Multifamily Load Shift Evaluation

ECOTOPE

Final Report

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EXECUTIVE SUMMARY

Multifamily domestic hot water accounts for a significant portion of total building load, and daily peak hot water loads tend to align with critical utility load periods. Seattle City Light has adopted a pilot time-of-day rate to incentivize reductions in costly afternoon peak loads. SCL plans to move from a “pilot” to a permanent “opt-in” ToD rate within a few years. This paper analyzes the impact of deploying commercial heat pump water heater (CHPWH) systems to reduce multifamily hot water loads during the afternoon peak. The basic characteristics of centralized CHPWH systems – which employ large storage volumes, high stored water temperature, or both – result in significant peak load reductions. By altering design configuration, SCL can achieve peak load reductions beyond the basic centralized CHPWH characteristics. These alterations include increased water storage capacity, increased temperature setpoints, and lowered aquastat fraction to allow heat pump compressors to ‘coast’ through grid peak periods, relying on system capacity to meet peak domestic hot water loads. This study compares the impacts of various CHPWH configurations to an electric hot water baseline, a configuration that currently represents nearly 80% of the multifamily sector in the Pacific Northwest. Because the design alterations result in similar outcomes, this study uses hot water storage as a legitimate strategy and a proxy for other strategic configurations.

This paper also analyzed the impact and interaction of potential electric vehicle and on-site solar loads on building peak load, in conjunction with the deployment of CHPWH systems. In the scenario analyzed, electric vehicle charging peak loads have approximately the same magnitude as the peak savings from deployment of CHPWH and represent an important opportunity to deploy charge management strategies to reduce the degree to which EV loads are coincident with ToD peak periods.

In this case, the evaluation of solar impacts provides less opportunity to offset ToD peak loads. Neither EV nor DHW loads tend to be simultaneous with PV availability, so the ability to maximize the value of on-site solar in limiting ToD peak loads is limited.

The savings impacts of various load shift strategies analyzed in this report are considered in the context of ToD rates to assess the degree to which the adopted ToD rates incentivize load reduction strategies.

INTRODUCTION

Evolving energy sources on utility grids across the country are driving a more acute focus on strategies to reduce building peak loads, even as overall energy efficiency remains a priority. Recent trends in the multifamily sector targeting decarbonization, solar deployment, and electric vehicle proliferation are driving significant changes in building load and energy use characteristics and represent opportunities for utilities to engage with projects to manage the load shape and grid impacts of these technologies actively.

SCL‘s Grid Modernization Plan recognizes the need to manage new loads to reduce the carbon impacts of energy power market purchases and support integrating demand response and distributed generation resources on the grid. To support this effort, SCL has adopted a pilot time of day (ToD) pricing structure to encourage behavior change and technology deployment that seeks to minimize afternoon grid peaks from building loads. This study analyzes the impact on building load shape of two key multifamily load types (DHW and EV charging) and one distributed energy resource (on-site solar) and explores the potential impact of response to ToD rates on overall building load shape.

Domestic hot water loads represent 25 to 30% of multifamily building end-use energy consumption and a significant portion of daily peak energy use. Therefore, this end-use is an important target for programs to deliver efficiency and load reduction. Commercial heat pump water heaters (CHPHWs) offer a compelling strategy to reduce overall energy use and peak loads and support decarbonization in multifamily projects. Ecotope has deep experience with the development, design, and deployment of this technology and is exploring strategies to configure CHPWH systems to deliver managed load shapes in multifamily buildings. This study uses a modeling analysis to explore the potential impact of load shifting strategies for CHPWH systems, vehicle charging loads, and on-site solar deployment on a current project in Seattle.

To examine SCL's load-shift opportunities with CHPWHs in MF buildings, Ecotope modeled a series of load scenarios at the White Center Hub, a 4-story 74,000ft^2 multifamily building with 76 affordable units. This development initially targeted net-zero energy performance while seeking an ultra-high-energy efficient (UHEE) grant to deploy on-site renewables. Although the project did not receive the UHEE grant, all elements were present to examine load-shifting capabilities to impact building operation and tenant energy costs in a project designed to be highly efficient.

The project also examined the impact on utility costs to the occupants as various technologies and load shift strategies were deployed. Utility cost impacts were evaluated for all of the permutations of DHW system deployment, including baseline electric systems and CHPWH systems with and without load shift. In addition, the cost impacts of vehicle charging strategies with and without load shift controls were compared to different DHW system operating cost impacts.

This study first models the energy consumption of the White Center HUB's DHW draw profile using a code-minimum in-unit electric resistance water heater as a base case. Seattle energy code generally requires centralized CHPWHs in multifamily new construction. However, code permits tank-type in-unit electric resistance water heaters under some exceptions, where the combined capacity of all in-unit electric resistance water heaters do not exceed central CHPWH at 40F. However, in-unit DHW comes at a space premium at odds with rent dollars per square foot.

To determine the load shift capacity gained moving from electric resistance to heat pumps, we then compared the electric resistance DHW load shape to the load shape for a CHPWH system. Next, we increased hot water storage to achieve 100% load shift capacity during SCL's target peak rate period. With 100% load shift capacity established, we then examined the load shape and customer cost impacts of a) CHPWH loads managed to SCL's pilot ToD rate periods, b) EV charging controlled and uncontrolled to avoid ToD rate periods, and c) the impacts of on-site generation. Appendix B examines hot water draw profiles across a sample of multifamily properties, including low-rise, mid-rise, and senior housing.

Multifamily Domestic Hot Water Loads

Over 80% of all commercial energy use for domestic hot water production in the Pacific Northwest is from four building types; multifamily, food service, grocery, and lodging, as shown in Figure 1 (Fernandez, Xie and Katipamula). Within these four sectors, multifamily buildings represent the most significant single sector for DHW loads, representing over 30% of commercial sector DHW energy use.

Addressing DHW energy use in the multifamily sector represents an opportunity for an outsized impact on overall energy use.

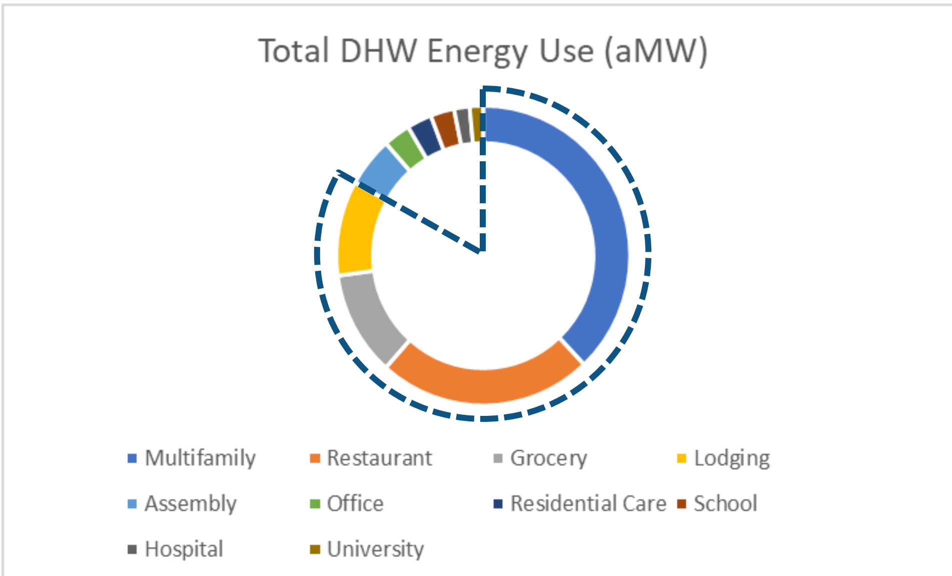


Figure 1: Domestic hot water energy end-use by building type in the United States (source: EIA, PNNL)

In the Pacific Northwest, building characteristics data suggests that in the existing building sector, less than 20% of multifamily buildings currently have central hot water systems for DHW, and of those buildings, only a few have installed heat pumps for this load. However, according to code officials in Seattle, nearly all new multifamily projects over three stories tall install central DHW systems, and the new 2018 Seattle Energy Code strongly encourages CHPWH deployment in this building type. Figure 2 below shows the current distribution of DHW system types by fuel in the existing multifamily sector (Ecotope, Inc.).

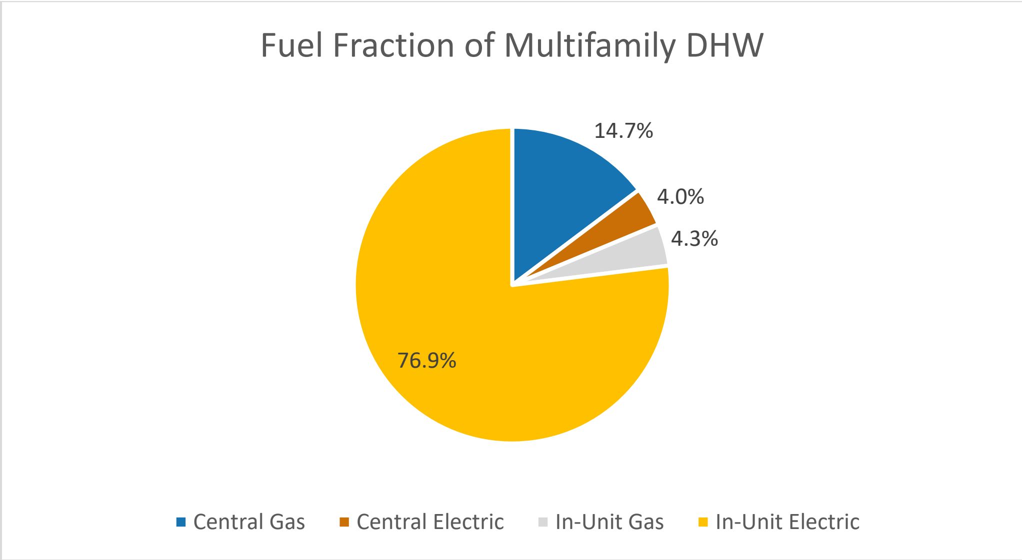


Figure 2: Distribution of DWH System Types by Fuel in Existing Multifamily Sector

For central systems, central gas boilers serve nearly 75% of existing installations. Central electric hot water systems most often utilize commercial electric water heaters or electric boilers. Several manufacturers have introduced heat pump water heaters configured as central systems designed to replace central electric or gas boilers. The nameplate efficiency of a commercial heat pump appliance ranges from a coefficient of performance (COP) of 3.0 to 4.0 or higher. However, the overall system performance efficiency when pumps, storage loss, and recirculation systems are accounted for in total performance ranges between 2.5-3.5 COP. (Conventional systems are also subject to some of these additional losses.) (Northwest Energy Efficiency Alliance). Nameplate efficiencies (Heating Coefficient of Performance – COP_H) are derived from DOE CFR 430 or 431 testing[1]. Because DHW represents such a major component of multifamily energy use, the impact of deploying CHPWH leads to significant energy and cost savings. Figure 3 shows the energy use of a CHPWH system compared to an electric resistance baseline in multifamily buildings.

[1] The Department of Energy requires manufacturers to test equipment at either 80.6°F or 67.5°F depending on the connected electrical capacity and an outlet water temperature of 120°F. Unfortunately, these variable test conditions can cause confusion when comparing HPWH model performance. Additionally, the test requirements encourage manufacturers to optimize equipment around unrealistic outdoor air temperatures and outlet water temperatures. The California Energy Commission's test procedure determines efficiency from realistic climate conditions described in the Advanced Water Heating Specification. Ecotope recommends DOE adopt the CEC test procedure based on the AWHS conditions.

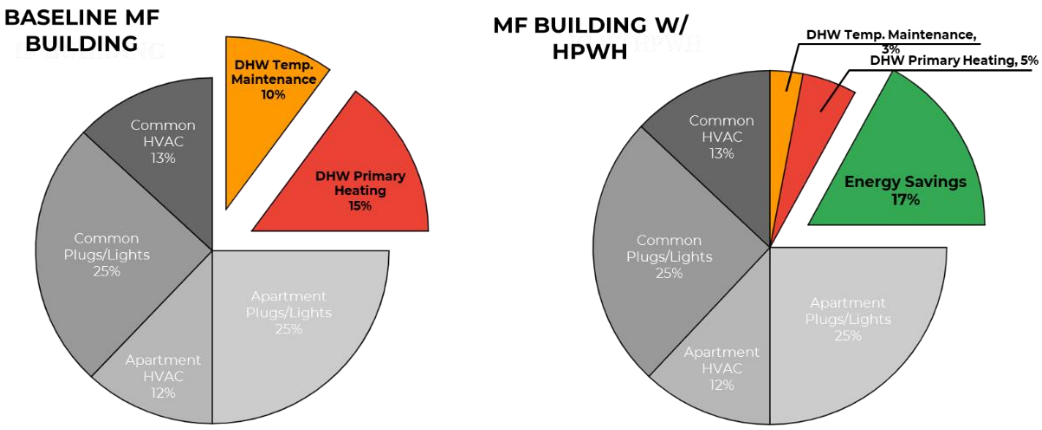


Figure 3: Comparison of multifamily energy end-use; electric DHW baseline to CHPWH. **(Ecotope, Inc.)**

CHPWHs have the potential to reduce the annual energy consumption of MF DHW by nearly 70% (Ecotope) when compared to electric resistance water heaters, making them a highly viable option for utility incentives to increase cost-effectiveness where not required by code or for building retrofits.

Domestic Hot Water Load Characteristics

In addition to significant energy impacts, DHW loads also contribute to overall daily peak energy loads in multifamily buildings. This contribution occurs because DHW demand in these buildings is concentrated in two periods, aligning with other daily building load patterns. The *DHW draw profile,* the equivalent of a load shape for hot water demand, drives energy use in DHW systems. The shape of the DHW draw profile consists of peaks in total gallons demanded and variations in consumption summarized by building or per apartment. In the case of conventional DHW systems, load shape aligns with the draw profile; conventional DHW systems are generally sized to respond directly to hot water draw for tenants by using energy (rather than storage) to meet most of the hot water demand. In the case of CHPWH, the systems use increased storage capacity (or other configurations) to meet hot water draws and recharge the storage tanks with hot water generated over time.

For this discussion, there are two key characteristics of multifamily DHW draw profiles:

DHW demand in multifamily buildings is seasonal.

Figure 4 below shows the season variation of DHW draw profile in a market-rate apartment building. This data shows that the average daily water draw is approximately 20% lower than the peak daily demand. DHW systems must be sized to meet peak demand.

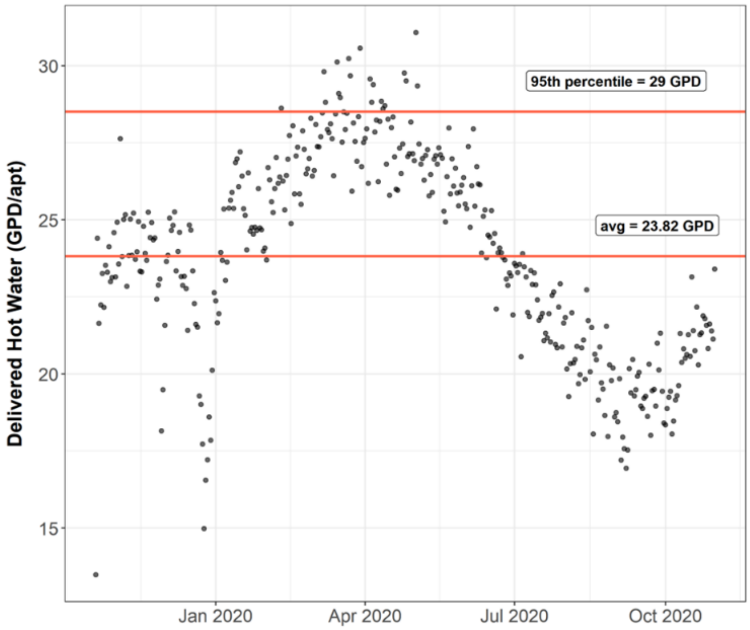


Figure 4: Seasonal DHW draw pattern

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

The second characteristic is that DHW draw profiles have two daily peaks in market-rate housing: a significant morning peak and a less significant late afternoon peak. (Elderly housing and low-income housing demonstrate slightly different daily load shape patterns.)

Based on collected data, figure 5 shows how this daily hot water draw pattern plays out in an average day and on a peak day. The DHW system for these buildings must be designed with a capacity to meet peak daily loads, so on an average day, the system will have excess capacity, primarily in the storage volume.

Because incoming water temp fluctuates, energy use increases marginally when the incoming water temperature drops over the winter and spring months. However, this study controlled these variables to simplify the analysis and demonstrate potential load shift capacity; the modeled electric resistance DHW baseline system assumes a static daily consumption pattern and static incoming water temp (55°F in this case) and a COP of .95 for the heating.

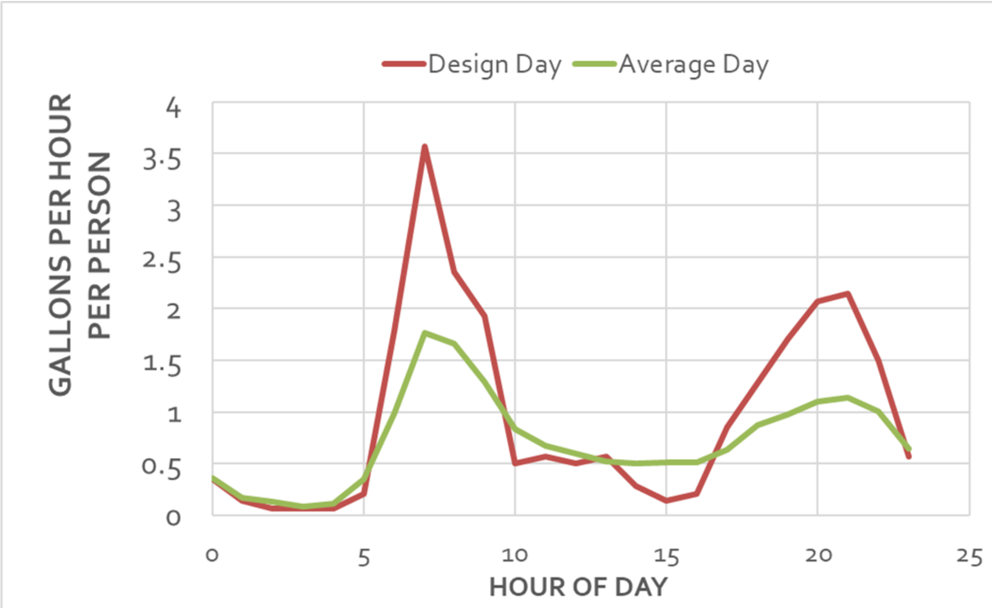


Figure 5: Market rate apartment peak and average daily load shape

These characteristics have significant implications for energy demand and daily load shape in multifamily buildings. The following describes the methods and scenarios used to model CHPWH load shift capabilities within MF buildings.

METHODS

This study developed an energy model for the White Center HUB in IES-VE to determine a baseline whole-building energy profile (Figure 6). Modeling of end uses aligned with ASHRAE 90.1-2010 App guidelines. G. In the baseline scenario, we modeled in-unit electric water heaters, which tend to "turn on" with any significant occurrence of hot water demand. This co-occurance means that, in aggregate, electricity demand for the DHW system directly tracks domestic hot water demand.

Using this baseline, we then developed a series of scenarios to assess the energy and load impacts of CHPWH system deployment, CHPWH with additional storage capacity, and the energy and load impacts of CHPWH operation alone and in concert with emerging loads and generation capacity from EVs and on-site renewables, respectively. Finally, all load shape permutations were analyzed in the context of SCL's ToD rate structure to determine the impact of these permutations on utility costs to building occupants.

Commercial Heat Pump Water Heaters and Load Shift Capacity

We used Ecosizer, a free tool developed by Ecotope for sizing central HPWH systems in multifamily buildings, to determine the size and operating profile of the CHPWH within the White Center HUB to provide the baseline CHPWH scenario. This information was used in the whole building energy model, altering the DHW loads. The models were identical in all other parameters. In order to limit the model variables to compare load shift capacity from storage alone, all load shift scenarios were identical in all parameters except for storage capacity.

SCL's afternoon ToD rate period coincides with the afternoon hot water draw peak. Therefore, limiting heat pump operation to periods outside of the on-peak period resulted in faster hot water drawdown from storage. To ensure the system would meet DHW demand, we calculated the storage tank capacity needed to deliver 100% of the hot water draw without heat pump operation during all SCL ToD afternoon peak hours for the entire year.

