Thermal Load Shifting with Heat Pump Water Heaters: Technology Brief

Considerations for Applications and Strategies

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This technology brief is intended for building owners, architects, MEP engineers, green building consultants, utilities, 3rd party demand response aggregators, and homeowners who are making design decisions around heat pump water heating (HPWH) systems in new construction multifamily buildings. This paper draws from the findings of the EPIC research project (EPC 15-097) optimizing domestic hot water in four multifamily affordable all-electric new construction projects in California. The research focused on the evaluation of domestic hot water heat pump systems in four multifamily affordable all-electric new construction projects in California. Final Report: Getting to All-Electric Multifamily ZNE Construction Publication Number: CEC-500-202X-XXX.

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Introduction

Domestic hot water accounts for roughly 40% of energy consumption in multifamily buildings in California (EIA 2015). To decarbonize this end use, existing gas systems must be converted to high efficiency heat pump water heaters (HPWHs). With increased installations of HPWHs, electrical demand and strain on the grid will increase. Therefore, it is critical to control these loads not only to minimize additional grid strain, but also to help promote a harmonized grid while meeting hot water needs. Carbon-intensive consumption must be minimized while taking advantage of solar production.

HPWHs can be used as thermal batteries by pre-heating water during renewable electricity's peak midday availability. That pre-heated water can then be used during the evening when the grid's electricity demand peaks and solar availability plummets, which results in a shifting of that water heating electricity use from the evening grid peak hours to the peak solar production hours. This general process is referred to as "thermal load-shifting".

To that end, through this research project, thermal storage strategies and load shifting were evaluated for individual HWPHs and a central HPWH system in two multifamily projects.

A series of thermal storage and load shifting experiments were performed using 50- and 80-gallon Rheem Prestige HPWHs at a multifamily development in California designed to achieve zero net energy (ZNE). Set points, modes, and schedules were adjusted using remote scheduling functionalities based on real-time, iterative analysis of second-by-second energy consumption. The maximum output period from the onsite photovoltaic system occurs from about 9:00 a.m. to about 6:00 p.m. during most of the summer. However, one of the peak times for usage of hot water by households occurs from about 4:00 p.m. to 9:00 p.m. The goal of these experiments was to find the optimal strategy for pre-heating water during solar peak times, storing it at a higher than standard temperature, and minimizing energy use of water heaters during grid peak hours, while simultaneously minimizing total daily energy use. The study had the additional goal of minimizing tenants' awareness that their water heaters were being adjusted during grid peak hours, by assuring that they always have enough hot water for their needs.

Additionally, some load shifting tests were performed on a central HPWH system comprised of 12 Sanden heat pumps connected to 1,500 gallons of storage at another multifamily development in California whose common area was designed to achieve zero net energy (ZNE).

The following sections summarize important thermal load shifting considerations informed by those experiments. It is important to note that the study was somewhat limited in terms of sample size (22 individual HPWHs and 1 central HPWH plant), demographic diversity (one farmworker housing property and one single mixed occupancy), number of experiments performed, and equipment type. Therefore, findings and recommendations described herein are likely to continue to evolve as research efforts are ongoing and additional data is being collected. In addition to the direct findings from the field experiments, the hot water demand, or draw profiles derived from these efforts were used in parallel modeling exercises that helped inform sizing recommendations.

Thermal Load Shifting Considerations

There are a variety of factors to consider when assessing the opportunity for thermal load shifting with HPWHs including, identifying the primary objective of the load shifting effort, choosing the load shift control strategy, system sizing (particularly storage capacity), type/manufacturer of the HPWH product, location of the system/s, and associated climatic considerations.

Load Shifting Objective:

Load shifting can be optimized for different outcomes. For example, some strategies that may be very effective at minimizing HPWH runtime during grid peak hours may result in higher than typical daily energy usage, and vice versa. Therefore, it is important to identify the primary goals of any load shifting effort prior to selecting an optimization strategy. Load shifting can be optimized for one or more of the following outcomes:

- Reduced peak demand (kW) during grid peak hours
- Reduced energy use (kWh) during grid peak hours
- Reduced utility cost ($)
- Reduced carbon emissions (MTCO2)

The experiments conducted under the study aimed to achieve a balance between a number of these different outcomes, namely overall reduction during grid peak (kW and kWh), and minimizing to the greatest extent possible electric resistance run time during off-peak hours so as to reduce overall daily energy consumption.

