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# Electrification Options for Multi-Family Water Heating in Cold Climates - Final Report


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August 2024

OAK RIDGE National Laboratory

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Building and Transportation Science Division

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# 1. ABSTRACT

In multi-family buildings, large water storage tanks in centralized domestic hot water (DHW) systems can serve as thermal energy storage (TES) batteries to mitigate grid impact. These systems offer demand shift and efficiency benefits, significantly reducing peak power consumption, particularly in cold climates.

This study evaluates the load-shifting benefits of a centralized heat pump water heater (HPWH) system equipped with a CO2 heat pump in multi-family buildings through simulation. The heat pump system and water storage tank are sized using design-day sizing. A finite-element-based stratified tank model and CO2 heat pump performance map from a commercial DHW product are used. Annual simulations are conducted to assess the benefits of the centralized DHW system for energy efficiency improvements, load shifting, and emission reductions. These simulations incorporate utility tariffs and marginal grid emission data from Los Angeles and Chicago.

In Los Angeles, using a water tank as a thermal battery achieves 7.4% utility cost savings and 10.2% emission reduction. In Chicago, compared to HPWH conventional operation without preheating, TES-enabled central HPWH provides 15% utility cost savings and 13% emission reduction. The case study demonstrates that the demand reduction potential of central CO2 HPWHs is significant in cold climate regions.

# 2. STATEMENT OF OBJECTIVES

Water heating, or domestic hot water (DHW) production, ranks as the third most significant energy consumer in residential buildings, following appliances and space conditioning. In the state, approximately 90% of homes utilize natural gas for water heating, 6% rely on electricity, and a minor percentage use liquefied petroleum gas (LPG) or solar-powered systems. While the energy expenditure for residential water heating is comparatively small within the broader context of residential energy usage, it nonetheless contributes to greenhouse gas (GHG) emissions. Enhancements to hot water systems can yield savings on bills and reduce energy and water usage.

Centralized heat pump water heaters (cHPWH) have proven to be a highly effective technology for significantly reducing electricity use in household hot water production. Numerous monitored initiatives across the U.S. have demonstrated energy savings of 50-70%, as evidenced by the operational coefficient of performance (COP), compared to traditional electric resistance storage tank systems (Willem et al., 2017). Advances in compressor technology and other design improvements have led to even higher operational COPs in newer models. Besides conserving energy for water heating, these systems also help reduce peak electricity demand. However, there has been limited research on how the load-shifting capabilities of HPWHs could assist utilities in achieving load control objectives.

Moreover, cHPWH could serve as grid batteries by leveraging their thermal storage capabilities. Aggregating electric DHW systems to store surplus electricity during periods of peak generation or when utility rates are lowest can help mitigate issues with curtailed renewable energy in the power grid. This strategy not only lowers carbon emissions but also reduces costs for consumers. It is anticipated that HPWH designs using a CO2 heat pump can be effective for most of the year, with supplemental electric resistance heating required only during the very coldest days of the year. The thermal storage will provide a buffering effect to minimize peak power consumption during these periods and enable load shifting for demand response, but the use of a heat pump-based system with integrated TES also enables other functionality that Steffes intends to exploit in future developments.

On the other hand, with the shift of the electricity sector from a traditional centralized system to a smart grid device (Alibabaei et al. 2017), the rapid proliferation of the 'Internet of Things' (IoT) (Siano 2014) allows major loads, such as heat pumps, to be controlled with the goal of reducing peak power consumption. In a smart grid, heat pumps can be considered part of the demand side and its operation can be actively managed to stabilize voltage fluctuations caused by the high penetration of renewable energy (Fischer and Madani 2017). One goal of smartly controlled central HPWH is to achieve emission reduction. