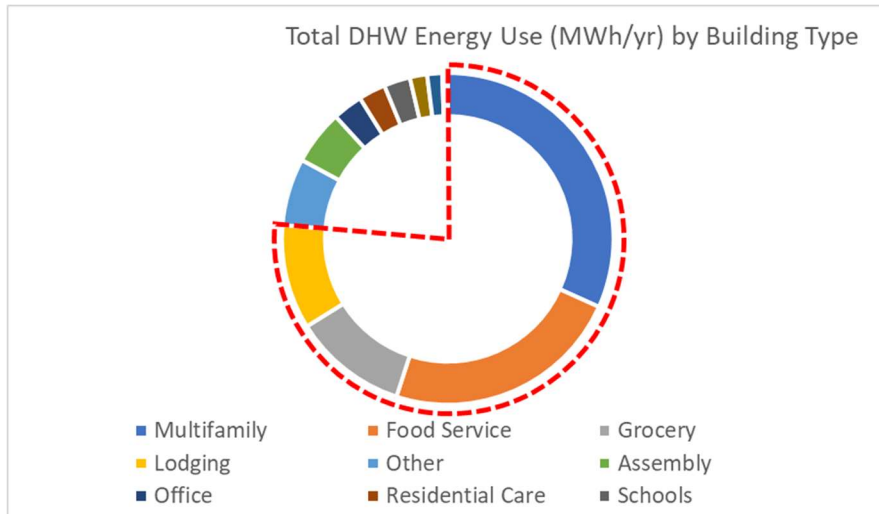


Figure 1: Domestic hot water energy end use by commercial building type in the United States (source: analysis of EIA 2003 and PNNL 2014 data)

Multifamily DHW Energy Use

Meeting DHW Loads in Multifamily Buildings

Multifamily buildings may adopt central or in-unit appliances to provide DHW to living spaces. In-unit appliances most typically consist of electric hot water tanks located in closets or other service spaces in the living unit, although gas-fired tanks are also sometimes used in individual units. Central DHW systems include a central boiler plant consisting of a gas-fired or electric boiler, a central storage tank, and a distribution system to supply individual units. In many multifamily buildings, the distribution system provides continuous recirculating flow of hot water through the building to make sure hot water is readily available near each individual unit. The energy impact of these recirculation systems is not well documented, but estimates suggest that recirculation systems account for approximately 25% of the energy use of multifamily hot water systems.

In the existing multifamily sector across the US, the fuel used for DHW generation is split roughly equally between gas and electricity (AHS 2019). In-unit DHW systems are much more likely to deploy electric hot water tanks, while central systems are more likely to incorporate gas-fired boilers. Anecdotally, newer multifamily buildings seem to be moving toward greater adoption of central systems over in-unit systems.

Heat pump water heating (HPWH) technology has been available in the residential sector for approximately two decades, though market adoption has been slow. For single family applications, HPWH tend to be unitary systems, where the heat pump compressor and storage tank are combined into a single unit and sold as a direct replacement for residential gas or electric storage water heaters. While these units make an excellent choice for single family applications, the units are challenging to install in multifamily settings due to their thermal interaction with the living space, operating noise, and generally larger equipment size. In particular, the unitary HPWHs extract heat from the occupied space and dump cold air back into the occupied space. This can represent a comfort impact in apartments where the water heater is located directly in the living space.

In the last few years, several manufacturers have introduced central heat pump water heating (CHPWH) systems into the multifamily market. These systems are designed to replace central electric or gas boilers. Although some larger capacity unitary systems are available in the market, for larger commercial and multifamily loads it is more common to see built-up central systems, where a series of heat pump appliances are combined with a series of independent storage tanks to create a central system.

Central heat pump water heaters represent a significant opportunity to reduce energy use in multifamily buildings. The nameplate efficiency of the central heat pump appliance typically ranges from a coefficient of performance (COP) of 3.0 to 4.0 or higher. This is roughly three times as efficient as conventional electric resistance systems, and even better when compared to gas-fired system efficiency. However, the overall system performance efficiency when pumps, storage loss, and recirculation systems is accounted for in total performance is more likely to be in the range of 2.5-3.5 COP. (Conventional systems are subject to some of these additional losses as well.)