Load Shifting Control Strategy

There are three primary approaches to controlling water heaters for load shifting purposes (Delforge P., Vukovich J.2018):

Simplest- On/off: This strategy simply blocks HPWH operation during peak hours (4 pm to 9pm) when power is comparatively expensive. This approach requires little investment to implement—a user could install a simple timer. This simplicity is also its chief limitation. If hot water draws during this period exceed the tank's storage capacity, it is unable to recharge. This can result in water being delivered to the customer at lower a temperature than desired. Increasing the set point temperature increases storage capacity, but also leads to higher energy losses from higher operating temperatures and standby losses.

Smarter- Load-up/Shed: A more sophisticated strategy is to load-up (preheat) water during off-peak hours in time for peak, thereby reducing (or shedding) the amount of energy needed to heat the water during the on-peak hours. The load-up phase is an essential precursor to the shed phase, to increase storage capacity and allow shedding over peak with minimum risk of hot water runout.

The load-up/shed strategy is designed to improve upon the on/off strategy while remaining relatively simple. It works well with a TOU price schedule and can be implemented by a local control module and does not require a program offered by the utility or a third-party. The local control is limited to specified static schedules, and it cannot handle dynamic price signals such as from a utility or third-party aggregator, or learn and adapt to household specific hot water use profiles.

Smartest- "Optimal Price" Optimization: The most advanced strategy uses the projected hourly price of energy over the next 24 hours to compute the optimal pattern of pre-heating to minimize cost and hot water runouts for this 24-hour price schedule. The price schedule can be either a 24-hour day-ahead price signal from the utility, or a fixed time-of-use price signal. The algorithm considers the effects of reduced efficiency at higher operating temperatures, and balances price arbitrage with efficiency losses. For example, it only preheats minimally if peak prices are low that day, but preheats to maximum temperature on days when the differential between on- and off-peak prices is the highest.

The field experiments involving individual residential tank type HPWHs focused on testing variations of the second strategy described above, Load-up/Shed, while the experiments performed on the central HPWH plant utilized the simple on/off approach. Therefore, this technical brief will focus on those approaches for the respective HPWH types. However, it is worth noting that as the market for HPWHs expands, fleet sizes increase, communications methods and control algorithms improve, and the 3rd party aggregator market matures, the "Optimal Price" optimization strategy will likely become more prevalent and preferred. The findings and results from the load/up shed experiments may prove useful to third parties developing Optimal Pricing algorithms, as they can provide some understanding of the implications associated with various mode and set point changes.

The variations to the Load-up/Shed experiments included modifications to the following variables:

- Set point temperatures during standard operating hours, load up period, and shed
- Start and end times for standard operating hours, load up period, and shed
- Operating mode during standard operating hours, load up period, and shed

Changes to each of these variables comes with associated tradeoffs. For example, the higher the temperature set point, the lower the operating COP of the unit's heat pump. The lower the temperature set point, the more likely it is that occupants will experience insufficient hot water, or increased use of electric resistance to meet demand. Hybrid mode (which for Rheem's product is called Energy Saver mode) has a higher likelihood of triggering resistance than Heat Pump Only mode, while Heat Pump mode may have a more difficult time maintaining adequate temperatures during high demand periods or low ambient temperature conditions. The longer the shed period, the lower the tank temperature will be at the end of the shed, making it more likely for the resistance element to turn on when in Energy Saver mode immediately following the shed event. All of these variables and associated trade-offs must be considered when developing an appropriate Load-up/Shed strategy.

System Sizing

Individual Residential HPWH

Sizing of individual HPWHs needs to be considered from two perspectives: standard operation and load shifting operation. Ultimately the amount of demand that a HPWH can keep up with is dependent upon the tank temperature at the beginning of a period of demand, the recovery capacity (which is strongly dependent on ambient conditions and heat source), and the amount of hot water demand sustained. This constantly moving target increases the difficulty of adequately sizing HPWHs to limit auxiliary resistance backup, and even more difficult to consistently reduce electrical demand and shift thermal load without draining the tank. In addition, recovery time should also include considerations for 240 V versus 208 V equipment. A HPWH supplied with 208 V will incur longer recovery times, as the heating element capacity is devalued by 75.11%. This can be a 7 GPH difference in recovery. Higher apartment occupancy increases the amount of random variation in daily draw profiles, making both sizing and optimization for thermal storage and reduced energy consumption challenging.