Building Model Parameters

The following parameters defined the non-DHW systems within the White Center HUB. These parameters remained constant across all scenarios.

- Square Footage and Occupant Density
  - 4 Floors
  - 74,000 ft^2
  - 76 units
  - 250 ft^2/person[2]
- Envelope
  - Walls – 2x6 Wood Studs at 24 in. o.c. w/ R-19 + R-8 C.I.
  - Roof – R-40
  - Slab – R-24+R-5 CI.
  - Windows – U-0.27
- HVAC
  - Cooling: PTACs (EER – 14)
  - Heating: Electric Resistance heaters (COP – 1.0)
- Lighting
  - Dwelling Units: 0.42 W/ft^2
  - Corridors: 0.4 W/ft^2
- Infiltration
  - 0.1 ACH
- Receptacle/Plug Loads
  - 0.25 W/ft^2

The following parameters were used for the electric resistance DHW baseline scenarios.

- Electric Resistance Tank
  - 15 Gallon Capacity 95% efficient electric resistance tank-type water heater in each unit
  - COP: .95
  - KW load derived from resistance heating elements activating when hot water demand occurs
  - Aggregate electricity demand of all tanks directly tracks domestic hot water demand
  - Static daily consumption pattern
  - Incoming water temp: 55°F

The following parameters were used for the baseline CHPWH scenarios.

- Commercial Heat Pump Water Heater, designed as a central system
  - Commercial heat pump water heater for building with recirculation system and swing tank

  - Storage capacity-optimized for heat pump capacity by Ecosizer – 725 Gal.
  - 40 kW (11.4 ton) nominal capacity

The following parameters were used for the load shift CHPWH scenarios.

- Commercial Heat Pump Water Heater, designed as a central system
  - Central heat pump water heater for building with recirculation system and swing tank
  - Storage capacity optimized to capture the entire 5 PM to 9 PM load shift period – 1050 Gal.
  - 10 ton(nominal capacity) Mitusbishi QAHV CO2 heat pumps

Electric Vehicle Charging Parameters

With baseline and controlled and uncontrolled load shift capacity established for the DHW system, we evaluated the impact of EV charging on load shift by comparing EV loads controlled and uncontrolled to avoid the SCL afternoon ToD peak period for the baseline electric resistance and CHPWH load shift scenario.

We used NREL published data to determine charging patterns for EVs and EV ownership rate as a percentage of total occupancy in the building. Uncontrolled EV charging is based on these rates. Controlled charging assumes that 80% of EV owners choose not to charge during the SCL ToD afternoon periods and delay charging until after the ToD period. Charging that occurs outside of the on-peak period is spread evenly over the remaining non-peak periods (from 9 PM to 6 AM).

The following parameters were used for the EV load shift study:

- Baseline and CHPWH load profiles: same as above
- Typical Level 2 EV Charging times and draw (Blonsky, Munankarmi and Balamurugan)
- Average daily miles driven (Blonsky, Munankarmi and Balamurugan)
- Current quantity of vehicles and forecasted quantity of vehicles (IEA)
- Predicted times when EVs will charge in residential projects (Blonsky, Munankarmi and Balamurugan)
- SCL rates and load shift period (Tables 1 and 2 below)

EV Assumptions

- kWh per mile: 0.346
- Miles driven per day per EV: 37
- kWh electricity needed per day per EV: 12.8
- EV quantity: 20
- Level 2 EV chargers: 30
- Percent of EVs participating in peak load shift: 80%
- Load Shift Periods: 5PM to 9PM

Scenarios

- Electric Resistance Tank with uncontrolled EV charging
  - EV charging curve is based on published NREL Data
  - Assumes one vehicle per household and 10% of vehicles are EVs
- Electric Resistance Tank with 5PM to 9PM Load Shift EV charging

- EV Charging curve is based on modified NREL curve assuming that 80% of EV drivers chose to participate in the Load Shift program. These EVs do not charge from 5PM to 9PM and instead their charging load is distributed throughout the hours of 9PM to 6AM
- Other assumptions same as above

On-Site Solar Parameters

We evaluated the opportunity to align on-site solar electricity generation with EV charging and the coincident impact on DHW load shift. We use an electric resistance baseline and controlled CHPWH load shift scenarios to establish the effect.

Photovoltaic (PV) generation capacity is based on TMY3 incident solar radiation data.

The following parameters were used for the EV with solar load shift study:

- Baseline and CHPWH load profiles: same as above
- EV charging assumptions: same as above
- TMY3 incident solar radiation data
- 9,400 SF of roof area
- 65 SF per kW of generating capacity
- SCL ToD rates and load shift period
    - Current rate structure (see Reference values on next page)

Cost Impacts

All scenarios use SCL's Pilot ToD rates and ToD periods to determine cost impacts. Predicted kWh loads for each time period were multiplied by utility rates for each ToD period to establish costs for each scenario.

Table 1 – Current Residential Rates

	Seattle, Renton, Unincorp. King County
Base service charge per day	$0.1974
1st block per kWh*	$0.1056
2nd block per kWh	$0.1307

**1st block equals 300 kWh per month from April-September and 480 kWh per month from October-March.*

Table 2 – Time of Day Pilot Rates

Time	Sun	Mon	Tues	Weds	Thu	Fri	Sat
12AM-6AM	$0.07/kwh	$0.07/kwh	$0.07/kwh	$0.07/kwh	$0.07/kwh	$0.07/kwh	$0.07/kwh
6AM-5PM	$0.11/kwh	$0.11/kwh	$0.11/kwh	$0.11/kwh	$0.11/kwh	$0.11/kwh	$0.11/kwh
5PM-9PM	$0.11/kwh	$0.16/kwh	$0.16/kwh	$0.16/kwh	$0.16/kwh	$0.16/kwh	$0.11/kwh
9PM-12AM	$0.11/kwh	$0.11/kwh	$0.11/kwh	$0.11/kwh	$0.11/kwh	$0.11/kwh	$0.11/kwh

Tools

IES-VE - a CIBSE & ASHRAE qualified dynamic whole-building energy modeling platform that can provide detailed building and systems design evaluations. IES-VE can be used to account for several variables that affect building performance, such as site weather data, building orientation and geometry, envelope construction, occupancy schedules, heating & cooling loads, and energy use of various equipment (lighting, HVAC, DHW systems, etc.).

Ecosizer – a web-based tool for sizing central water heating systems based on heat pump water heaters (HPWHs) in multifamily buildings. Ecosizer is designed to support the building industry to adopt HPWHs to improve energy efficiency and reduce greenhouse gas emissions. The Ecosizer load shift tool is under development and subject to continuing measurement and verification. Results do not include potential load shift gains from improved controls that do not rely on increased storage volumes.

Other calculations:

- PV data was calculated based on TMY3 incident solar radiation data and assumes 65 SF per kW of generating capacity and 9,400 SF of roof area.

- EV energy consumption based on assumption of 37 Miles per day EV use (Federal Highway Adminstration) and 0.346 kWh/mile (U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy) (Eco Cost Savings)

RESULTS

Baseline Model Load Shape and End Use

In the baseline model, the daily load shape demonstrates two daily peaks, in the morning and afternoon. When individual end-use contributions are considered, it is clear that DHW loads represent a significant element of the daily peak configuration. Figure 6 displays the daily end-use building loads modeled for a winter day at the White Center HUB with electric resistance tank-type water heaters in each unit (baseline).

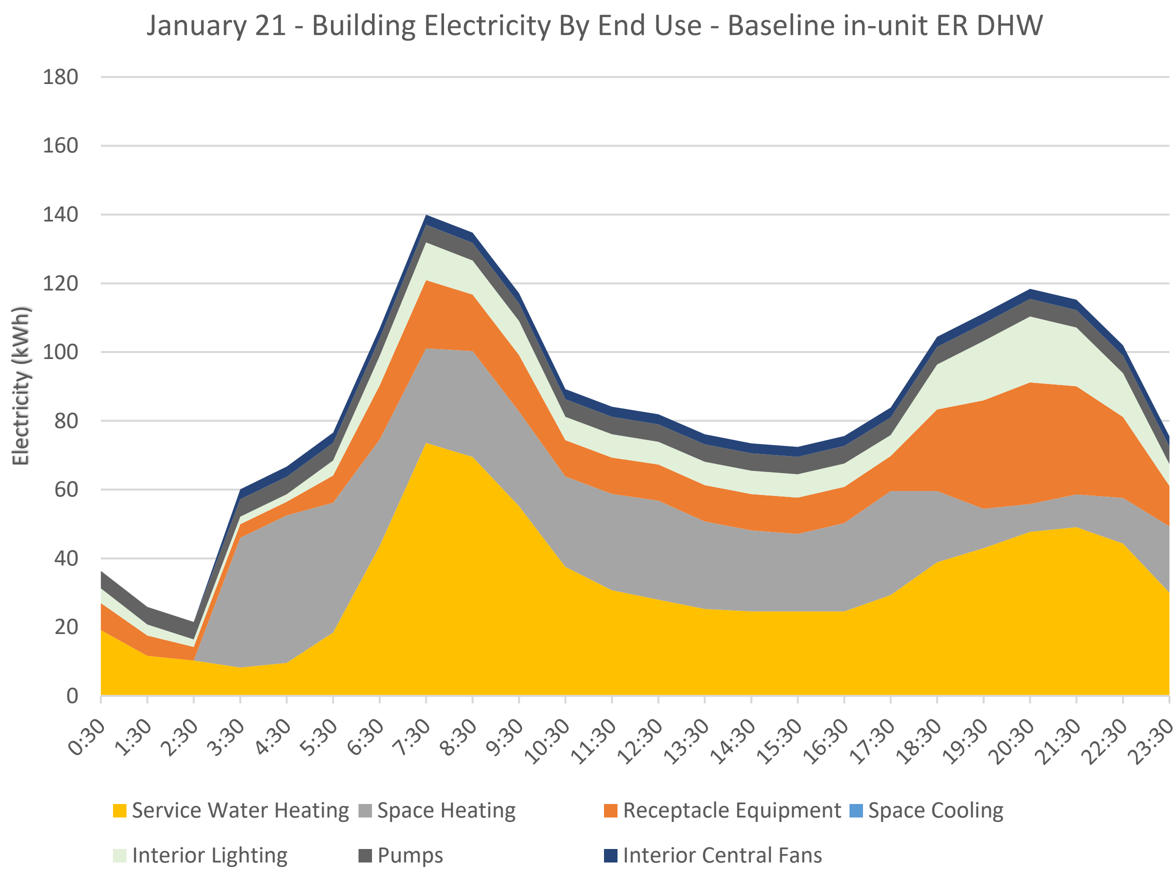


Figure 6: Daily building energy use load shape, by end use, with electric resistance DHW

Note that White Center Hub was designed to exceed baseline energy code performance significantly. Our baseline model consists of a very efficient envelope and lighting features with a code minimum electric DHW system, electric resistance heating, and added unitary cooling from packaged terminal air conditioners (PTACs). This configuration is the baseline input to compare against the CHPWH scenarios.

The Jan 21 snapshot of a typical winter load shape indicates that electric resistance DHW consumption comprises over half of the total winter morning peak and over 1/3 of the total winter afternoon peak for the building. Four seasonal snapshots representing other daily load shapes provide additional granularity to this analysis in Appendix B. Across all days, electric resistance DHW comprises 61% of morning peak and 40% of afternoon peak on average. Electric resistance is the current fuel choice for DHW in nearly 80% of existing multifamily buildings in the Pacific Northwest (NEEA).

Focusing on the impact of Commercial Heat Pump Water Heaters on load shape

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 relatively large storage volume in highly insulated tanks. The HP is designed to operate 12 to 16 hours a day to generate hot water that is then held in large storage tanks. When the peak periods of the day occur, the storage volume, not the HP itself, is used to meet building DHW load. As the storage volume is depleted, the HP is used to replenish the storage tanks. From a load shift perspective, as long as the storage tanks contain enough hot water to meet peak hot water draw, energy is not necessarily needed to operate the heat pumps simultaneous to peak water draw. The heat pump will begin operating to replace DHW volume as users deplete the stored hot water past predetermined volumes.

Between the increased system efficiency and the impact of large storage volume, deploying a CHPWH system to serve DHW loads substantially reduces total building peak loads.

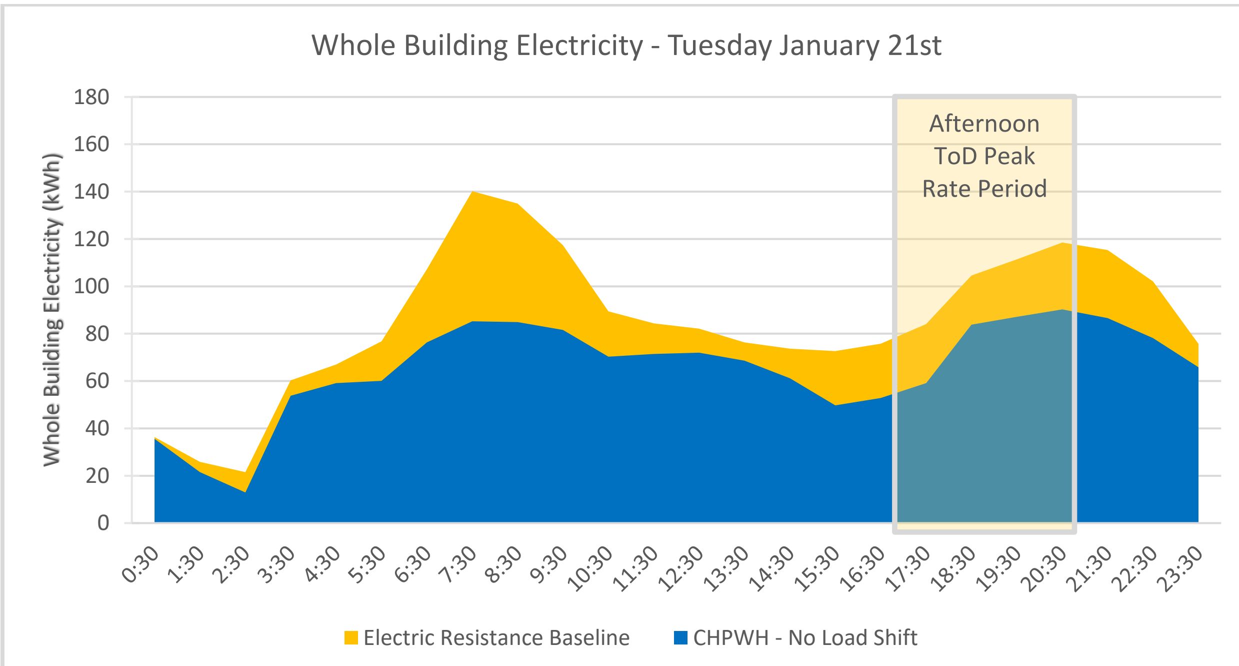


Figure 7: Total building daily load shape, electric resistance DHW vs CHPWH, with ToD peak rate period indicated

The Jan 21 snapshot seen in Figure 7 compares a representative winter day. The change from electric resistance to CHPWH DHW represents a 39% reduction in morning peak and a 24% reduction in afternoon peak for whole building consumption. This reduction represents the passive impact of the technology in the absence of any load shape management strategies. This graph highlights a key finding of this study: in addition to significant energy savings, CHPWH technology deployment alone achieves significant peak reduction during ToD peak rate periods. Figure 7 also shows how SCL's pilot ToD peak rate period aligns with building peak loads. Table 1 summarizes the differences in afternoon peak load of our four seasonal snapshots.

Table 3 – Seasonal Afternoon Building Peak Load Analysis

Season (day)	Base Afternoon Building Peak Load [kWh]	Building Afternoon Peak Load w/CHPWH [kWh]	Percent Reduction
January 21st	119	90	24%
April 21st	112	80	29%
July 21st	137	103	25%
October 21st	114	83	27%

Domestic Hot Water Analysis: Comparing Scenarios

Considering the DHW loads in isolation helps clarify the load shape impacts of DHW system alternatives. In Figure 8, we compare the baseline DHW energy use (yellow) and CHPWH system energy use (blue) to show the load shift achieved from the CHPWH technology alone (without deploying any additional storage capacity beyond that required to meet daily DHW loads in the building). The change in systems resulted in a 75% reduction in morning DHW peak and a 59% reduction in afternoon DHW peak.

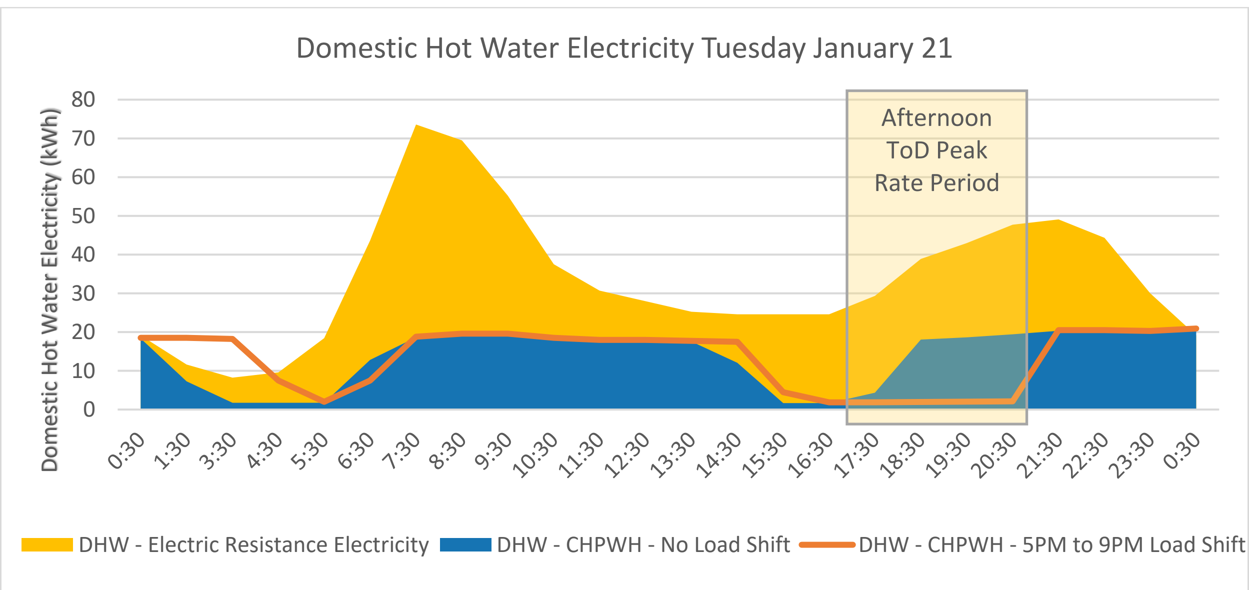


Figure 8: Load shift in DHW with CHPWH and oversized storage capacity compared to CHPWH without load shift and electric resistance DHW baseline.

Building on this, the analysis next considered the impact of increased storage volume with grid responsive controls to maximize peak load reduction in the peak afternoon period. In this scenario, the volume of CHPWH system storage was increased so that the HP system could remain off during peak afternoon ToD rate period of 5-9, relying on storage volume to meet DHW demand during this period for every day of the year. The system was assumed to have a storage volume large enough to meet all hot water loads during the peak afternoon period, any day of the year, without relying on HP operation until after the end of the peak period.

The orange line represents this ToD load shift scenario in the Jan 21 snapshot of a typical winter load profile. Adding storage and controls to avoid afternoon ToD peak rates resulted in a significant additional reduction in afternoon DHW peak below the electric resistance baseline, totaling a 96% reduction in DHW afternoon peak (39% of total building load). The whole building results for these scenarios can be seen in Figure 9. Four seasonal snapshots of Figure 9 provide additional granularity to this analysis in Appendix B.

At the end of the afternoon peak period, the heat pump compressor resumes operation to recharge the depleted storage volume, with heat pump runtime extending into the early morning to replenish the storage tank. Because this model controls for heat pump compressor size, overall energy consumption remains approximately the same between the uncontrolled (blue) and load shift (orange) scenarios. Energy use is simply shifted from afternoon and evening hours to nighttime hours.

Several studies (Bonneville Power Administration), (Upadhye, Domitrovic and Amarnath) have demonstrated the demand response potential from connected electric resistance DWH storage. However, because of the limited storage and variability in hot water draw, this DR strategy requires extensive unit aggregation across a community to be effective beyond a single multifamily building.