Since DHW represents such a significant component of multifamily energy use, the impact of deploying CHPWH leads to a significant energy savings. Figure 2 shows the energy use of a CHPWH system compared to an electric resistance baseline in multifamily buildings.

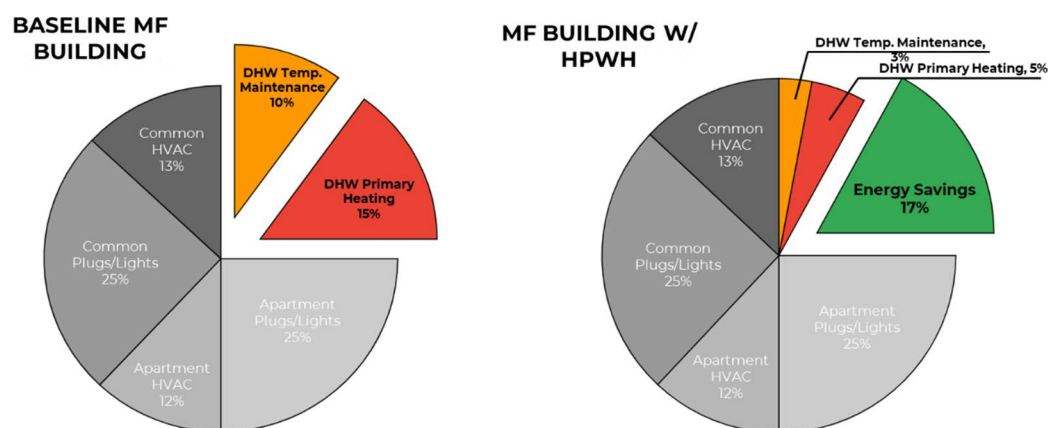


Figure 2: Comparison of multifamily energy end use; electric DHW baseline to CHPWH. (source: Heller et al. 2009)

A key characteristic of a well-designed CHPWH system is that the volume of the storage tanks is significantly larger than conventional gas or electric central systems, while the nameplate instantaneous capacity of the heat pump itself is significantly smaller. In this configuration, the storage volume capacity is designed to meet peak building loads, while the heat pump is designed to replenish the storage volume over time. This is an important distinction when it comes to the daily operating patterns of CHPWH compared to conventional systems. In conventional systems, the central appliance (gas or electric) is designed with a capacity to meet most of the peak building load, while a smaller storage tank provides a buffer for off-peak operation.

When designing central DHW systems, an understanding of building peak loads and use patterns allows for a more efficient system deployment, where the capacity of the system is more closely aligned with building loads.

CHPWH Load Characteristics

Through the monitoring and analysis of how water demand patterns in several dozen multifamily buildings, Ecotope has developed load shape estimates for domestic hot water use in this sector. This has become the basis of design tool for sizing multifamily CHPWH systems that is publicly available, the Ecosizer. (Ecotope 2020)

For this discussion, there are two key characteristics of multifamily DHW load shapes:

DHW demand in multifamily is seasonal in nature

Figure 3 below shows the season variation of DHW demand in a market rate apartment building. This data shows that the average daily water demand is approximately 20% lower than the peak (95th percentile) daily demand.