For standard operation, it is recommended to increase the tank size to better correlate with expected occupancy. HPWHs have longer recovery times than gas water heaters, while higher occupancy residences have higher loads and higher potential for consecutive draws. Since HPWH performance is significantly influenced by incoming water temperature and ambient air temperature, sizing for winter loads would represent a worst-case scenario and is therefore the safest approach. Additionally, the sizing can be approached to minimize the use of electric resistance elements, regardless of whether one is load shifting or not.

The Rheem HPWH's used in this study have 3 modes of operation:

- **Heat Pump**: Relies almost exclusively on the heat pump and minimizes the use of the resistance elements.
- **Energy Saver**: Relies primarily on the heat pump, but still uses electric resistance elements to ensure faster recovery.
- **High Demand**: The most aggressive configuration which prioritizes fast recovery over efficiency and thus relies heavily on the electric resistance elements to ensure customer satisfaction.

In a comparison of High Demand mode with a set point of 140°F to Energy Saver at 125°F conducted during the study, there was an overall decrease in energy consumption while in Energy Saver mode at 125°F but an *increase* in the fraction of electric resistance usage. This is in part due to the fact that the smaller volume of available hot water that is exists when storing water at lower temperatures (125°F in this case) results in the water heater having to spend more time trying to recover. The algorithms governing the electric resistance operation for these particular HPWH's may also be playing a role in the frequency of electric resistance operation under that control scenario; however, the black box nature of those algorithms makes that difficult to determine conclusively. For the period analyzed from January through August across 33 apartments, electric resistance comprised an average of 64 percent of energy usage while in Energy Saver mode. With larger storage volumes and higher set points, heat pump only mode can be more prominently utilized and electric resistance will be minimized. Therefore, to ensure hot water delivery and minimize resistance usage, this limited study demonstrated the need to increase stored water at higher temperatures and then utilize the heat-pump only mode.

For units with higher occupant per bedroom ratios, a two-bedroom apartment should have a 65 gallon tank and three- and four-bedroom apartments should have an 80 gallon tank. Each should be installed with a mixing valve to support a higher temperature set point.

Central HPWH Systems

Sizing central HPWH systems for load shifting applications is somewhat more straightforward than sizing individual units due to the inherent flexibility provided by having separated heat pumps and storage tanks. Additionally, the Ecosizer sizing tool that is now publicly available for free simplifies the sizing process and is able to account for load shifting needs. Adequate storage capacity is the key to successful load shifting, and tanks are relatively inexpensive components. Therefore, the primary limiting factor is having enough physical space to locate the additional storage capacity required, which in new construction applications is usually not an insurmountable issue.

Generally speaking, for low-income multifamily buildings using what the EcoSizer calls a Low-Medium demand profile (25 gal/person/day) (which is between ASHRAE's defined Low and Medium profiles) is sufficient to meet demand with an adequate safety factor in most situations. In the case of this demonstration, averaged over the course of a year the daily consumption was 21.8 gal/person/day. Using the Low-Medium demand profile would have provided a 24% safety factor across all demand lengths, while using the Medium (49 gal/person/day) demand profile would have provided a 127% safety factor. The actual system at the Sunnyvale site was sized based on a one-hour peak demand typically used to size gas water heating systems. This amount was allocated entirely to the storage tanks, and then an additional safety factor was added to the storage until the base system of 500 gallons of storage with 60,000 btu/hr was determined. This base system was then used as the basis of the two hot water plants in the building. One plant having one of these 500 gal 60 kbtu/hr base systems, and the second plant having three of them in parallel. The emphasis on storage over recovery, along with the considerable safety factor included by the engineer, made load shifting a promising and relatively low-risk proposition.

A general rule of thumb for sizing for load shifting is to size the storage volume to meet the entire load for the four-hour peak period, and then size the heat pumps to be able to recover the depleted storage during the time between the peak periods. Since heat pumps are generally sized to meet the load with long runtimes on the worst-case winter day when their heat output is lowest, it may be possible to not increase the heat pump size to recover larger storage tanks between peaks during the summer when heat pump heat output is highest. However, if the goal is to load shift year-round, you must ensure you not only have enough storage volume to meet the peak load without turning on the heat pumps, but also more heat pump capacity to recharge the tanks during a shorter period between peaks with reduced winter heat pump output.