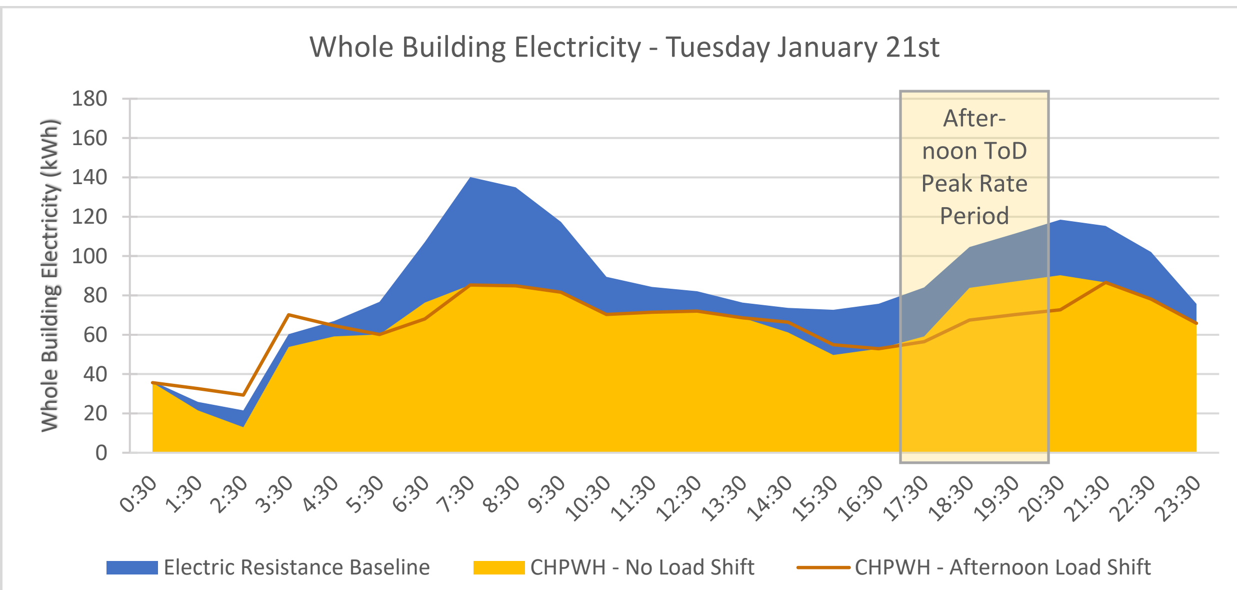


Figure 9 – Winter Afternoon Whole Building Load Shift

Winter Load Shape Day: Jan 21	Afternoon Peak KW: Electric Resistance	Afternoon Peak KW: CHPWH – no load shift (% change from ER)	Afternoon Peak KW: CHPWH – Afternoon load shift (% change from ER)
Whole Building Electricity (Figure 11)	119	90 (-24%)	73 (-39%)

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 5 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.

At the White Center HUB, multifamily CHPWH deployment achieves significant energy efficiency beyond code minimums 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 9)[3]. 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 SCL might be willing to pay for the incremental cost of additional DHW storage.

As seen in Figure 10, 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. Determining the ideal percentage of annual afternoon load shift hours available to SCL would inform the amount of incentivized storage needed for an individual installation.

Note that this graph does not indicate which hours of the year the load shift is not achieved. For example, the 'unachieved hours' could be clustered on a few peak days or represented by the 'last hour' of the ToD load shift period on a larger number of days. Additional analysis could assess the temporal characteristics of the load shift not achieved and how these might align with seasonal utility priorities.

[3] Storage costs vary based on a number of factors including available floor area, new construction vs. retrofits, and current market prices. Generally, adding storage or other load-shift control configuration is a small fraction of the initial baseline CHPWH investment.

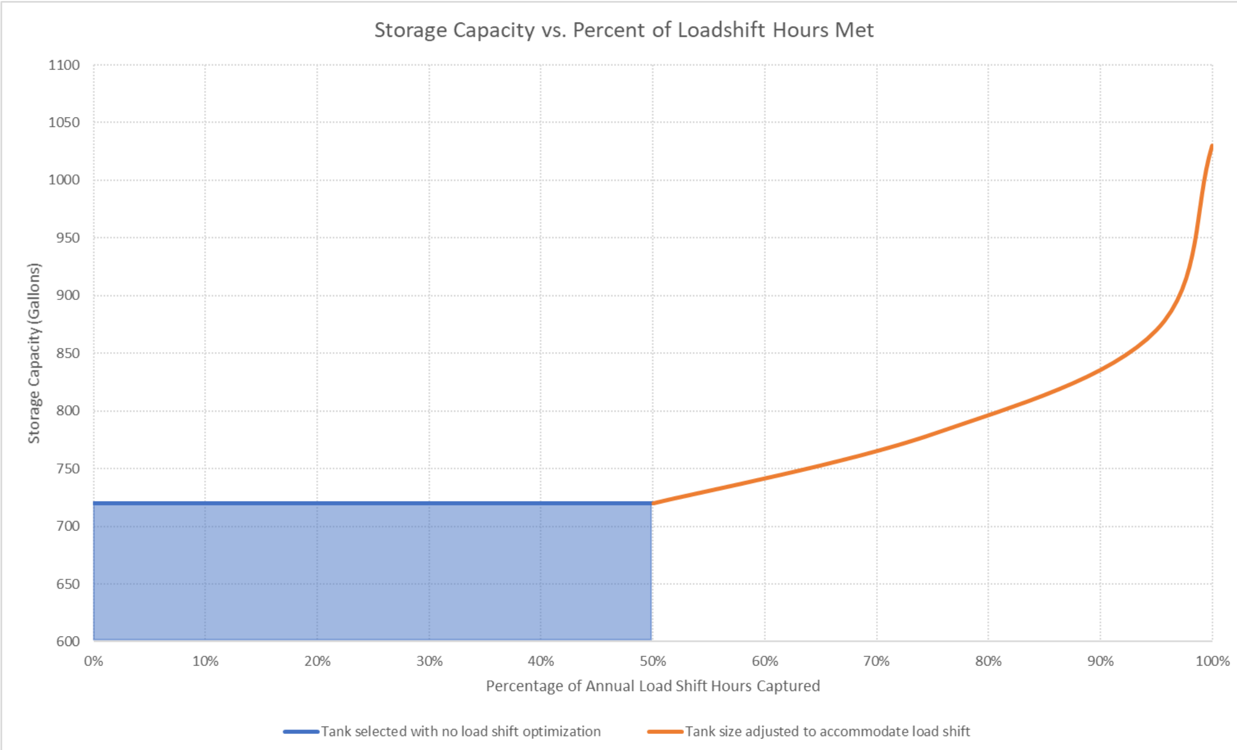


Figure 10 – Storage Capacity vs. % of Load Shift Hours Met

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. However, in the absence of controls to manage how the system is deployed, additional potential peak reductions that could be achieved by leveraging system storage capacity are not necessarily achieved.

In WA, manufacturers of DHW systems are required to include a CTA-2045 port as part of the equipment, which can receive signals to deploy various grid integration strategies. (The CTA-2045 port itself is a standardized receiver for a third-party control module connected to grid signals; the DHW system controls are then able to respond to a specific set of load shift commands when deployed.) Supply constraints have delayed the deployment of this requirement, but eventually all DHW systems will have the capability to receive signals to manage load shift capabilities. The intention is to facilitate the deployment of simple control devices by utilities or third-party aggregators to deploy load shift in DHW systems. The cost of these control modules has not yet been determined.

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 25% 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.

Electric Vehicle Charging Impact on Load Shift

A combination of efficiency and load management strategies can help SCL manage the expected load growth from electric vehicle charging. Controlling for afternoon peak for both EV charging and CHPWH runtime provides a picture of the potential impact of ToD rates on both loads. The following assesses the potential impact of EV charging on the White Center HUB's load shape and sets the stage for a deeper analysis of the potential interactive effects between on-site solar generation, CHPWH load shift, and EV charging.

The Jan 21 snapshot of a typical winter load profile in Figure 11 describes the baseline electric resistance DHW scenario without EV charging (blue), with uncontrolled EV charging (gray), and EV charging optimized to avoid ToD peak rates (green). The addition of uncontrolled EV charging results in a 25% (30KW) increase in afternoon peak. Controlling for afternoon peak ToD periods reduces the afternoon peak increase to 5% (6KW) above the "no EV" baseline, displacing charging to the early morning. Four seasonal snapshots provide additional granularity to this analysis in Appendix B.

The following matrix describes the permutations of the analysis focusing on afternoon peak, color-coded to the charts below.

Winter Load Shape Day: Jan 21	Afternoon Peak KW: No EV Charging	Afternoon Peak KW – Uncontrolled EV Charging (% change from no charging)	Peak KW: EV Charging Optimized for Peak (% change from no charging)
ER Baseline DHW (Figure 11)	119	149 (25%)	125 (5%)
CHPWH Load Shift DHW (Figure 12)	73	103 (41%)	79 (8%)

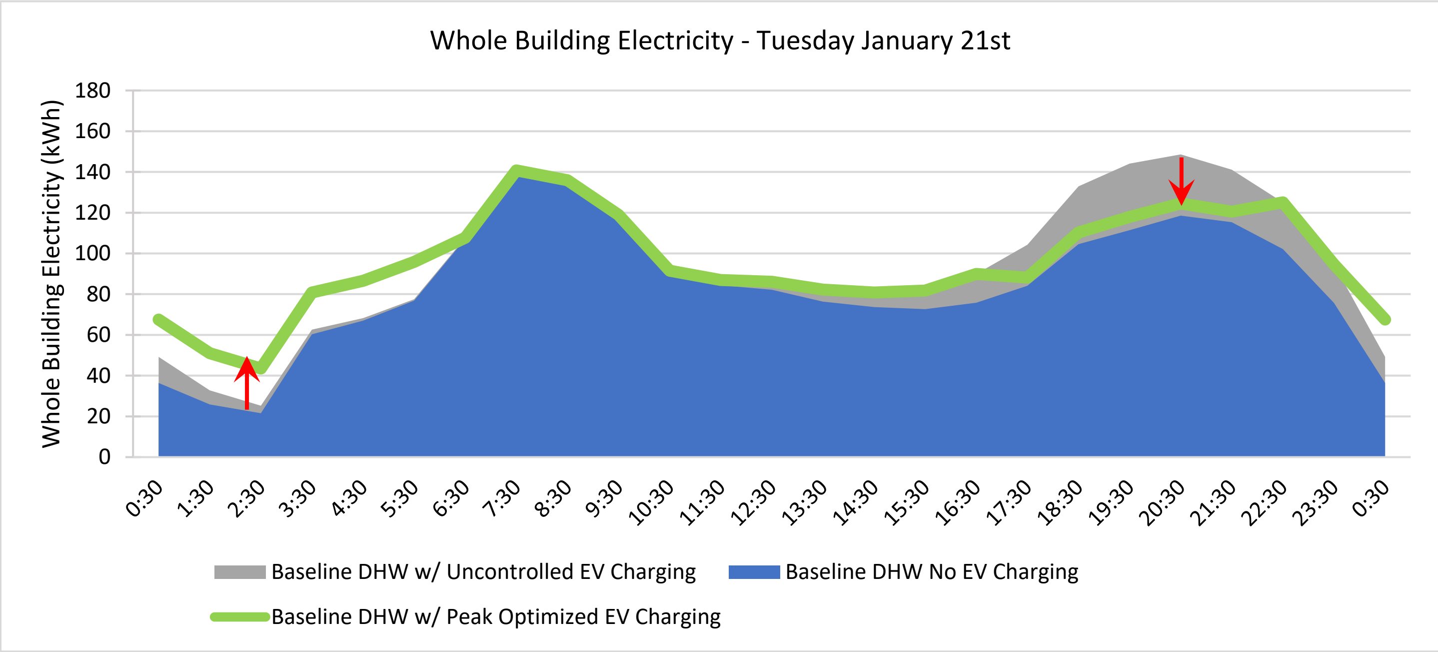


Figure 11 – Uncontrolled and ToD Optimized EV Charging with Electric Resistance DHW

Figure 12 shows our analysis of the controlled and uncontrolled EV charging variables under a CHPWH load shift scenario: No EV charging with load shift (light orange), uncontrolled EV charging with load shift (light brown), and EV charging optimized to avoid ToD peak rates with load shift (light blue line). In this scenario, the addition of uncontrolled EV charging results in a 41% (30KW) increase in the afternoon peak. Controlling for afternoon peak ToD periods reduces the afternoon peak increase to 8% (6KW) above the “no EV” baseline, displacing charging to just after the afternoon ToD period and well into the early morning. Four seasonal snapshots provide additional granularity to this analysis in Appendix B.

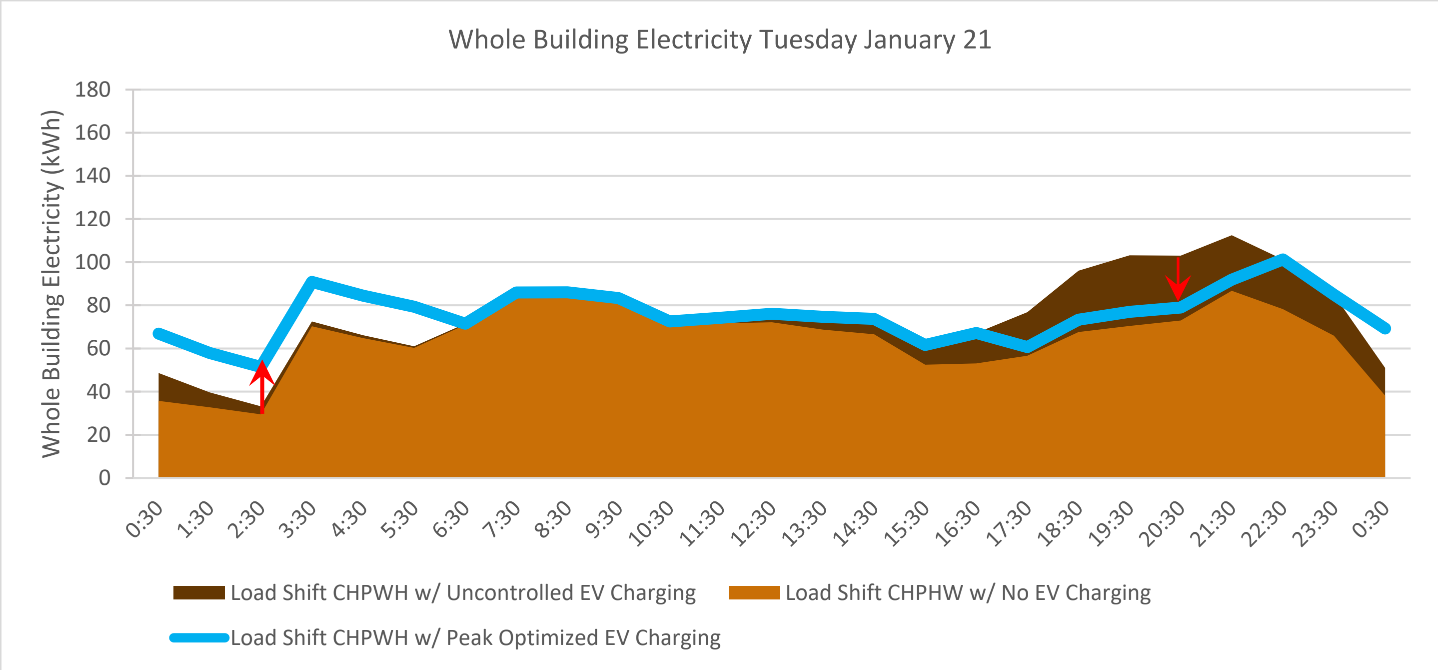


Figure 12 – EV charging with CHPWH Load Shift

Solar Interactions with Electric Vehicle Charging and Load Shift (Heat Pump Water Heater)

In addition to increased EV loads, distributed energy resources such as on-site solar are expected to impact building load shape in the coming years. The following evaluates the possibility of opportunistically aligning CHPWH loads to on-site solar energy generation at the White Center HUB while considering the load impacts of EV charging.

The winter load profile in Figure 13 represents the baseline electric resistance DHW scenario with uncontrolled EV charging (gray), on-site solar generation and uncontrolled EV charging (green), and on-site solar generation and with EV charging optimized to avoid afternoon peak ToD rates (dark orange line). The addition of solar to uncontrolled EV charging decreased loads during the mid-peak period from ≈7:30 to ≈4:30 by a maximum of 39.6KW for the 11 AM hour, resulting in a 45% load reduction. From 9:30 AM to 3:30 PM, solar generation reduced loads by 28.8KW or 33% on average. Controlling for afternoon peak ToD periods reduced the afternoon peak by 24KW or 16% during the peak hour, displacing EV charging to just after the afternoon ToD period and into the early morning. Four seasonal snapshots provide additional granularity to this analysis in Appendix B.

The following matrix describes the permutations of the analysis focusing on afternoon peak, color-coded to the charts below.

Winter Load Shape Day: Jan 21	Afternoon Peak KW – Uncontrolled EV Charging	Afternoon Peak KW – Uncontrolled EV Charging with solar generation (% change from uncontrolled)	Afternoon Peak KW – EV Charging Optimized for Peak w/ Solar Generation (% change from uncontrolled)
ER Baseline DHW (Figure 13)	149	No Change	125 (-16%)
CHPWH Load Shift DHW (Figure 14)	103	No Change	79 (-23%)

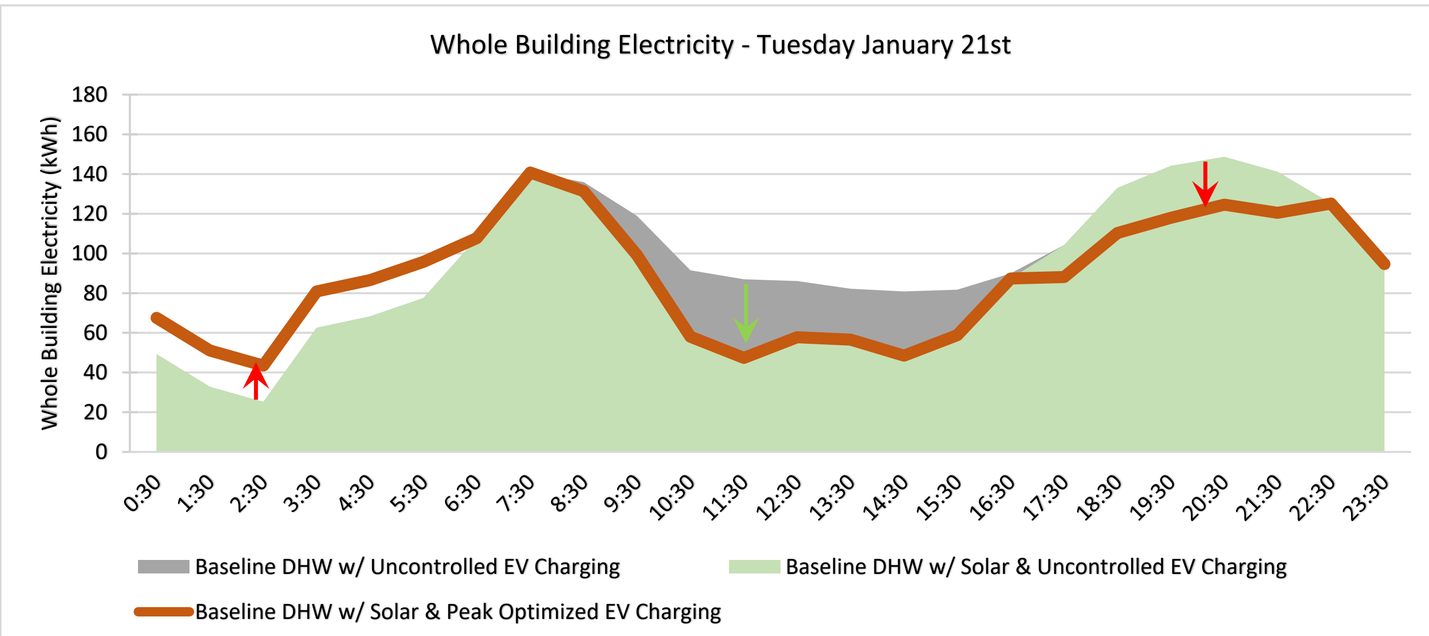


Figure 13 – Impacts of Solar Generation on EV Charging with Electric Resistance DHW

Figure 14 represents our analysis of the EV with on-site solar variables under a CHPWH load shift scenario: uncontrolled EV charging (light blue), on-site solar generation and uncontrolled EV charging (dark brown), and on-site solar generation and with EV charging optimized to avoid afternoon peak ToD rates (gold line). The solar additions provide the same generating capacity to the CHPWH load shift scenario but now comprise a larger portion of the whole building load. From ≈7:30 to ≈4:30, solar generation peaks at 11:30 with 39.6KW for the hour, resulting in a 53% load reduction. From 9:30 AM to 3:30 PM, solar generates on average 28.8KW or a 33% load reduction. The 24KW reduction resulting from ToD controls resulted in a 23% load reduction during the afternoon peak hour, displacing EV charging to just after the afternoon ToD period and into the early morning. Four seasonal snapshots provide additional granularity to this analysis in Appendix B.