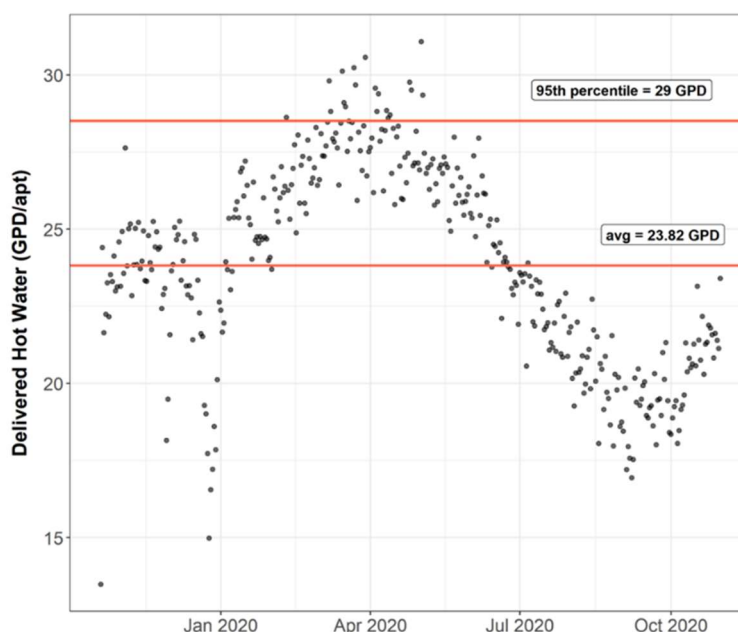


Figure 3: Seasonal DHW load pattern represented by individual daily water use measurement (source: Heller et al. 2016)

DHW loads in market-rate multifamily buildings have two daily peaks

The second characteristic is that in market rate housing, DHW loads have two daily peaks; a significant morning peak, and a less significant late afternoon/early evening peak. (Elderly housing and low income housing demonstrates slightly different daily load shape patterns.)

Figure 4 shows how this daily load pattern plays out in an average day and on a peak day, based on data collected by Ecotope from 16 market-rate multifamily buildings in the Seattle area. The DHW system for these buildings must be designed with a total system capacity to meet peak

daily loads, so on the average day the system will have excess capacity, primarily in the storage volume.

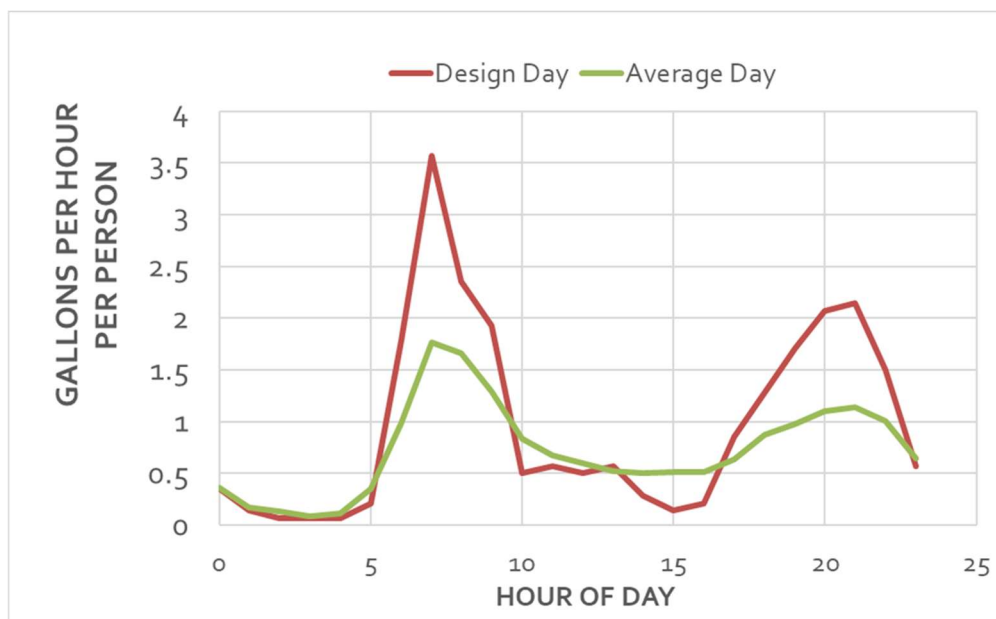


Figure 4: Market rate apartment peak and average daily load shape-weekday (aggregated from metered data)

Analysis of Load Shift Potential

To assess multifamily energy use patterns this study developed an energy model for a 76 unit apartment building currently under construction in Seattle, WA. The analysis used Integrated Environmental Solutions Virtual Environment (IES-VE) modeling software to determine a baseline whole-building energy profile. Modeling of end uses aligned with ASHRAE 90.1-2010 App guidelines. G. In the baseline scenario, in-unit electric water heaters were modeled. Using this baseline, scenarios were then developed to assess the energy and load impacts of CHPWH system deployment with and without additional storage capacity.