HPWH Product Considerations

While many of the unitary HPWHs in production today operate very similarly to one another and have nearly identical operational mode options, each manufacturer has their own proprietary control algorithm that dictates how and when the resistance elements are triggered. Minimizing the need for resistance run time is important from an energy efficiency perspective, and is a critical component of any effective load shifting strategy. Therefore, it can be difficult to predict the energy impact of various strategies without fully understanding how that HPWH's algorithm works. The research team has recommended to various manufacturers' that they provide more transparent operational information, and we hope that in the future it will be included in product literature; however, at this time, it is not. Therefore, the individual HPWH load shifting results and observations described here pertain only to the Rheem HPWHs used in the study. Due to the nature of the simple on/off control strategy used for the central Sanden system load shifting experiments, those findings are less product specific and could be applied to any central plant.

An example of a product specific control logic characteristic that impacted the load shifting strategy had to do with the sequence of mode and temperature set point changes. When coming out of a shed period, tanks will often be depleted and will need to start recharging immediately. The study revealed that when the individual HPWH heater was at a lower set point and in Heat Pump mode during the shed, and the mode and set point are switched simultaneously at the end of the shed (back to Hybrid mode at a higher set point), the electric resistance element would turn on and remain on until the tank was fully re-charged. In order to avoid that high energy usage snapback penalty, the mode needed to be changed first, followed later by the set point. This impact can be further mitigated by gradually increasing the set point incrementally over time. A number of other product specific control features impacted various load shift strategies throughout the project, which reinforces the need to better understand product specific characteristics to the greatest extent possible.

System Location and Climate Considerations

For the individual systems, the experiments revealed that load shifting was far less successful in the winter, regardless of schedule, set point, or mode configurations, than in the summer. Conditions during the winter make operation difficult for a number of reasons:

- Colder incoming water temperatures mean that the HPWHs must provide more energy to heat the same amount of water. Winter and summer cold water makeup temperatures varied on average by approximately 20°F during these experiments, a significant differential.
- Colder incoming water also means that warm water demanded by users must be mixed with more hot water to achieve desirable temperatures.
- Colder ambient air temperatures result in lower COPs and available compressor capacity for heat pumps as there is less heat to be extracted from the air. These HPWHs were installed in unconditioned space and frequently saw temperatures of 40°F in the winter, while daytime temperatures frequently exceeded 100°F in the summer.
- Thermal losses, while not the biggest source of difficulty, are greater in the winter in unconditioned spaces like those in this experiment. This includes both tank and pipe run losses.
- People tend to take longer showers in the winter increasing overall hot water demand.
- Manufacturer-specific programming logic prevents the compressors from operating with very low incoming water temperatures or very cold ambient air temperatures.

Central System Load Shifting

Thermal load shifting was carried out on a central heat pump water heating plant consisting of 12 Sanden heat pumps and three 500-gallon storage tanks. Each of the three storage tanks were fed by four of the heat pumps and the three tanks were piped together in parallel to feed the entire building. Load shifting was achieved by cutting power to a portion of the heat pumps in that plant during the evening peak demand period from 4pm to 9pm. In order to implement the load shifting, remote-enabled load controllers were installed on four of the twelve heat pumps.

The existing system load was analyzed to understand the viability of load shifting, and to identify which heat pumps within the plant were the best candidates to shift. Based on the measured average and peak loads on the specific bank of heat pumps during the identified time period, bank 1 heat pumps were identified as the least loaded bank and were therefore selected for the test. This was the safest option in that if the thermal load shift failed, the availability of hot water to the tenants would not be heavily compromised, if at all. However, it is also worth noting that using this relatively lightly loaded group of heat pumps for the thermal load shift experiment greatly limited the energy reduction potential of the experiment and was intended simply to demonstrate the viability of this load shifting strategy for a central heat pump water heating system. The results presented below show that this type of load shifting with this methodology is feasible; the results can be extrapolated to a more heavily-loaded bank of heat pumps or full systems to understand the impacts and true potential of this type of thermal load shifting.