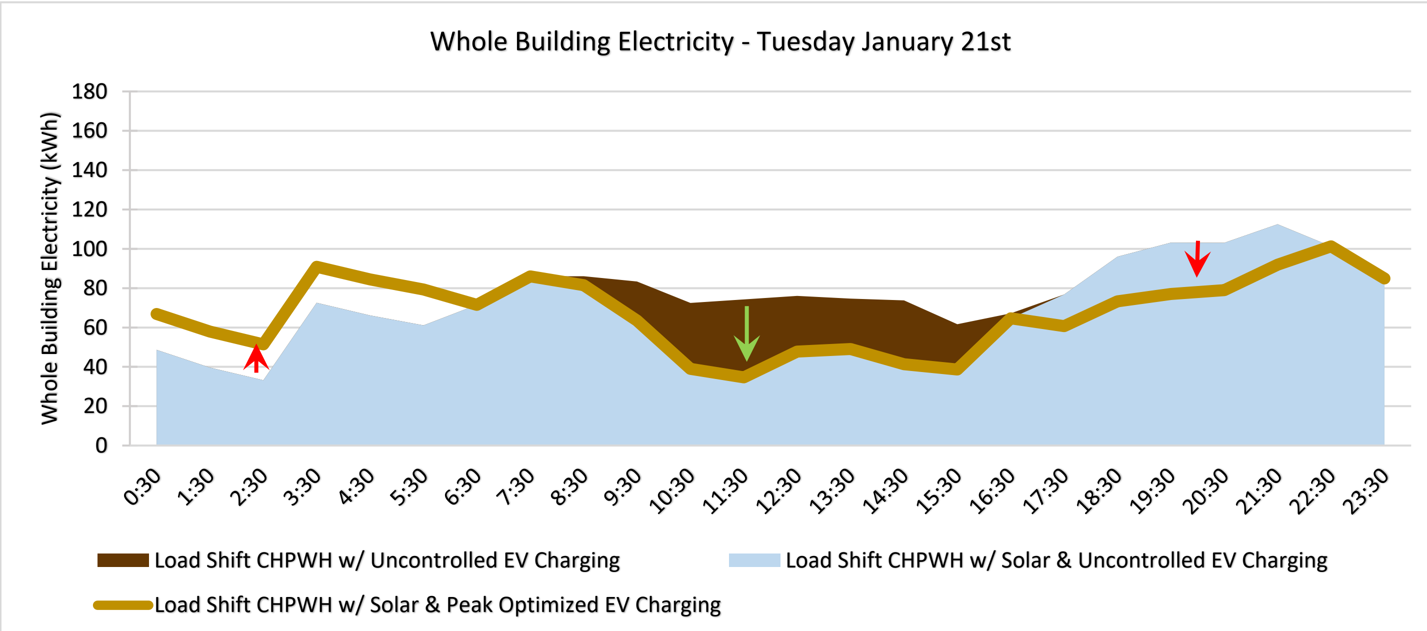


Figure 14 – Impacts of Solar Generation on EV Charging with Load Shifted CHPWH DHW

Market rate MF buildings do not typically see EV charging in the middle of the day. There is little opportunity to align these loads with solar generation in these buildings. However, weekend charging and growth in work from home may increase mid-day residential charging. Other residential classifications, such as senior housing and low income, have occupancy profiles potentially more conducive to mid-day charging. White Center HUB has an on-site community center, which may host more mid-day activities in much the same way as mixed-use developments with shopping and dining. Public parking for mixed-use within MF developments are ideal for taking advantage of mid-day solar.

WINTER VERSUS SUMMER PEAK

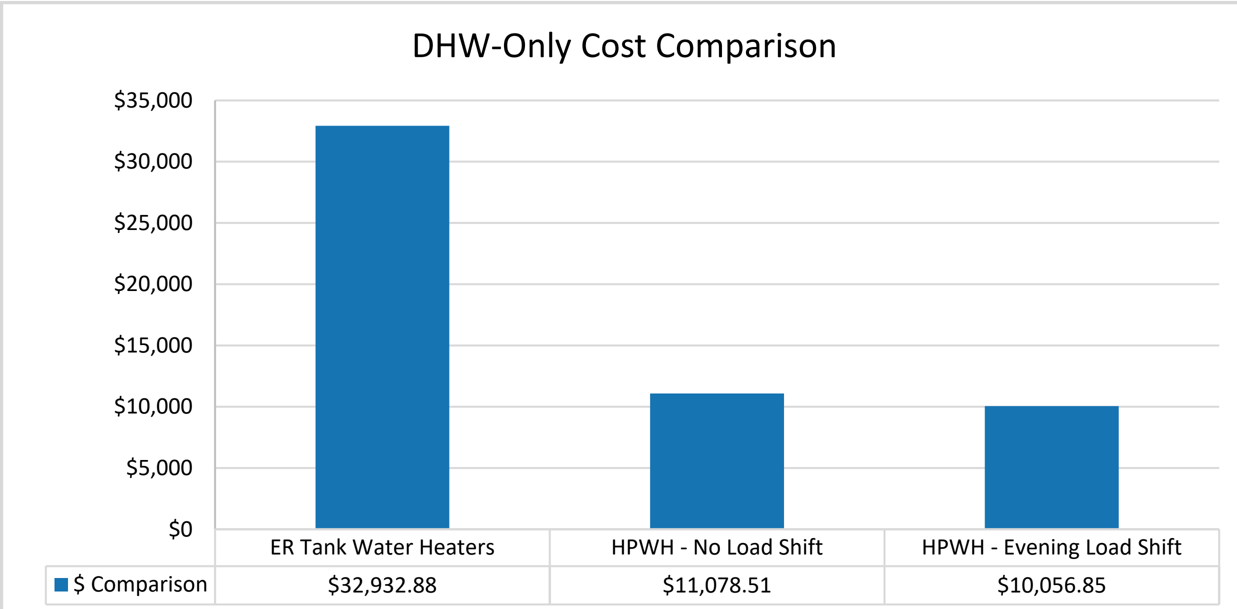
Typically, grid peak loads occur during the winter heating season in the Pacific Northwest. This study focuses on winter peak for that reason. However, the White Center HUB's highly insulated envelop modeled a summer building peak, as demonstrated in Appendix A's tables and charts. While the impacts of climate change are outside the scope of this study, the insights derived from the August snapshots may help SCL discern the importance of summer load shift as those months warm in the coming years.

For example, DHW morning and afternoon peaks typically misalign with solar availability. However, solar offsets a portion of the afternoon building peak load and the mid-day CHPWH loads in the August snapshot (Appendix A, Impacts of Solar Generation).

Because late-summer peaks tend to have the highest impact on power procurement and grid reliability, reliable multi-hour summer load shift may prove important in the coming years.

COST IMPACTS

All cost scenarios use SCL's Pilot ToD rates and ToD periods to determine cost impacts. The following DHW-only cost comparison contrasts the energy loads for water heating along as predicted by the modeling software and matched to the relevant rate for each ToD period, establishing the costs for each scenario. Our modeled CHPWH results in a $21,854.37 savings below the Electric Resistance baseline for the DHW load alone. Load shift combined with the ToD rates adds $1021.66 in savings.



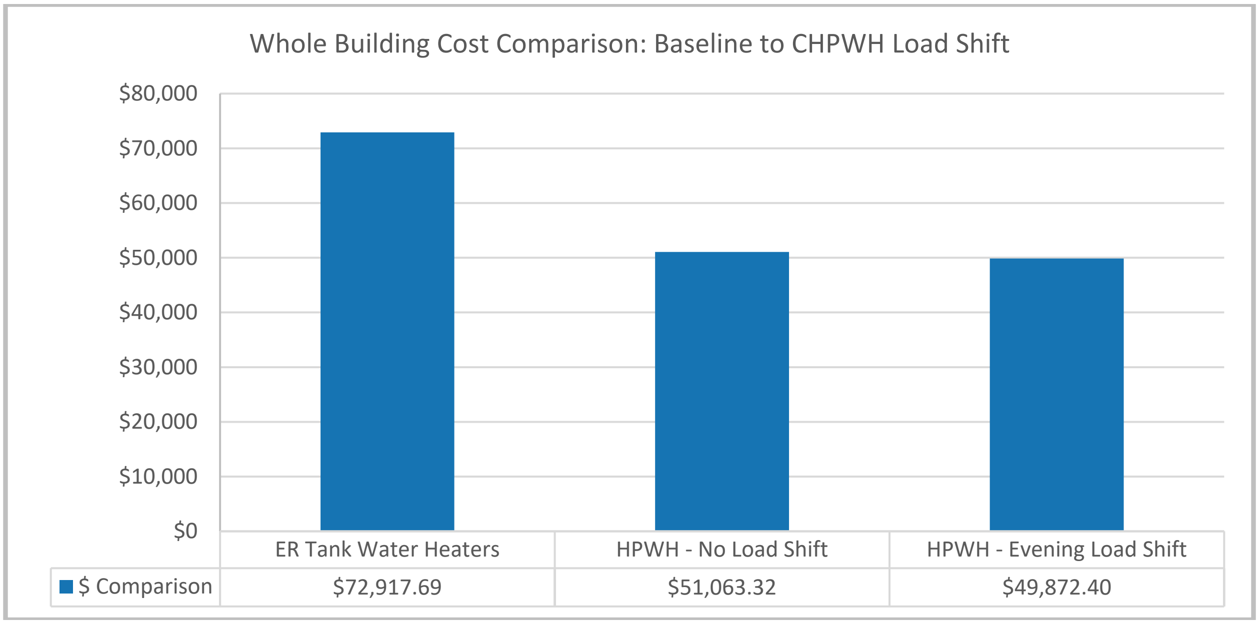
The costs in the following payback analysis were extrapolated from a real-world CHPWH installation at the Elizabeth James building, a low-income multifamily building managed by the Seattle Housing Authority. (Banks, Grist and Heller). Interestingly, though load shift results in slightly higher kWh consumption over twelve months, the ToD rates reduce the per-kWh cost by more than 11% from $0.112 to $0.100 per kWh for DHW heating. The estimated additional $18,000 for expanded storage is included in the HPWH with load shift simple payback calculation. Load shift results in a $1,021.66 per year savings for the building or $13.44 per apartment.

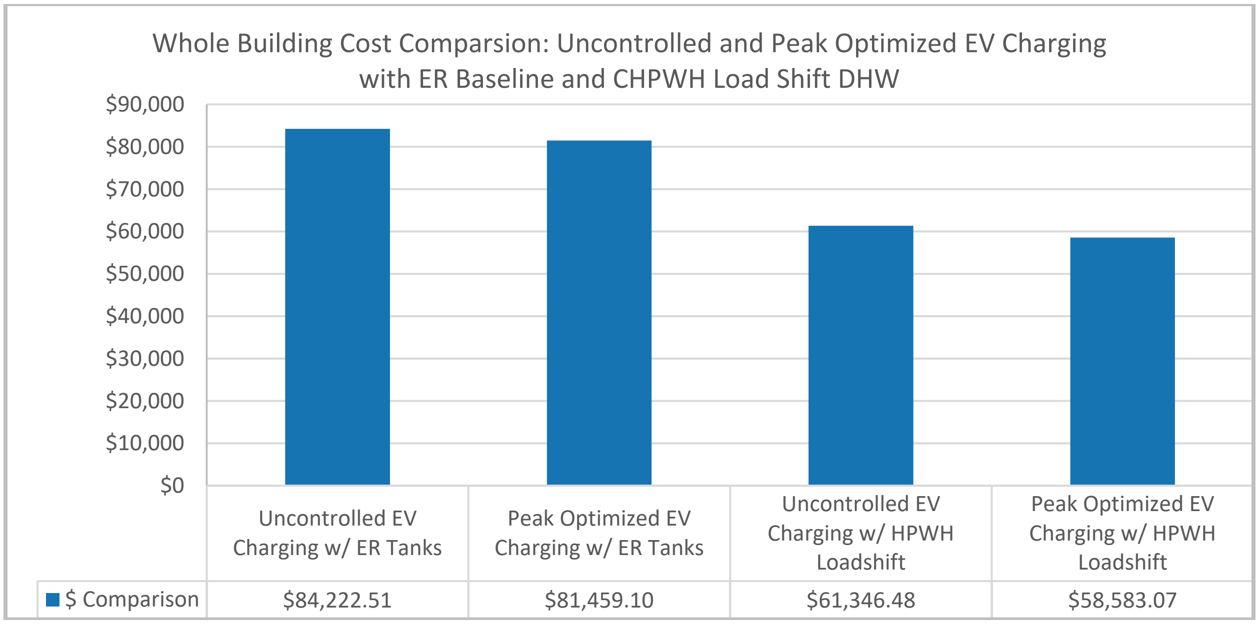
White Center HUB DHW Cost Analysis			
Building and Site Characteristics			
Apartments		76	units
Occupant Density		2	People/Apt.
Total Occupancy		152	People
Daily Water Usage		20	Gallons/person/day
Annual Water Usage		1,130,040	Gal/yr.
Estimated Electric Resistance DHW Installation Costs	$	38,000.00	$
Estimated HPWH Installation Costs (Standard Storage)	$	150,000.00	$
Estimated HPWH Installation Costs (with expanded Storage to achieve 100% Load Shift capacity)	$	168,000.00	$
Baseline Electric Resistance DHW System			
Annual Electric Resistance DHW Electric Cost	$	32,932.88	$
Annual Electric Resistance DHW Electric Use		290,807	kWh/yr.
HPWH System			
Annual HPWH Electric Cost (no load shift)	$	11,078.51	$
Annual HPWH Electric Use (no load shift)		98,529	kWh/yr.
Average $/kWh (no load shift)	$	0.112	$
Annual HPWH Electric Cost (with load shift)	$	10,056.85	$
Annual HPWH Electric Use (with load shift)		100,762.80	kWh/yr.
Average $/kWh (with load shift)	$	0.10	$
HPWH System Savings			
HPWH Electric Savings (no load shift)		192,278	kWh/yr.
Bill Savings (no load shift)	$	21,854.37	$/yr.
HPWH Electric Savings (with load shift)		190,044	kWh/yr.
Bill Savings (with load shift)	$	22,876.03	$/yr.

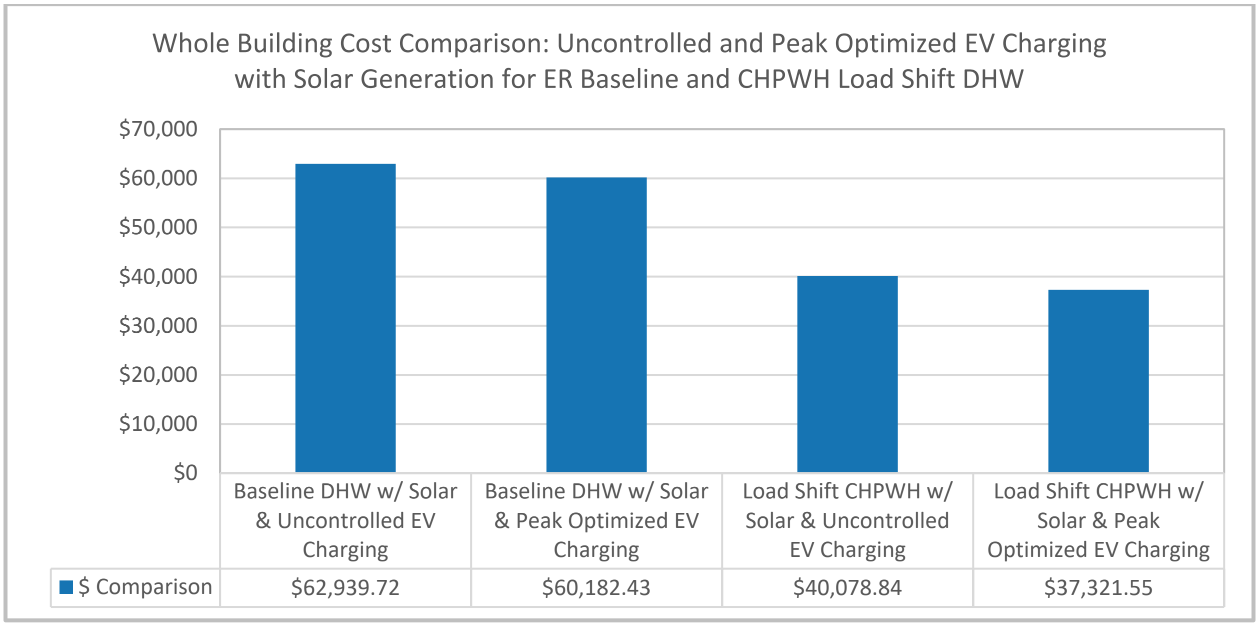
HPWH System Payback		
Estimated Incremental Cost (Standard Storage)	$112,000	$
Estimated Incremental Cost per Apartment (Standard Storage)	$1,474	$
Estimated HPWH Installation Costs (with expanded Storage to achieve 100% Load Shift capacity)	$168,000	$
Estimated Incremental Cost (Expanded Storage)	$130,000	$
Estimated Incremental Cost per Apartment (Expanded Storage)	$1,711	$
Simple Payback (no load shift)	5.1	yr.
Simple Payback (with load shift)	5.7	yr.

The following charts compare the cost relationship between the whole-building energy loads (kWh) as predicted by the modeling software to contrast the relative impact on whole-building energy costs between the baseline, CHPWH, and load shift scenarios.

Annual Cost summary tables based on Time of Day rates







CONCLUSIONS

It is a regular practice for SCL to incentivize energy efficiency beyond code. SCL's Grid Modernization efforts prioritize programs like load shift, which may ultimately lead to load shift incentives. For CHPHWs, the linkage between efficient technology and load shift is unique, especially in Seattle where the 2021 energy code requires CHPWHs in MF buildings but provides an exception for in-unit electric resistance DWH. Incentivizing CHPWH adoption offers significant savings beyond permissible code-minimum design with in-unit electric resistance DHW and adds substantial load shift capacity.

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 SCL priorities for load reduction in the afternoon. The basic CHPWH technology delivers these 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 SCL's target ToD rate period 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 the ToD rate structure would offset DHW load from 100% of annual peak load hours defined by the ToD rate. The incremental cost of these 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.

In multifamily buildings, since DHW loads represent such a significant percentage of total building loads and peak loads, this outcome represents a significant additional grid management advantage to the utility from the deployment of a technology primarily considered to deliver substantial energy efficiency outcomes. To the extent that SCL is considering incentives for load shift strategies, there may be opportunities to link efficiency and load shift incentives together to increase uptake of CHPWH technologies in the market.

This analysis did not evaluate other strategies to achieve additional load shift capacity with CHPWHs or in-unit HPWHs, such as additional controls, configuration alternatives, and elevated storage temperatures. A more thorough evaluation of these configurations could compare the costs and relative advantages of alternate approaches to load shift for this technology but was outside the scope of this analysis. Additionally, in-unit electric resistance tanks may demonstrate load shift capability when aggregated, which is not addressed here.

The anticipated impact of electric vehicle loads on building load shape was also evaluated. Typical charging patterns for EVs in residential buildings lead to coincident peak EV load with afternoon building peak load, which is simultaneous with the ToD peak period targeted by SCL's pilot peak rate structure. In this analysis, increased afternoon EV peak loads were comparable in magnitude to the peak load reduction impact of CHPWH on afternoon peak load. Deploying a controlled charging strategy for EVs to shift charging behavior out of peak load period led to a significant reduction in peak loads. This strategy magnified the potential peak savings achieved by deploying CHPWH systems.