The variability of peak, average, and seasonal load shape characteristics described above have significant implications for energy demand and daily load shape in multifamily buildings. When considered in the context of overall multifamily buildings loads, hot water service loads represent a significant portion of the overall peak energy use. Figure 5 shows an end use breakdown of multifamily building energy use on a winter day, based on energy modeling of a project in Seattle, WA. In this example, service hot water is provided by electric resistance, which currently represents the fuel choice for DHW of nearly 80% of existing multifamily buildings in the Pacific Northwest (NEEA 2014), and 50% of existing multifamily buildings nationally (EIA 2015).

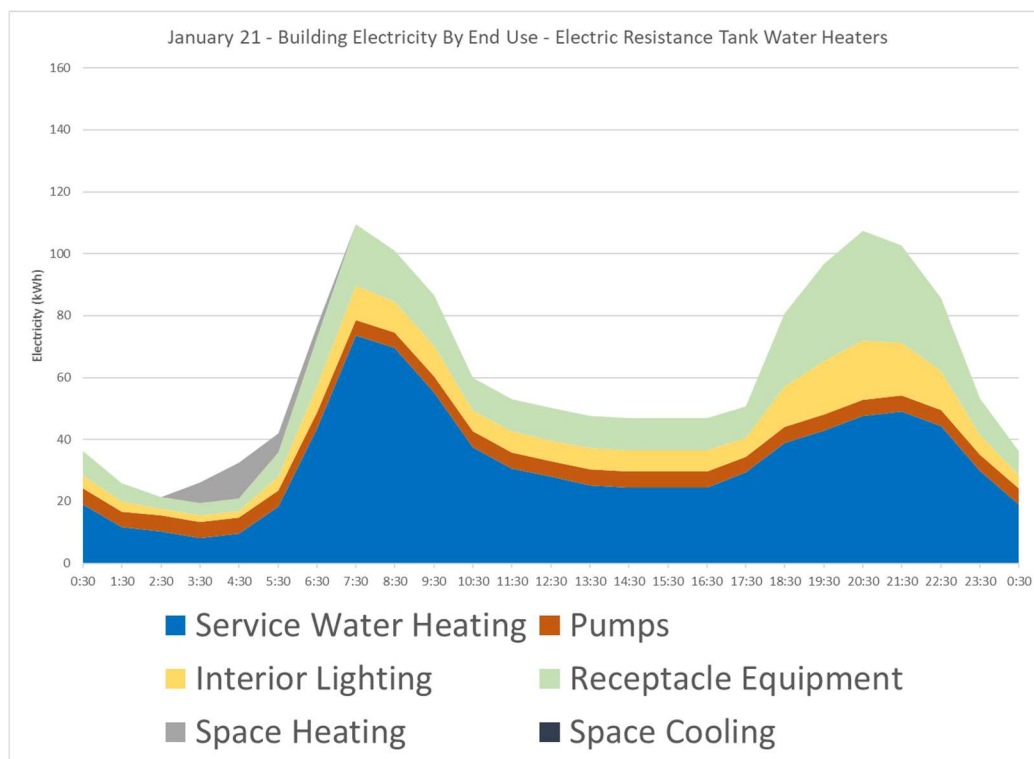


Figure 5: Daily building energy use load shape, by end use, with electric resistance DHW

Focusing on the Impact of CHPWH on Load Shape

Many will recognize the implications for utility planners of morning and afternoon peak loads. Summer afternoon load peaks represent a significant capacity challenge for utilities in many areas as building peak loads are driven by peak afternoon high temperatures and their impact on cooling loads. Winter morning peak loads are likely to increase in significance to utilities if momentum grows for a transition away from natural gas as a heating source, since morning heating loads will increasingly fall on the electric grid.

The configuration of CHPWH systems is the key to understanding load shape impacts of these systems. CHPWH systems rely on a relatively small HP engine, coupled with a relatively large storage tank volume. The HP is designed to operate 12 to 16 hours a day to generate hot water that is then held in the large storage tanks. When the peak periods of the day occur, it is primarily the storage volume, not the HP itself, that is used to meet building load. As the storage volume is depleted, the HP is used to replenish the storage tanks. From a load shift perspective, this means that as long as the storage tanks contain enough hot water to meet peak loads, energy is not needed to operate the heat pumps simultaneous to peak water draw. Of course, as the stored hot water is depleted, the heat pump will begin operating to replace the depleted volume.