All in all, the experiment was effective within the limitations of its range. No load was incurred by the bank 1 heat pumps during the 4-9pm power cutoff window, and despite modest energy reduction due to the already lightly loaded bank, energy savings were still achieved. There was no discernable impact on either volume or temperature of hot water delivered to the building. The energy reduction from the bank 1 heat pumps being powered down from 4-9pm every day resulted in a 20% reduction in daily electricity consumption for that bank compared to an equivalent time period prior to instituting the testing. Because this bank of heat pumps carried such a small portion of the DHW production load, this change only resulted in a 4% reduction of overall DHW plant electricity consumption. This finding suggests that, had this system been designed with fewer heat pumps and the same volume of storage, it still would have been able to meet the building's demand, we would still have been be able to successfully load shift, and the load shifting would have achieved a higher percentage of overall DHW electricity reduction.

Conclusion

The experiments performed over the course of the research project demonstrated that there are effective ways to reduce energy consumption and demand of both individual and central heat pump water heaters during grid peak hours to help reduce grid strain. Load shifting with the central system was easier to implement with less risk of tenant dissatisfaction, but that testing was a very limited part of the overall study and no optimization efforts were attempted. Therefore, further research is needed to identify the best optimization strategies for central systems.

For individual systems, all of the factors described above should be considered when developing a load shifting strategy. Some of the key factors to account for include:

- Higher temperature set points result in lower operating compressor COP's.
- Lower temperature set points are more likely to result in insufficient hot water.
- Energy Saver mode (hybrid heat pump and resistance) has a higher likelihood of triggering resistance than Heat Pump mode
- Heat Pump mode will have a more difficult time maintaining temperature set points during high demand periods or low ambient air and incoming water temperature conditions.
- The longer the shed period, the lower the tank temperature will be at the end of the shed, making it more likely for the resistance element to turn on after the shed period when in Energy Saver mode.
- Sizing should be based on winter loads, be done based on occupancy rather than number of bedrooms, and should factor in as much excess storage as possible. At a minimum, two-bedroom apartments should have a 65 gallon tank and three- and four-bedroom apartments should have an 80 gallon tank with a mixing valve to support higher set points (i.e. 140°F).
- Letting tank temperatures drop too far during the shed period can result in large peak loads in the evening after the shed as the HPWH attempts to recover with resistance energy. Gradually increasing the set point over a longer period of time after the shed may reduce this impact.
- Changing the mode from Heat Pump to Energy Saver and increasing the set point simultaneously after the shed will trigger the resistance to run continuously until the new set point is met. Subsequent testing found that changing the mode first, and then subsequently changing the set points minimized that impact and allowed the compressor to operate during the recovery. This finding may only apply to Rheem HPWHs. Similar testing would need to be

performed with other manufacturers' HPWHs to confirm if it applies to other hybrid mode control algorithms.

When ambient air conditions are unfavorable for keeping up with demand, it was better to take a conservative approach to load shifting by keeping the temperature as hot as possible with just the heat pump with a mixing valve set to 120°F, rather than risking resistance-driven recovery by attempting to eliminate compressor use entirely during peak hours. This point is particularly salient when considering populations of unpredictable and highly variable hot water users. Therefore, based on 7 experiments, the best approach for this property for winter to limit not only total energy consumption, but also demand during peak hours was to operate the water heaters in Heat Pump Only mode at 140°F set point at all times. This approach also yielded the lowest overall daily kWh use and lowest overall costs (compared to other winter experiments). The drawback of allowing the heat pump to maintain 140°F during the shed event is that it resulted in greater average peak demand than some of the other load shift strategies tested. Additionally, thermal losses do increase when storing water at higher temperatures; however, this negative impact is insignificant compared to benefit seen from the reduction in resistance heating associated with very low tank temperatures. This is especially true when looking at two experiments that involved actual load shifting during peak hours. In those cases, load-shifting efficacy often suffered towards the end of the peak period when tank storage was depleted. Maintaining a set point of 140°F in Heat Pump mode for all hours results in: (1) Thermal storage depletion due to large coincident demands being less of an issue; (2) Variable demand is smoothed out, especially in apartments that have outlying usage patterns such as very late peaks or unusually high peaks driven by behavior or high occupancy; (3) Very low delivery temperatures are mitigated; and (4) COPs are lower (elevated tank temperatures reduce heat pump efficiency), but still not significantly enough to offset the gains realized by reducing the frequency of resistance energy. This approach resulted in a 7% reduction in costs and 6% in GHGs when compared to the default settings of 125°F and Energy Saver mode.

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