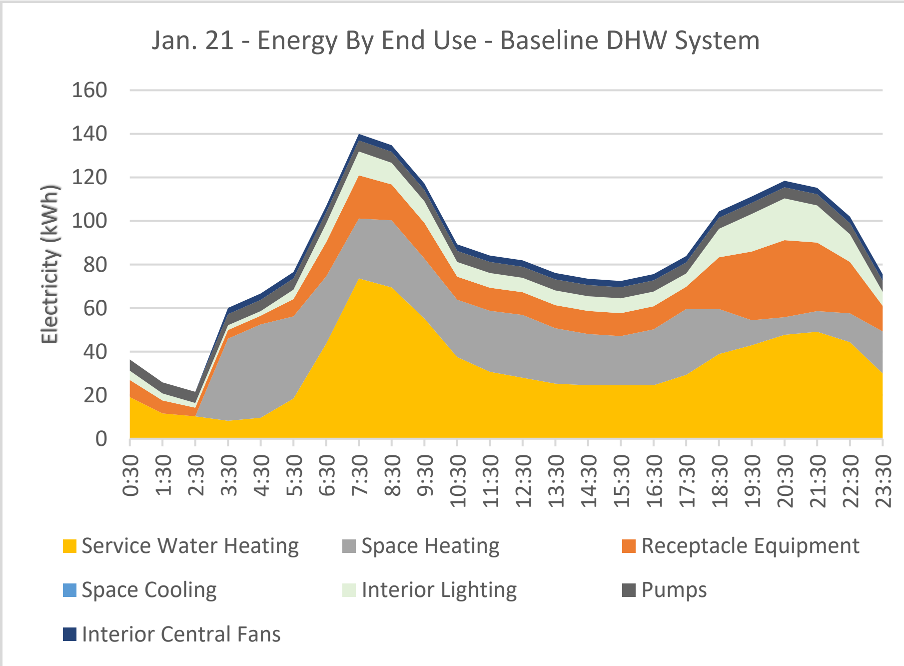
The analysis also reviewed the impact of on-site solar generation on building peak loads. In this analysis, solar energy availability does not align well with the peak load shapes of multifamily buildings, and on-site solar generation has little to no impact on building peak loads in the ToD rate period. Only in peak summer did solar availability offset part of the afternoon building peak load. Due to the morning and afternoon peak characteristics of hot water loads, there is no good alignment with solar availability to offset DHW peak loads. However, solar availability does offset mid-day DHW loads with CHPWHs, as the system 'recovers' from morning peak DHW use.

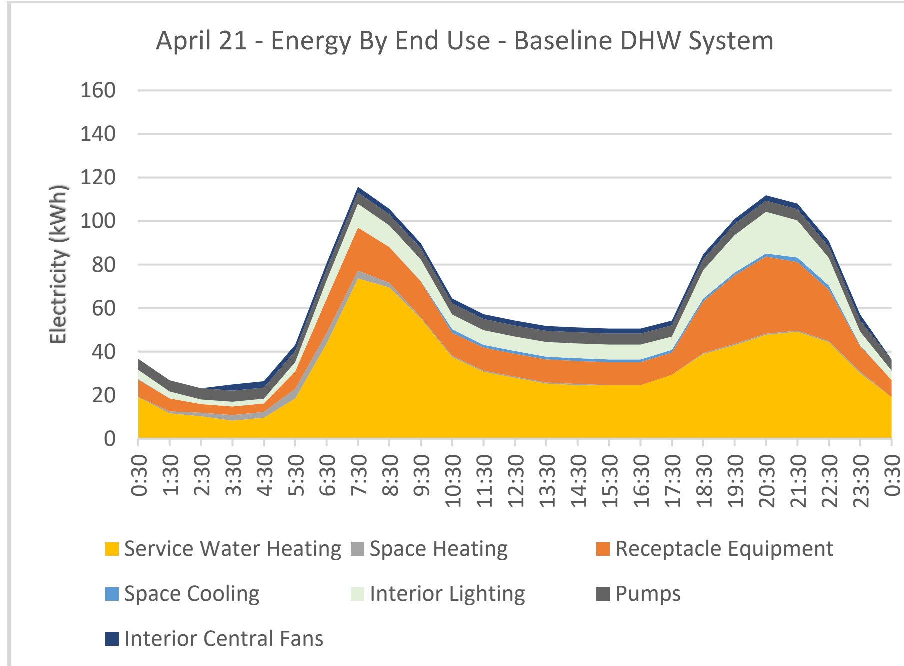
DHW and EV load shift scenarios were also evaluated from the perspective of utility cost savings using the pilot ToD rates adopted by SCL. Although all load shift strategies demonstrated some savings under the ToD rates, the incremental savings was negligible in all cases. The rate structure alone may not include enough time of use rate differential to drive the adoption of active load shift strategies.

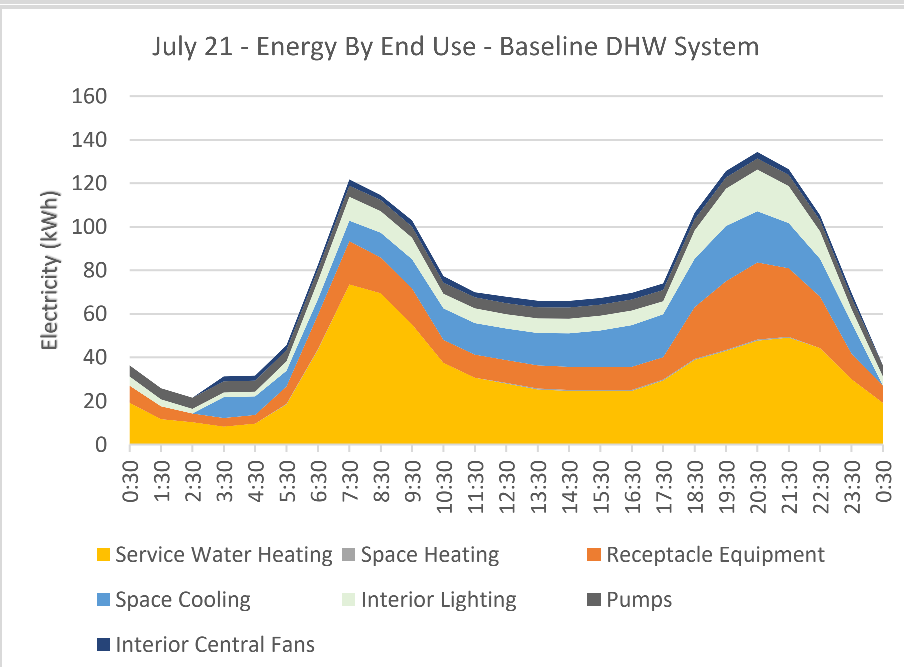
The significant potential load shift capabilities with CHPWHs indicated by this analysis suggest that additional avenues of evaluation should be pursued to support load shift deployment. In addition to alternate configurations to achieve load shift, it may be helpful to better understand the seasonality of load shift capabilities in these systems. CHPWH systems are designed for peak loads that occur in early spring, but grid-critical peaks tend to occur in late summer. Since these peaks are offset, achieving the vast majority of critical load peak reduction may be possible without deploying significantly increased storage capacity. Evaluating the temporal relationship between system peaks and gird peaks would help optimize the most cost-effective approach to peak load reduction in these systems.

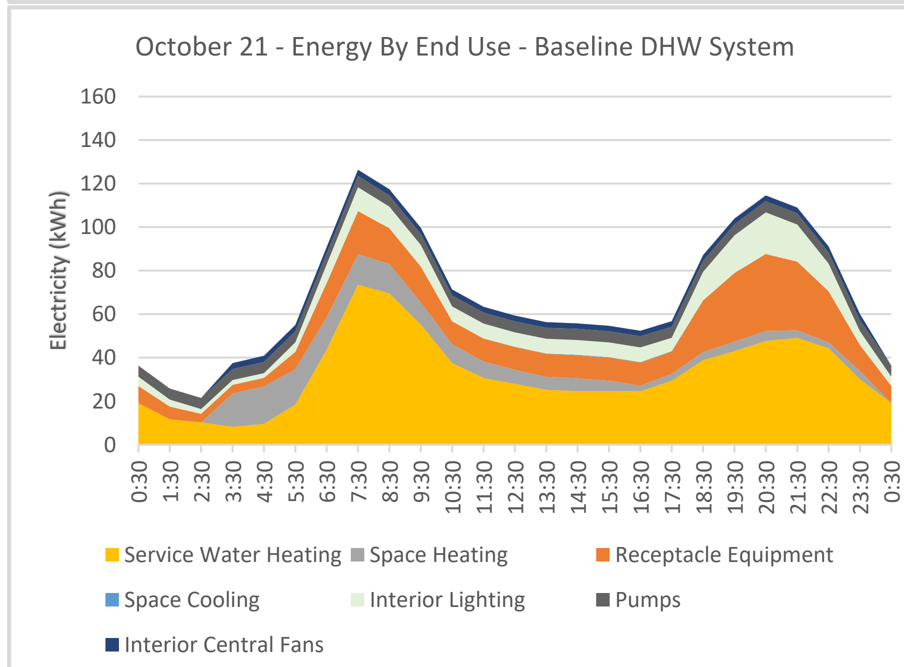
APPENDIX A – SEASONAL LOAD SHAPES

Whole Building Energy By End Use









Seasonal Afternoon Whole Building Load Shift Tables

The following describes the permutations of the whole building analyses, focusing on afternoon peak, color-coded to the charts below.

Winter Load Shape Day: Jan 21	Afternoon Peak KW: Electric Resistance	Afternoon Peak KW: CHPWH – no load shift (% change from ER)	Afternoon Peak KW: CHPWH – Afternoon load shift (% change from ER)
Whole Building Electricity (Figure 11)	119	90 (-24%)	73 (-39%)

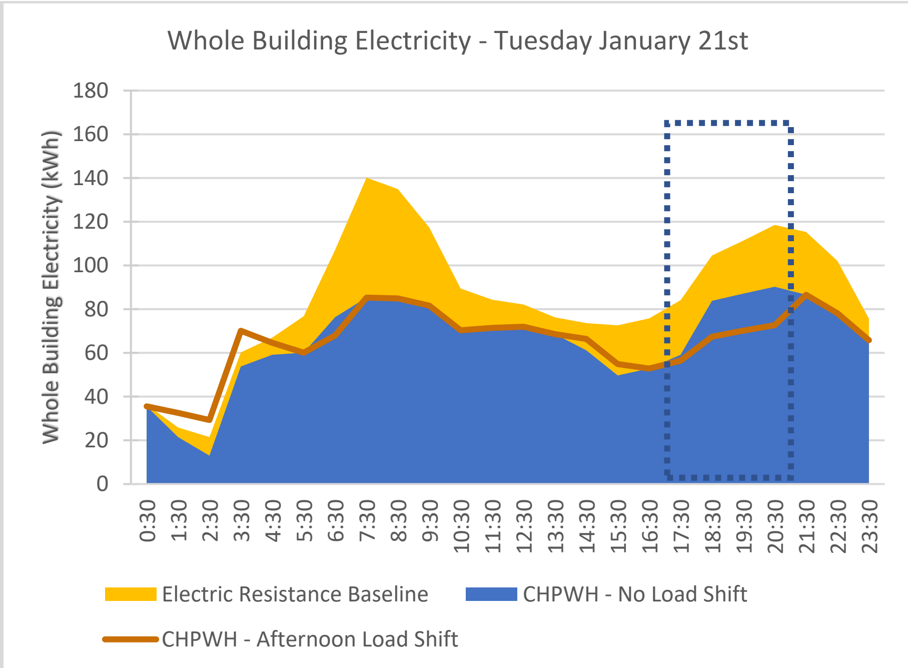
Winter Load Shape Day: Apr 21	Afternoon Peak KW: Electric Resistance	Afternoon Peak KW: CHPWH – no load shift (% change from ER)	Afternoon Peak KW: CHPWH – Afternoon load shift (% change from ER)
Whole Building Electricity (Figure 11)	112	80 (-29%)	66 (-41%)

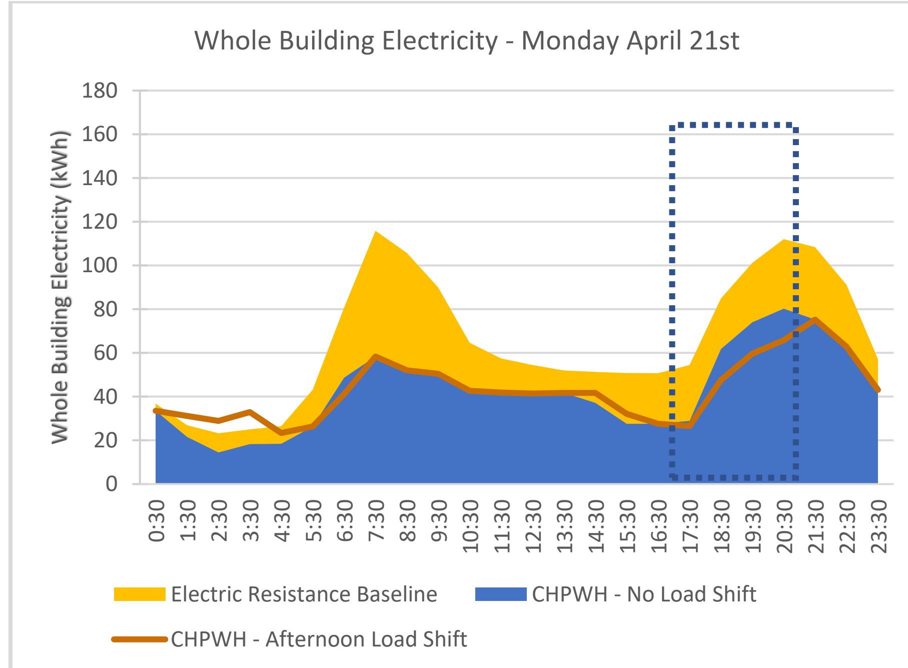
Winter Load Shape Day: Jul 21	Afternoon Peak KW: Electric Resistance	Afternoon Peak KW: CHPWH – no load shift (% change from ER)	Afternoon Peak KW: CHPWH – Afternoon load shift (% change from ER)
Whole Building Electricity (Figure 11)	138	103 (-25%)	91 (-34%)

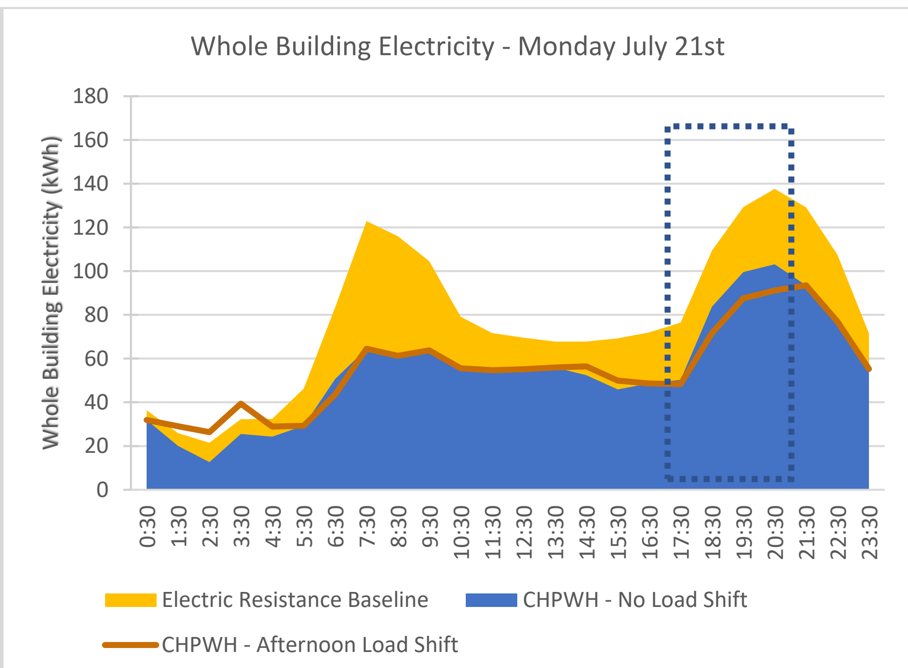
Winter Load Shape Day: Oct 21	Afternoon Peak KW: Electric Resistance	Afternoon Peak KW: CHPWH – no load shift (% change from ER)	Afternoon Peak KW: CHPWH – Afternoon load shift (% change from ER)
Whole Building Electricity (Figure 11)	115	83 (-28%)	68 (-41%)

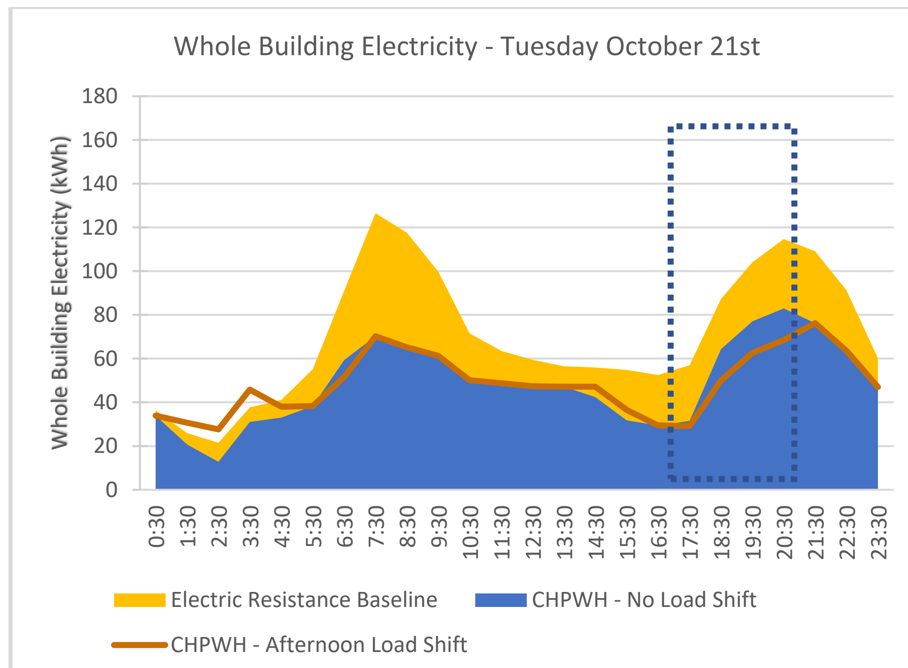
Seasonal Afternoon Whole Building Load Shift Charts

Dotted line represents the SCL Afternoon ToD Period.









Electric Vehicle Tables

The following describes the permutations of the EV analyses, focusing on afternoon peak, color-coded to the charts below.

Winter Load Shape Day: Jan 21	Afternoon Peak KW: No EV Charging	Afternoon Peak KW – Uncontrolled EV Charging (% change from no charging)	Peak KW: EV Charging Optimized for Peak (% change from no charging)
Baseline DHW	119	149 (25%)	125 (5%)
Load Shift DHW	73	103 (41%)	79 (8%)

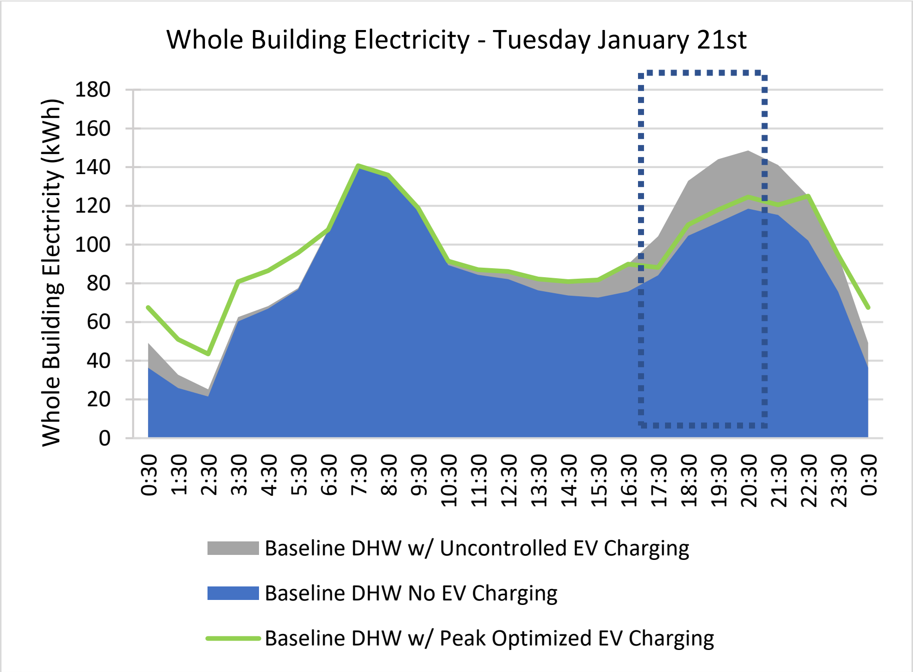
Winter Load Shape Day: Apr 21	Afternoon Peak KW: No EV Charging	Afternoon Peak KW – Uncontrolled EV Charging (% change from no charging)	Peak KW: EV Charging Optimized for Peak (% change from no charging)
Baseline DHW	112	142 (27%)	118 (5%)
Load Shift DHW	66	96 (45%)	72 (9%)

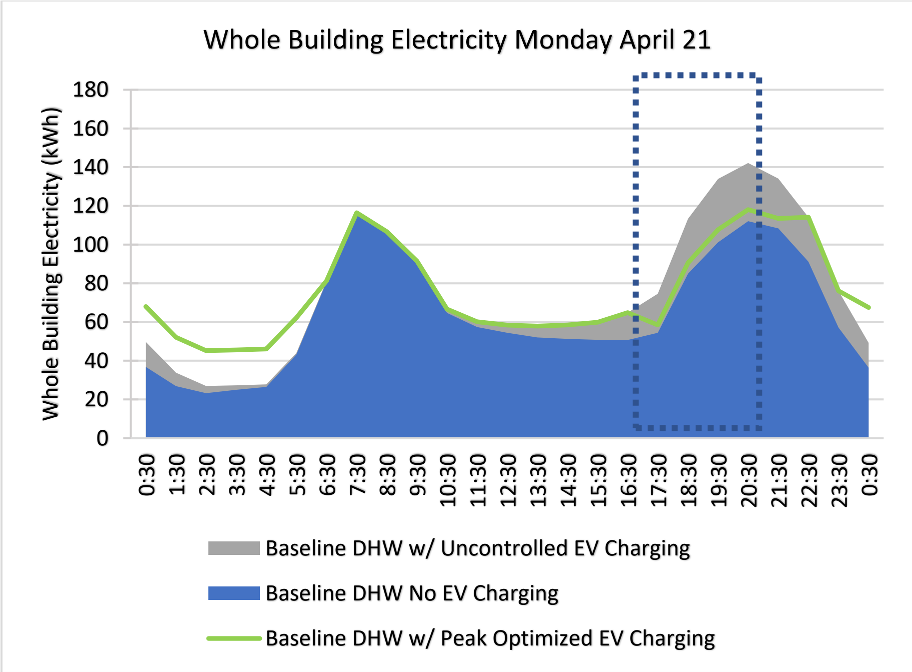
Winter Load Shape Day: Jul 21	Afternoon Peak KW: No EV Charging	Afternoon Peak KW – Uncontrolled EV Charging (% change from no charging)	Peak KW: EV Charging Optimized for Peak (% change from no charging)
Baseline DHW	138	168 (22%)	144 (4%)
Load Shift DHW	91	121 (33%)	98 (8%)

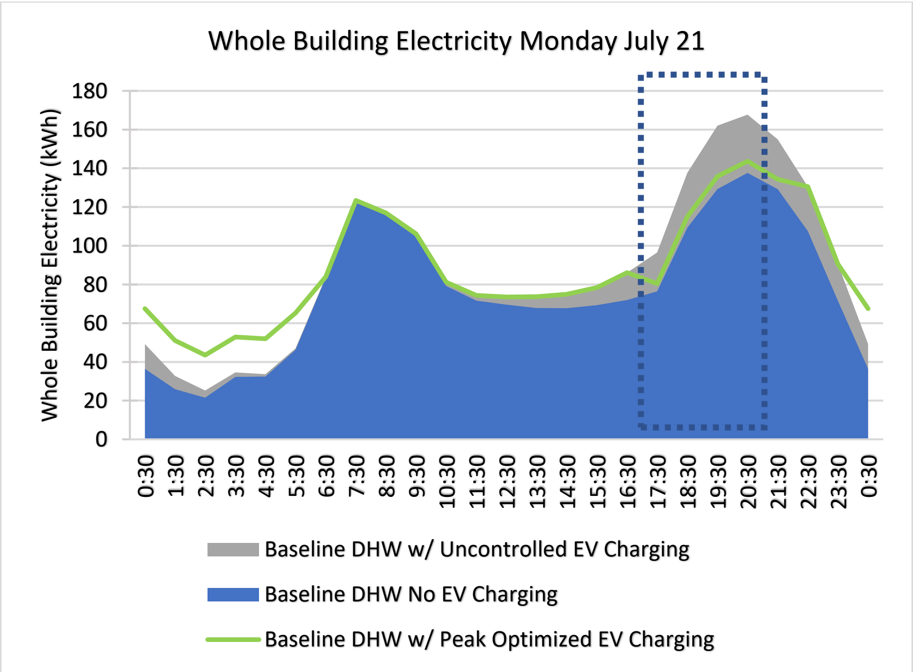
Winter Load Shape Day: Oct 21	Afternoon Peak KW: No EV Charging	Afternoon Peak KW – Uncontrolled EV Charging (% change from no charging)	Peak KW: EV Charging Optimized for Peak (% change from no charging)
Baseline DHW	115	145 (26%)	121 (5%)
Load Shift DHW	69	99 (43%)	75 (9%)

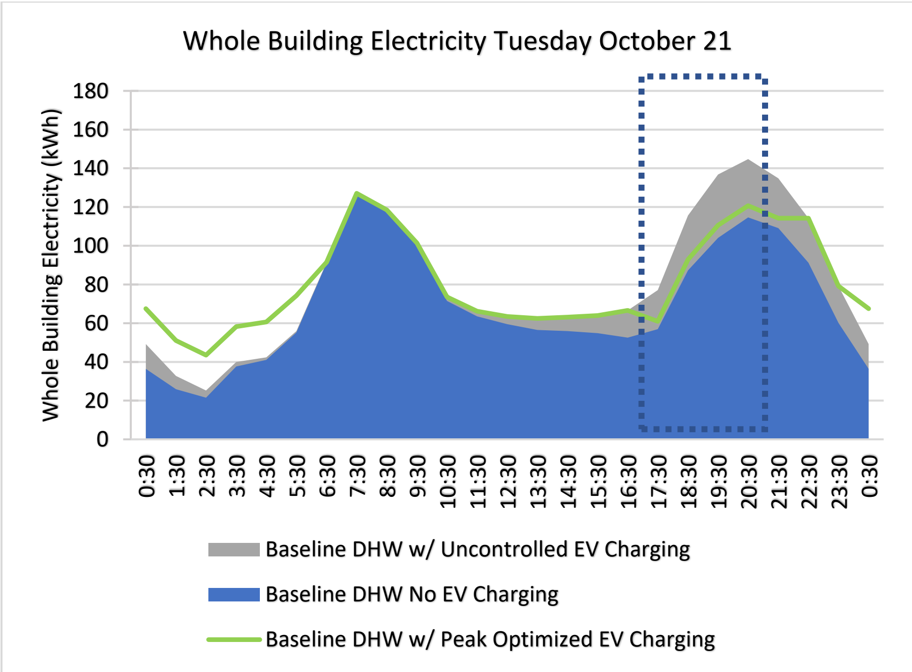
Uncontrolled and Time of Day Optimized Electric Vehicle Charging with Domestic Hot Water (Electric Resistance)

Dotted line represents the SCL Afternoon ToD Period.



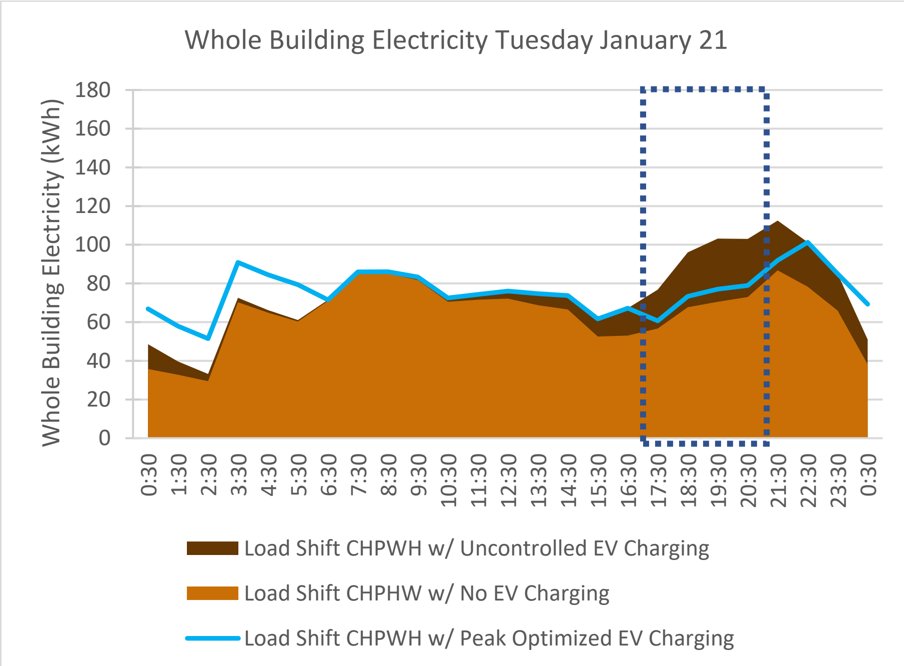


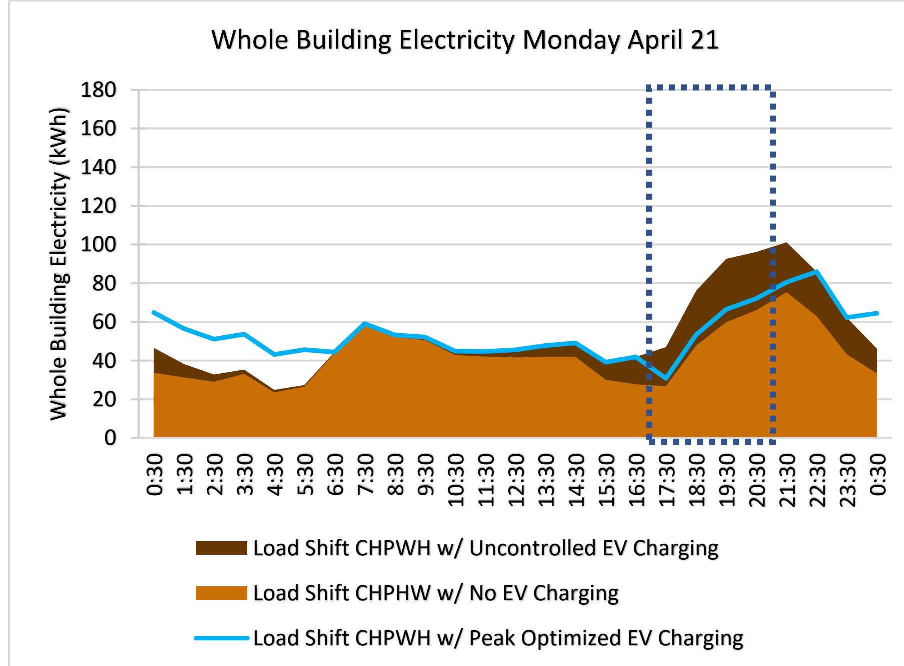


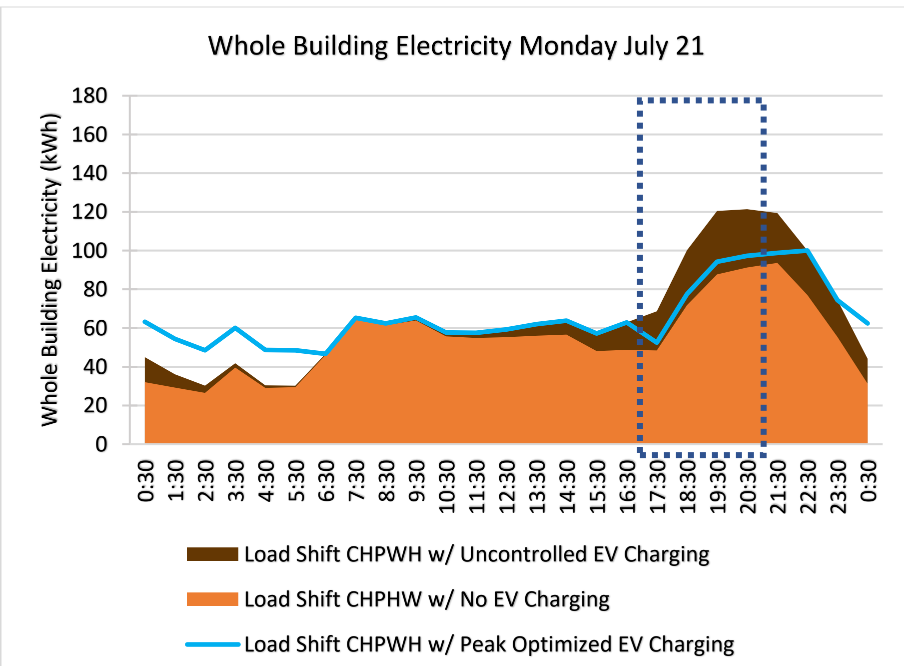


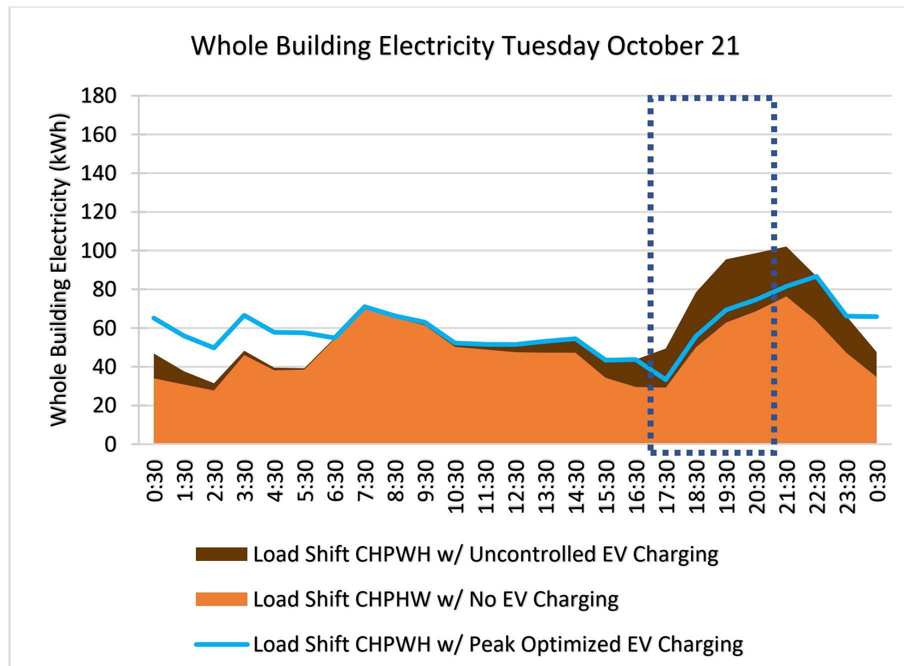
Electric Vehicle charging with Load Shift (Heat Pump Water Heater)

Dotted line represents the SCL Afternoon ToD Period









Electric Vehicle with Solar Tables

Winter Load Shape Day: Jan 21	Afternoon Peak KW – Uncontrolled EV Charging	Afternoon Peak KW – Uncontrolled EV Charging with solar generation (% change from uncontrolled)	Afternoon Peak KW – EV Charging Optimized for Peak w/ Solar Generation (% change from uncontrolled)
Baseline DHW	149	No Change	125 (-16%)
Load Shift DHW	103	No Change	79 (-23%)

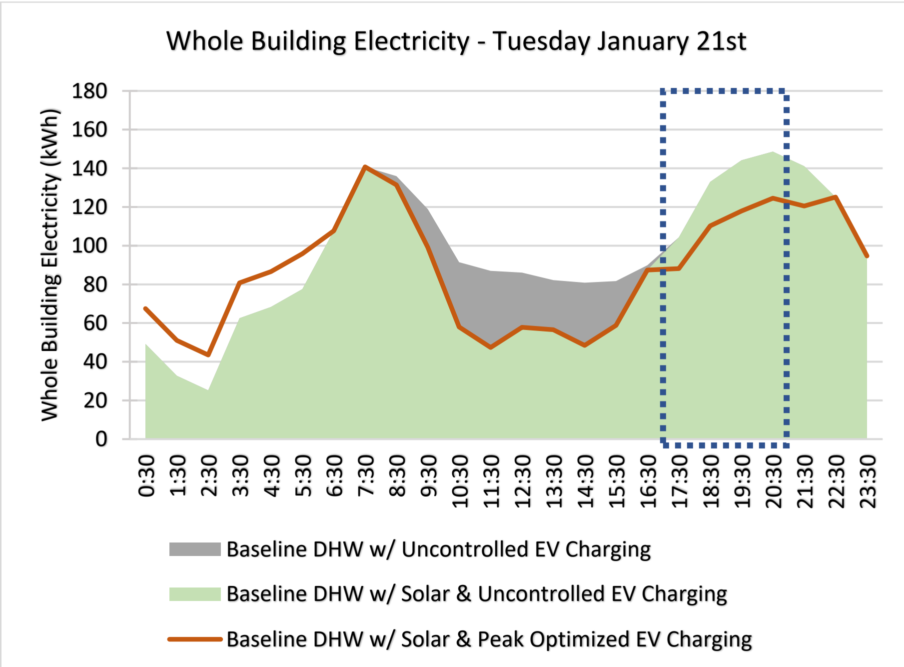
Winter Load Shape Day: Jan 21	Afternoon Peak KW – Uncontrolled EV Charging	Afternoon Peak KW – Uncontrolled EV Charging with solar generation (% change from uncontrolled)	Afternoon Peak KW – EV Charging Optimized for Peak w/ Solar Generation (% change from uncontrolled)
Baseline DHW	142	No Change	118 (-17%)
Load Shift DHW	96	No Change	72 (-25%)

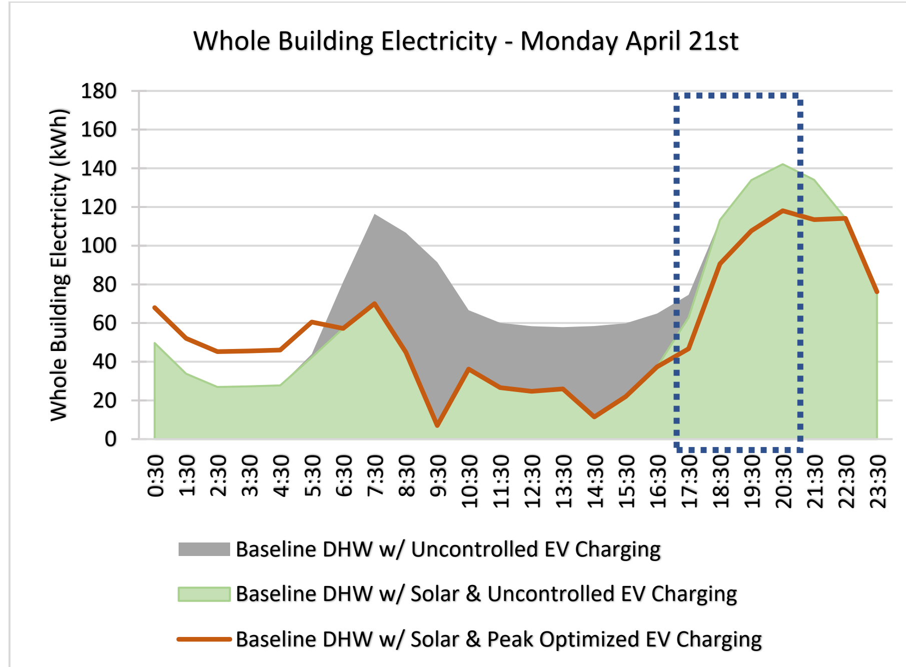
Winter Load Shape Day: Jan 21	Afternoon Peak KW – Uncontrolled EV Charging	Afternoon Peak KW – Uncontrolled EV Charging with solar generation (% change from uncontrolled)	Afternoon Peak KW – EV Charging Optimized for Peak w/ Solar Generation (% change from uncontrolled)
Baseline DHW	168	No Change	144 (-14%)
Load Shift DHW	121	No Change	97 (-20%)

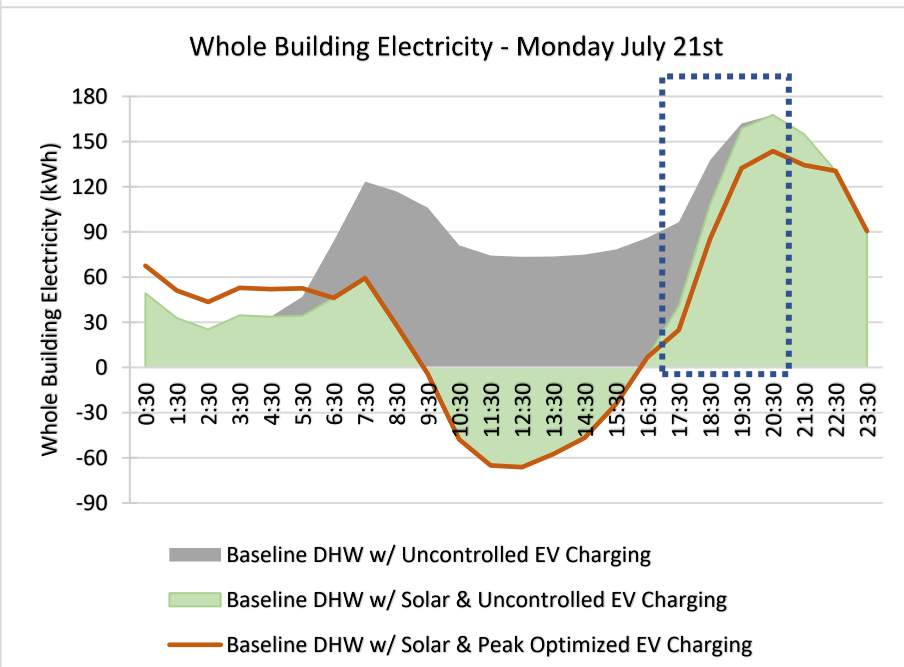
Winter Load Shape Day: Jan 21	Afternoon Peak KW – Uncontrolled EV Charging	Afternoon Peak KW – Uncontrolled EV Charging with solar generation (% change from uncontrolled)	Afternoon Peak KW – EV Charging Optimized for Peak w/ Solar Generation (% change from uncontrolled)
Baseline DHW	145	No Change	121 (-17%)
Load Shift DHW	99	No Change	75 (-24%)

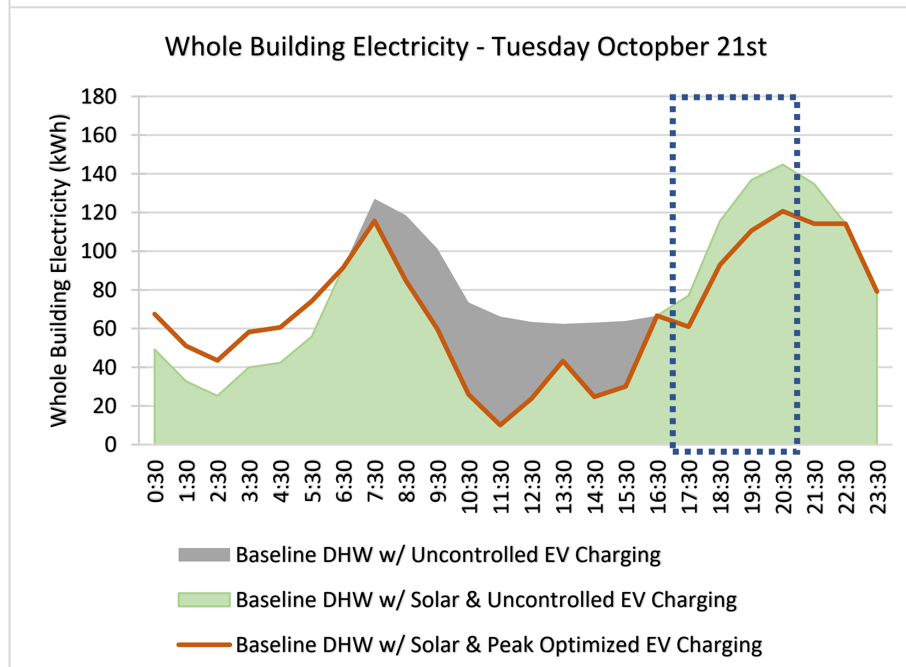
Impacts of Solar Generation on Electric Vehicle Charging with Domestic Hot Water (Electric Resistance)

Dotted line represents the SCL Afternoon ToD Period

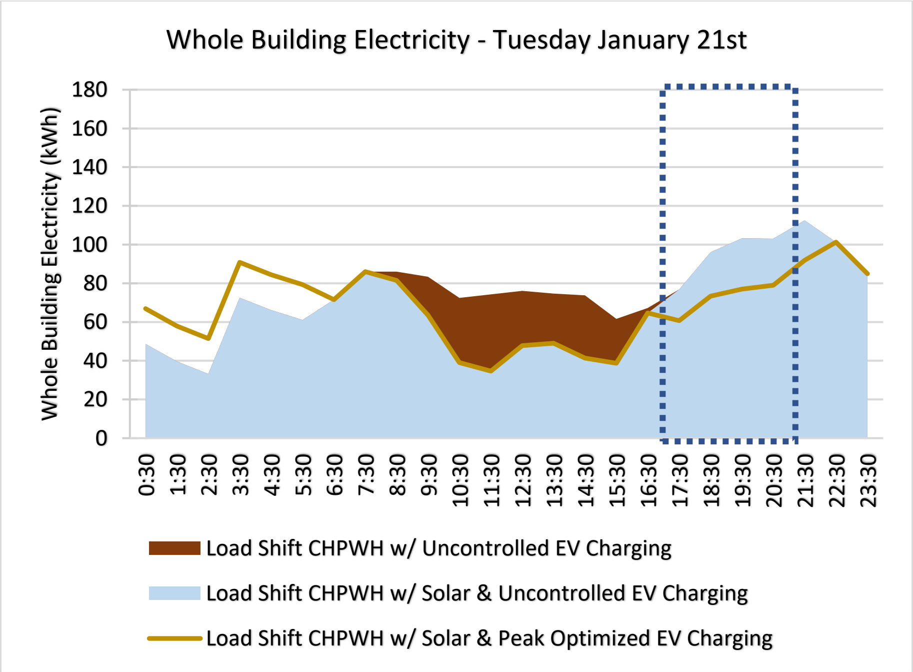


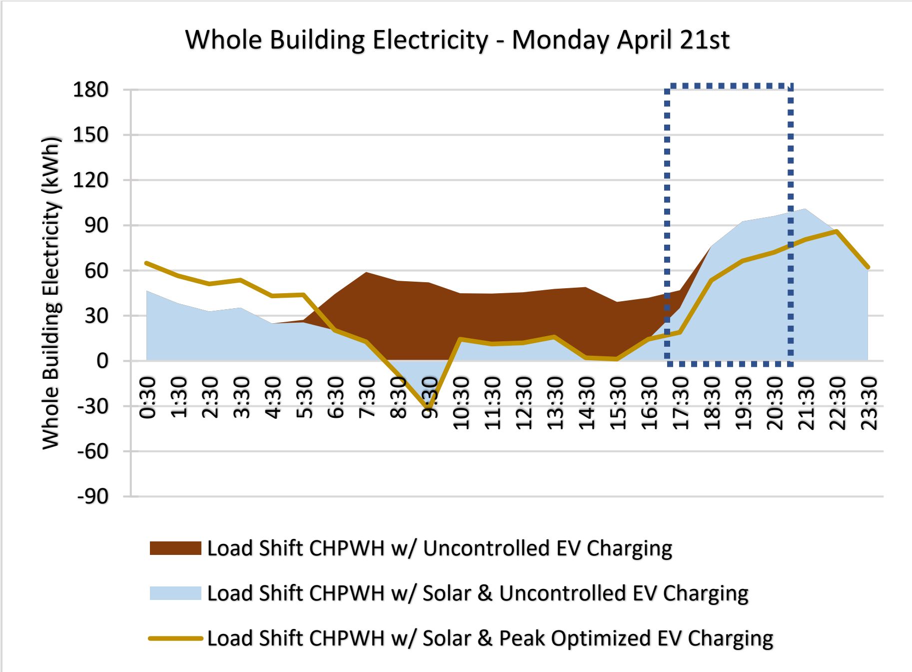


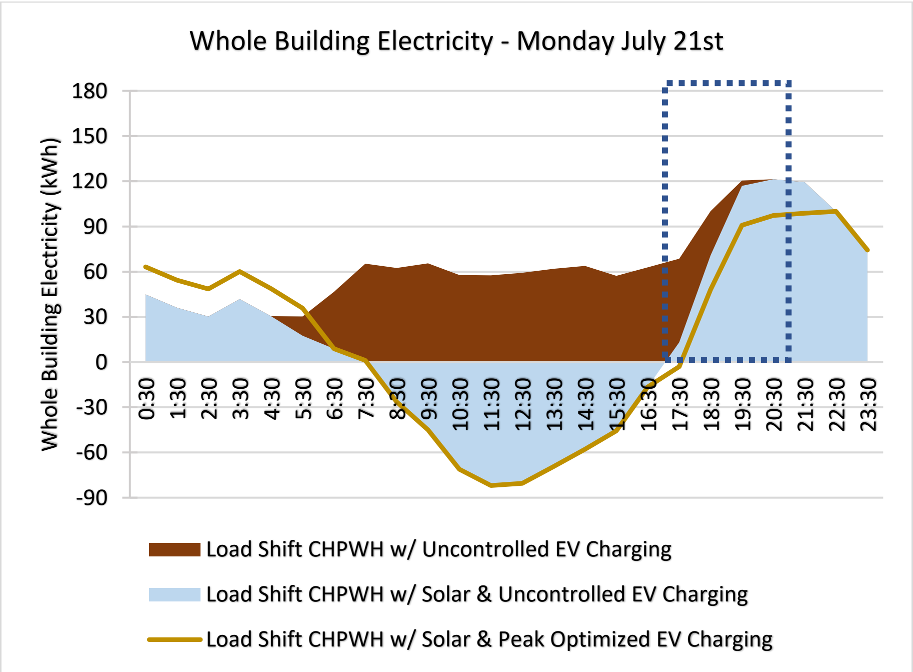


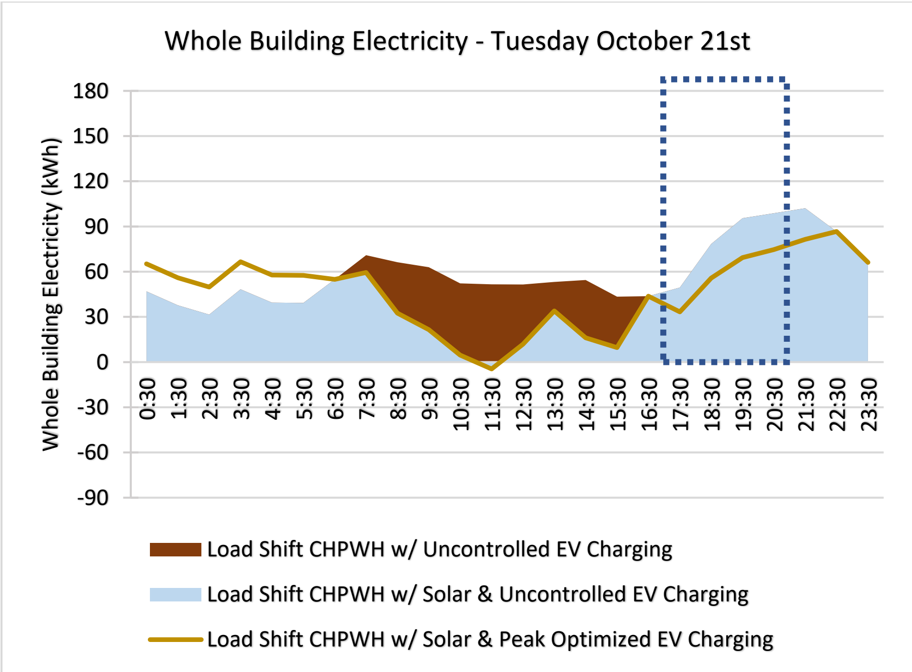


Impacts of Solar Generation on Electric Vehicle Charging with Load Shifted Domestic Hot Water (Heat Pump Water Heater)
Dotted line represents the SCL Afternoon ToD Period









APPENDIX B – DOMESTIC HOT WATER DRAW PROFILES

Ecotope has designed over 100 heat pump water heater (HPWH) systems in multifamily and commercial buildings and collected measurement and verification (M&V) data on a significant subset of those projects. This memo provides high-level summaries of several representative datasets collected over the past decade. These identify patterns and variability of typical domestic hot water (DHW) draw profiles in buildings of differing occupant densities and demographics as a basis for considering load shape management in multifamily buildings.

M&V projects

Ecotope's HPWH systems have been installed in market-rate multifamily and a few supportive housing buildings, as well as in commercial applications. The table below summarizes the M&V library that Ecotope maintains for 12 multifamily buildings monitored for some period over the past 10 years:

Demographic	**Site**	**Low/Mid/High-rise**	**Apartment Units**	**Monitoring timeframe**
Market-rate	Sunset Apartment	Mid	92	2014/06 – 2018/11
	Stream/708 Uptown	Mid	118	2013/04 – 2018/11
	Grow A	Low	12	2016/08 – 2018/04
	Grow B	Low	12	2016/08 – 2018/04
	Grow D	Low	13	2016/11 – 2018/04
	Woodard Lane	Low	4	2018/01 – 2020/09
	Batik/Yesler 2	Mid	195	2018/08 – 2021/04
	Sitka/Block 11	Mid	384	2020/01 – ongoing
	Jackson Apartments (East)	Mid	166	2020/10 – ongoing
Supportive – with Families	Hopeworks Station	Mid	75	2020/06 – ongoing
Supportive – Senior	Elizabeth James House	Mid	60	2019/03 – ongoing
	Bayview Tower	High	100	2021/08 – ongoing

Data from many of these projects are accessible via online web applications[4,5,6]

Draw profiles

The hourly demand for domestic hot water (DHW) over a typical day describes residential building DHW draw profile, measured by two primary indicators:

1. Peak Draw: The shape of hot water draw between the 95th and 98th percentile of daily DHW usage and the upper percentile of 3- and 4-hour peak draw. Analysis of field-collected monitoring data suggests a correlation between the daily DHW usage and the peak hot water usage on the same day.
2. Average Draw: The annual average DHW draw profile, which accounts for seasonal and occupant diversity.

Building and energy professionals can use this information to estimate the peak *design-day* draw profile for multifamily buildings of varying sizes, maximizing the cross-correlation between measured data and the *average-day* used for sizing. For example, a *design-day* has a similar use pattern to the *average-day* draw profile but contains the peak hot water loads for a particular building. This cross-correlation is essential for sizing HPWH systems and helps predict the timing of peak DHW draw in a load-shift scenario. **Figure 15** shows the comparison of *design-day* and *average-day* draw profiles for a 118-unit multifamily building.

[4] https://ecotope.shinyapps.io/RCCViewer/
[5] https://ecotope.shinyapps.io/MFSandenRetrofit/
[6] https://ecotope.shinyapps.io/qahvviewer/

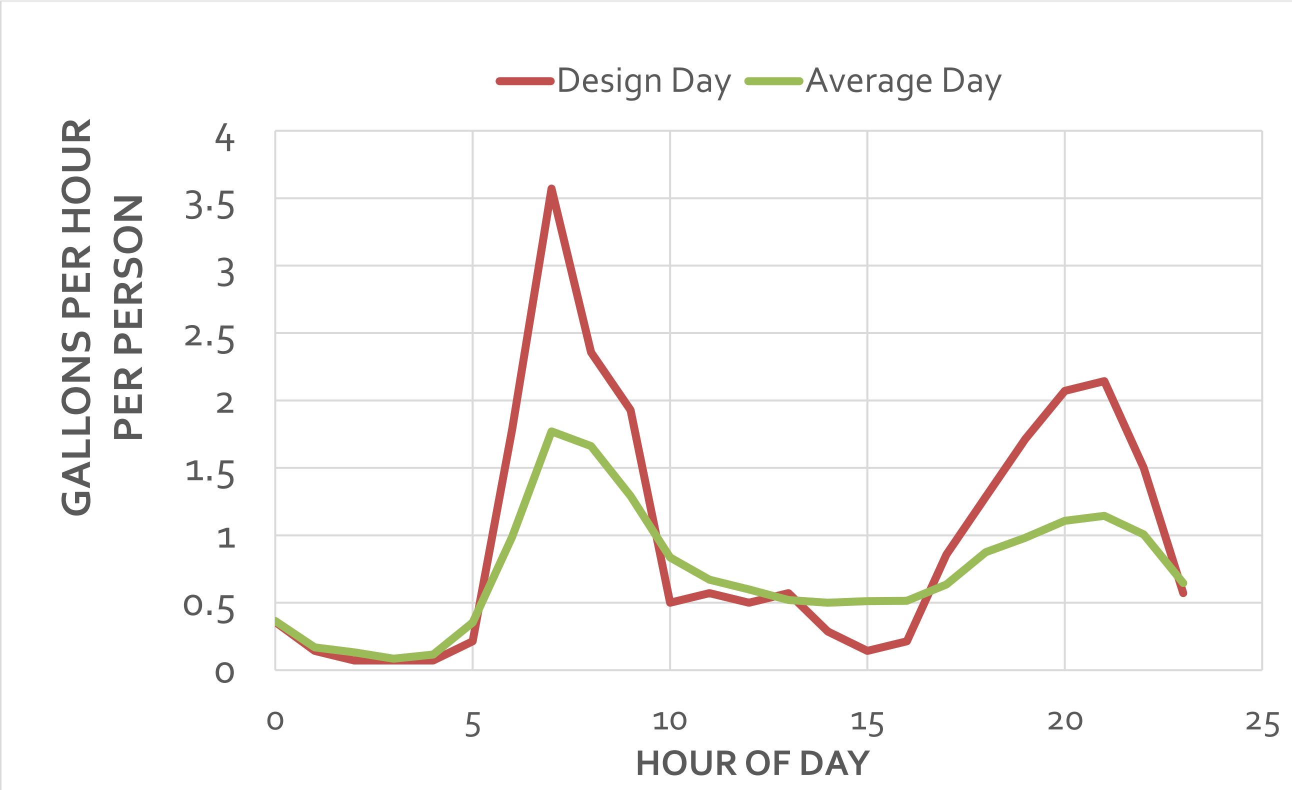


Figure 15. Measured design and average DHW draw profiles from a market-rate muti-family building

The peak *design-day* draw profile represents a likely worst-case multifamily draw profile with a very high morning peak driven by morning showers and cooking, very low mid-day usage, which indicates most occupants at work or school, and a second slightly smaller evening peak representing after work showers and dinner preparation. The *design-day* is critical in sizing HPWH systems to meet peak occupant usage scenarios. This draw profile is instrumental within the Ecosizer[7], Ecotope's online HPWH sizing tool. Note that this worst-case draw profile assumes some diversity of occupants in a multifamily building with high users and low users distributing their demand over the day. In small multifamily buildings with less than 20-30 occupants and less diversity, usage patterns could align in ways that produce higher peaks or higher total demand. Understanding the peak and average draw profile variability in low-occupant density buildings deserves additional research.

Variation by season

Peak *design-days* may be more likely to occur during seasonal increases in DHW usage. DHW usage tends to be highest during colder months. **Figure 16** describes hot water usage in a large (> 350-unit) market-rate apartment building. Here, the annual 95th percentile for daily DHW usage falls above 26 gallons per day per

[7] https://ecosizer.ecotope.com/

apartment. Such days occur when daily average outside air temperatures fall below 50F (circled in blue). Interestingly, weekend days represent a sizeable percent of all high-use days.

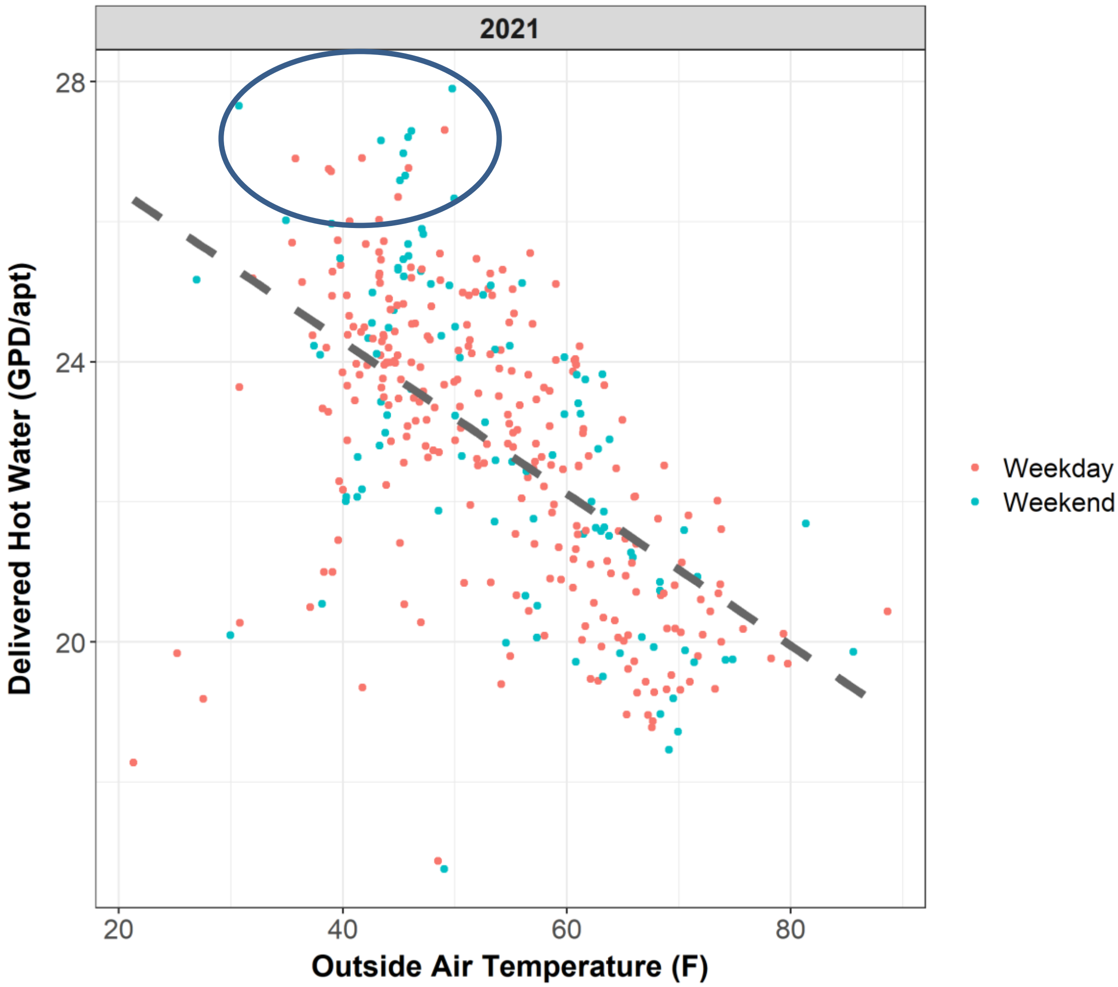


Figure 16. Daily DHW usage by Outside Air Temperature (F)

Figure 17 offers another way to examine the annual distribution of peak usage days. Here, the days above the 95th percentile line correspond to those circled in blue in **Figure 16**. Peak day co-occurrence at other times in 2021 is possible but unlikely; most peak usage days occurred in fall and winter.

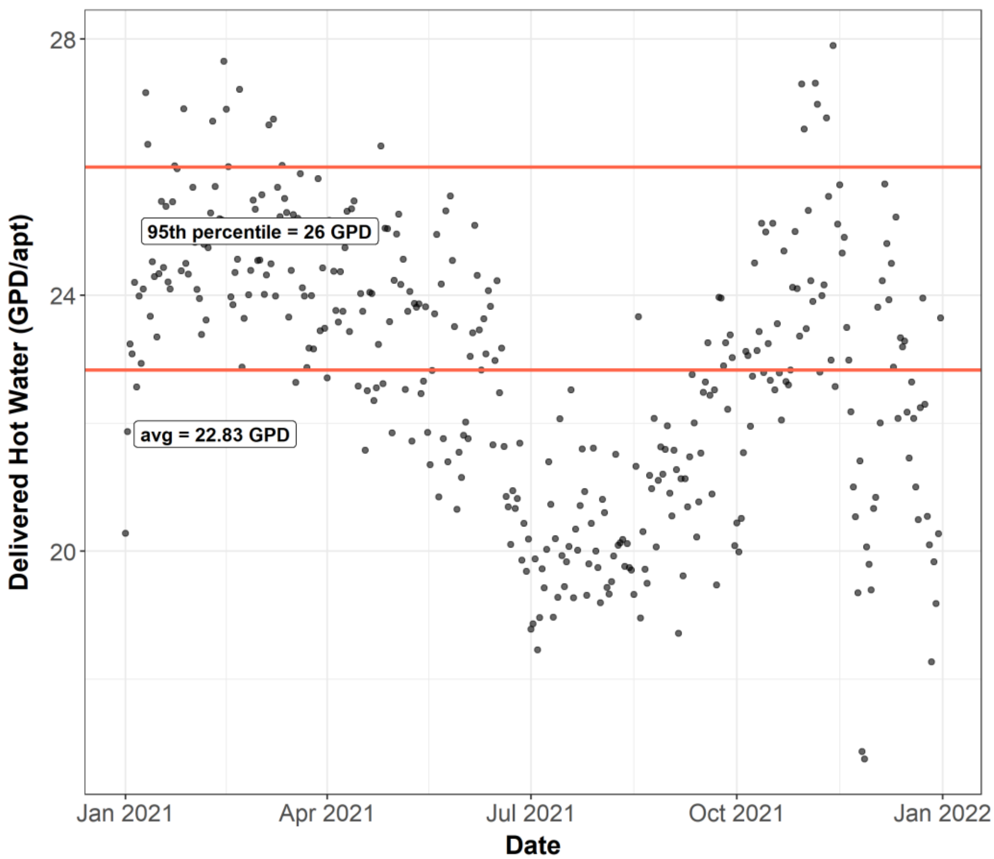


Figure 17. Daily DHW usage by Date

Behavioral variation

Analysis of behavioral changes in DHW demand resulting from demographic and seasonal variations offers insight into behavioral variations during colder vs. warmer months, employment status, place of work (e.g., work from home), and weekends and holidays. For example, the low-demand days on the right side of Figure **17**3 correspond to holidays at the end of November and December when occupants may be away from their apartments. This analysis could expand to include cultural or regional factors, among others.

Behavioral diversity is lower in smaller buildings with fewer occupants; each occupant's behavior may have a more pronounced impact on the average and peak draw than in a larger building. This increase in behavioral impact on DHW demand can make peak and average draw predictions more challenging in smaller buildings. Alternately, increased occupancy in larger buildings allows for observations of commonly shared behaviors within draw profiles across buildings. For example, building occupants tend to behave differently on weekdays and weekends. **Figure 18** shows the combination of demographic and weekly behavioral trends, in a low-income building (occupants are recently incarcerated or recently homeless – Hopeworks Station), a market-rate building (Batik/Yesler2), and a senior supportive building (Elizabeth James House). The red dotted line is aligned with the onset of the market-rate weekday morning peak demand in both weekday and weekend summaries. The following patterns are of note:

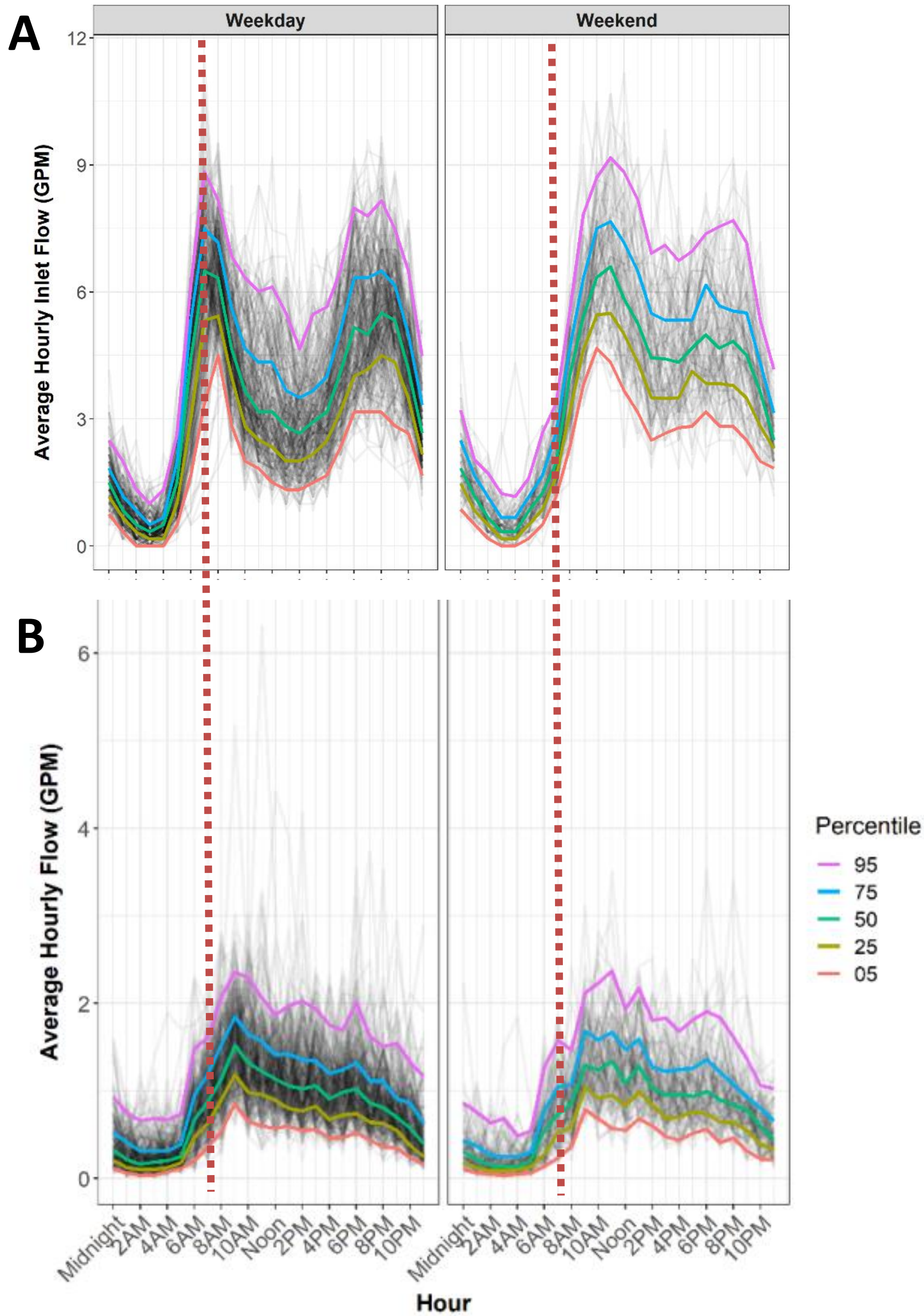


Figure 18. Weekday and weekend draw profiles in market-rate (A) and supportive senior (B) buildings

NEW PLOT

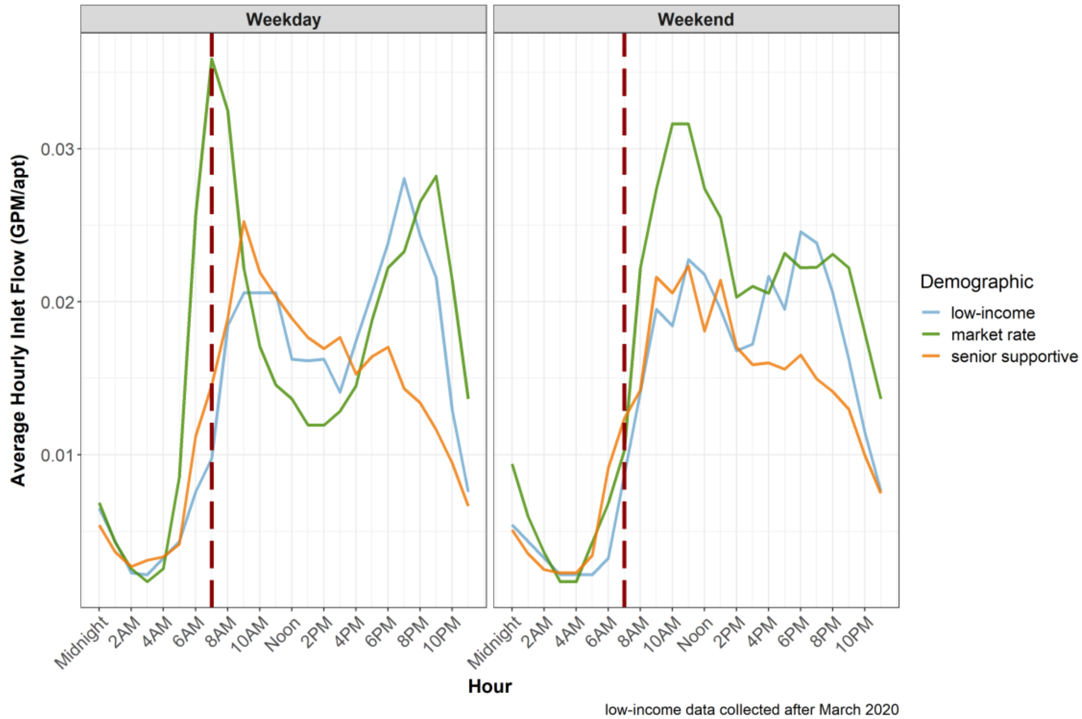


Figure 19. Weekday and weekend draw profiles in buildings with different demographics

1. Weekday morning peak occurs later in supportive senior and low-income buildings and later in both cases on weekends.
2. Morning peak is broader on weekends when workday schedules are less likely to affect water demand.
3. Weekend demand increases midday for market-rate buildings when occupants are home more often.

Broadly, differences in DHW demand are less pronounced in supportive senior buildings than market-rate buildings because fewer occupants have weekday/weekend distinctions in schedules.

The impact of COVID-19 resulted in behavioral shifts around occupant DHW demand patterns, particularly in market-rate multifamily buildings. **Figure 20** describes draw profiles (in the Sitka/Block 11 building) for the five months leading up to March 2020 and the following two months when Washington state residents were under the 'Stay Home, Stay Healthy' guidance. This plot also shows daily diversity (individual days in each dataset are grey lines), and median days in green while peak 95th percentile hourly loads are pink.

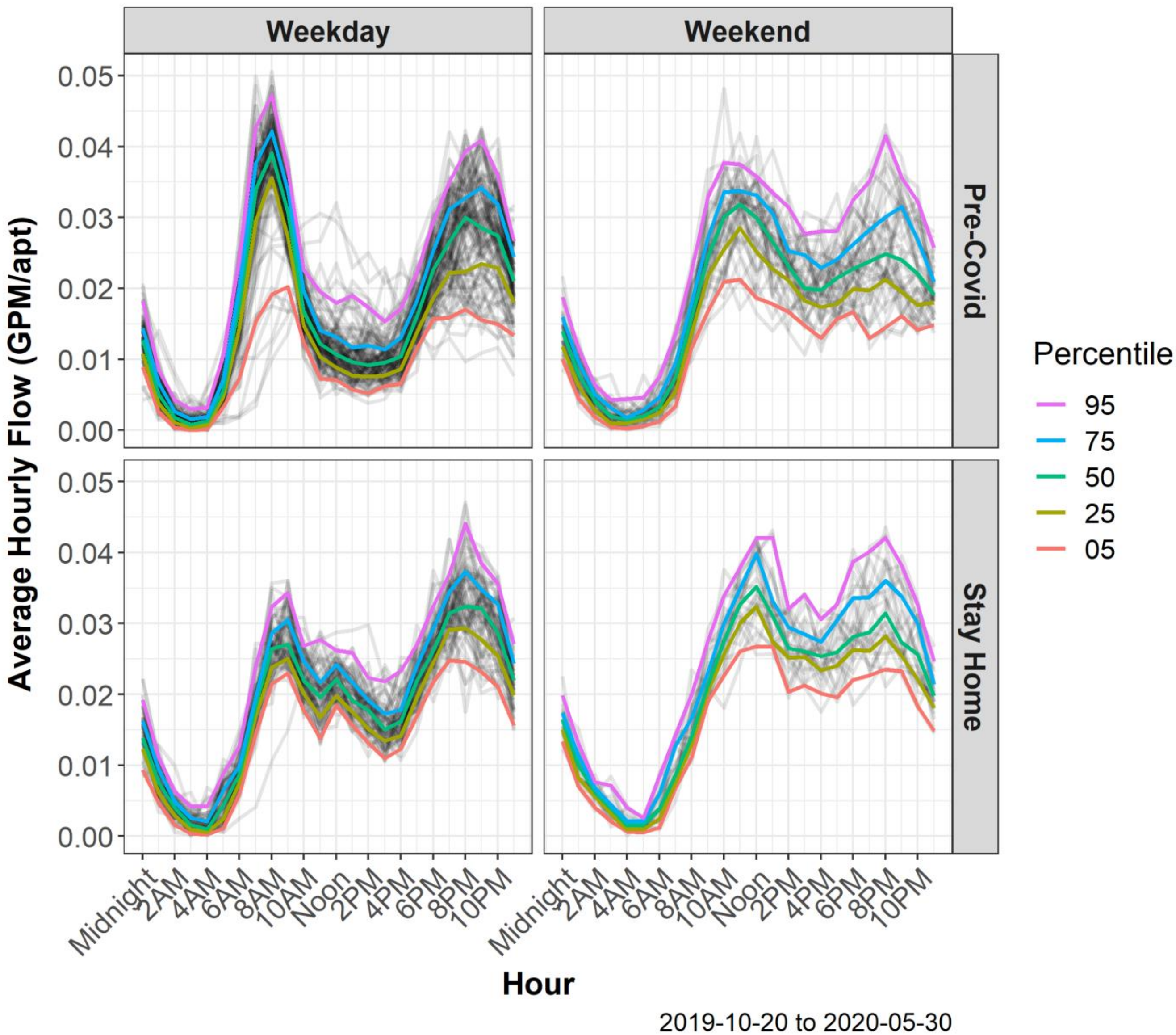


Figure 20. Draw profiles before/during Washington's 2020 'Stay Home, Stay Healthy' mandate

Unsurprisingly, the top panels' median shapes (50th percentile) look very similar to the market rate building in **Figure 18**. The bottom panel shows a marked shift in water usage; mornings peak slightly later, elevated midday usage with more occupants in the building during the week, and weekday usage becomes evening-dominated. Weekend differences are more negligible during 'Stay Home, Stay Healthy", except for the possibility of elevated flow levels, again due to more consistent occupancy.

Conclusion

This analysis of a selection of Ecotope's library of DHW demand data provides representative draw profiles for varying multifamily building types. This analysis highlights the variability of demand patterns and draw profiles in buildings of differing occupant densities and demographics, policy changes resulting in increased at-home time.

These analyses provide a basis for considering load shape management in multifamily buildings and provide insight into co-occurrence of peak *design-days* and actual demand, which is more likely to occur during colder months. Additionally, because weekend days represent a sizeable percentage of all high-use days, a cold weekend day likely has the highest chance of actual demand and design-day co-occurrence, though this analysis has not been conducted here.

Additional factors impact *average-day* demand, including employment status (often related to age), place of work (e.g., work from home), and, as mentioned, weekends and holidays. The difference between market-rate, low-income, and supportive senior buildings demonstrates demographic shifts in demand; results show shifts in weekend morning peaks for both demographics, flatter curves for market-rate during the weekends, and flatter curves in senior housing, in general. Washington's COVID-19 stay-at-home order, 'Stay Home, Stay Healthy', resulted in behavioral shifts in DHW demand that confirm weekend vs. weekday trends, particularly in market-rate multifamily buildings. Under 'Stay Home, Stay Healthy', DHW demand shifted later for morning and evening peaks on weekdays and flattened the curve on weekends.

A critical point of consideration is the difference between a *design-day* and *average-day* draw profiles (**Figure 15**) and the potential for load shift "built into" HPWH design for many *average-days.* This point will be addressed in greater detail in the forthcoming white paper on modeled DHW demand and load shift at White Center HUB.

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