Deploying a CHPWH system to serve DHW loads achieves a substantial reduction in total building peak loads, even without any specific load shift control deployment. In this analysis, the morning peak load reduction was 47%, while the afternoon reduction in total building peak load was 29%, as shown in Figure 6.

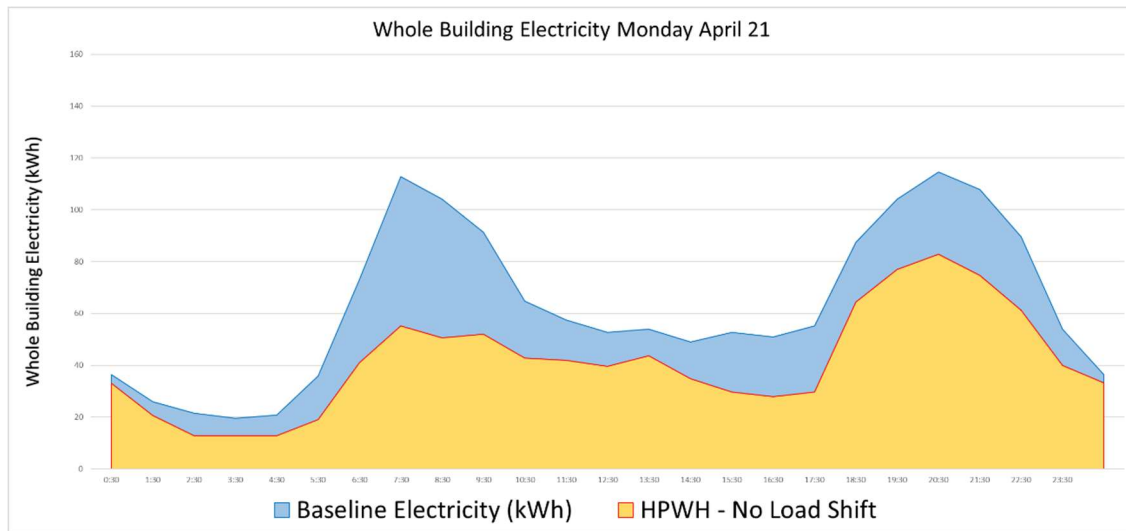


Figure 6: Total building daily load shape, electric DHW vs CHPWH

In Seattle, the local utility (Seattle City Light) is piloting a time of use (TOU) utility rate focused on reducing afternoon grid peaks. The pilot TOU rate from Seattle City Light includes a peak price between 5 pm and 9 pm, throughout the year. This TOU rate period can be overlaid on the graph of DHW energy use as a basis for additional control of the CHPWH system to achieve additional peak load reduction. In Figure 7 below, building DHW load is isolated from total building load. The baseline DHW energy use (blue) and CHPWH system energy use (grey) are compared to show the load shift achieved from the CHPWH technology alone.

Additional load shift is achieved by upsizing the storage volume and deploying TOU controls. The operation of the heat pump is locked out during the load shift period, as shown by the yellow line in the graph. The heat pump compressor then kicks on at the end of the afternoon peak period to recharge the storage volume, and the runtime of the heat pump is extended into the early morning hours to fully replenish the storage tank temperature. In the configuration shown here, the storage volume is ‘topped off’ before the morning peak.

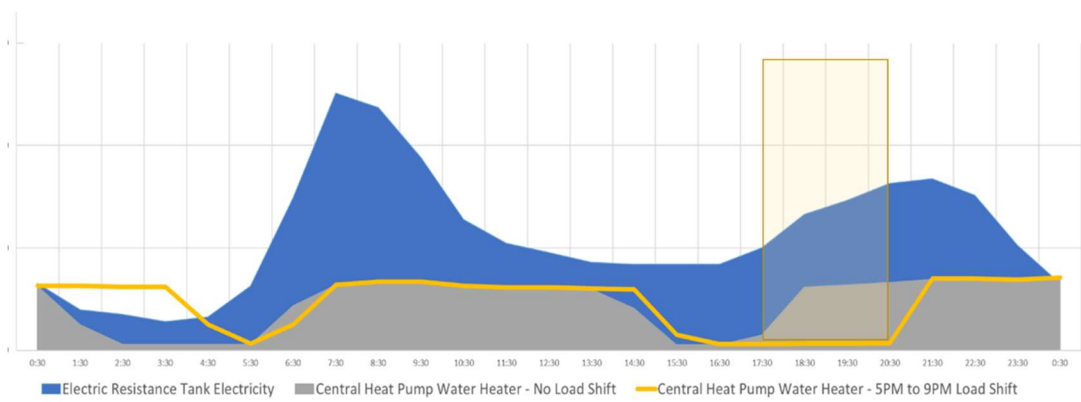


Figure 7: Load shift in DHW with CHPWH and oversized storage capacity compared to CHPWH without load shift and electric resistance DHW baseline.

In this example, the storage capacity of the CHPWH system is sized to allow the system to ‘coast’ through the peak rate period defined by the TOU rates defined in this analysis without

kicking on to replenish the storage volume. This requires the oversizing of the storage tanks to make certain that the system will glide through the peak period in all cases. If the tank is not adequately sized to achieve this, the heat pump will kick on before the end of the peak period and try to begin recovery of the heated storage volume.

Central Tank Storage Capacity vs Percent of Load Shift Hours Met

Although the load shift scenario discussed above increased storage capacity in the model to achieve all annual load shift hours, more conventionally designed CHPWH systems inherently have some potential for load shift deployment. Mechanical designers size CHPWH systems based on peak hot water draw rather than average hot water draw, as explained in Figure 4 earlier in this report. Because the average daily load peak profile is significantly smaller than the peak profile for which the system is designed, the system will inherently have excess storage capacity on most days.

In this analysis, multifamily CHPWH deployment achieves significant energy efficiency and load shape improvements. Standard storage tank sizing (with no additional capacity deployed for load shift) allows the system to meet 50% of annual afternoon load shift hours. Meeting 100% of load shift hours requires an increase in tank capacity from 725 gallons to 1050 gallons (Figure 8). Once the CHPWH system is deployed, increased investment in storage volume and controls can greatly improve load shift savings. Linking efficiency and load shift incentives has the potential to substantially improve the economics of deploying load shift in these buildings and increase the adoption of CHPWH technology. Anecdotally, the cost of CHPWH technology alone accounts for the vast majority of the cost to achieve the first increment of load shift capacity, in this case represented by the 725-gallon tank under the baseline CHPWH installation. Placing a value on the additional load shift capacity would inform the incentive price a utility might be willing to pay for the incremental cost of additional DHW storage.

As seen in Figure 8, increasing the system's annual load shift capacity from 50% to over 90% of all annual load shift hours can be achieved by increasing tanks storage capacity by ≈ 125 gallons. The remaining 8-10% must be met with an additional ≈ 175 gallons of storage. The shape of this curve aligns with many similar optimization analyses.

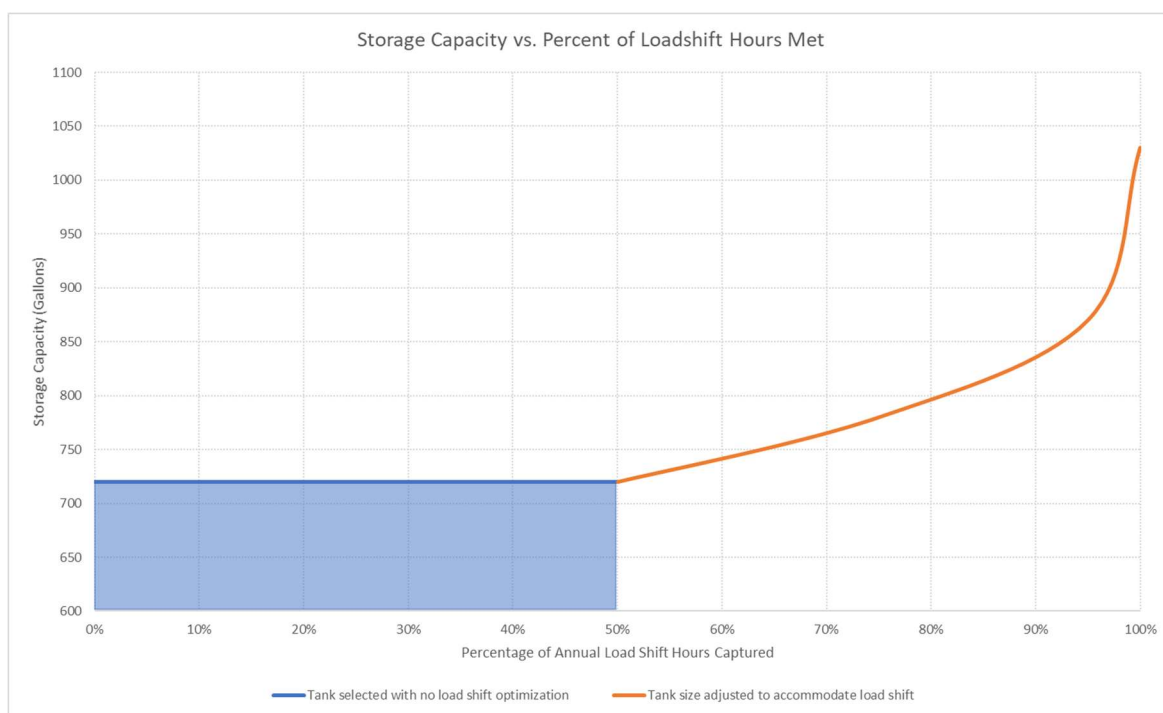


Figure 8: Storage Capacity vs. Percent of Load Shift Hours Met

Since DHW loads are such a significant component of multifamily energy loads, the efficiency of CHPWH systems delivers a significant peak daily savings compared to an electric resistance baseline without any additional investment beyond the deployment of the system itself. Incorporating controls that can deploy load shift signals would be necessary to more fully utilize this load shift potential. In the absence of these control capabilities additional potential peak reductions that could be achieved by leveraging system storage capacity are not necessarily achieved.

In this study, we modeled added storage capacity to the system design to achieve peak daily load shift during all load shift hours in the year. The evaluation suggested that an increase of less than 30% to the storage capacity would achieve this goal. Storage capacity is inexpensive relative to overall HP system cost, but not inconsequential. Additional storage requires additional floor area for more or larger storage tanks and may require additional piping if the number of storage tanks is increased. In this project, the basic storage capacity needed to meet DHW loads was 725 gallons. To ensure that all peak hour loads are shifted, the tank size was increased to 1050 gallons. The incremental hardware cost of this increase was estimated at \$18,000, a cost of approximately \$230/residential unit. This represents an increase on the order of approximately one tenth the cost of the base CHPWH system.

Conclusion

DHW energy use in multifamily buildings represents a significant percentage of total building end use energy, and a significant percentage of total commercial sector DHW energy use. CHPWH delivers significant energy cost savings and peak load reductions across the day compared to much more common electric resistance DHW systems. Furthermore, due to the daily demand profile of DHW loads, peak load reduction is particularly significant in alignment

with utility priorities for load reduction in the morning and afternoon grid peaks. The basic CHPWH technology delivers significant load reductions without additional storage capacity or controls to achieve peak load reduction. The design of CHPWH systems inherently includes significant storage volume that could be controlled to provide some level of additional load shift out of peak periods. This analysis suggests that DHW loads can be shifted out of peak periods for approximately 50% of total annual peak period hours with control adjustments but no change in storage capacity. More significant peak load reduction during grid peak periods can be achieved by increasing CHPWH storage volume. An increase of approximately 30% (in the configuration analyzed) and with the addition of load management controls to align CHPWH operation with time of use rate structures would offset DHW load from up to 100% of annual utility peak load hours. The incremental cost of these additional load shift features represents a fraction of the initial deployment cost of the CHPWH system but achieves peak load reductions of approximately the same additional magnitude as the peak load reduction achieved by the basic technology. In other words, the second increment of peak load reduction, in this case, is significantly less expensive to deploy than the first increment.

The analysis above has implications for utility programs to achieve load shift, by suggesting a potential linkage between efficiency incentives and load shape incentives. In this case, deployment of CHPWH in multifamily achieves not only significant efficiency improvements, but also significant load shape improvements. Once the CHPWH system is deployed, a small additional investment in increased storage volume and controls can practically double the load shift savings achieved. Linking efficiency and load shift incentives has the potential to substantially improve the economics of deploying load shift in these buildings.

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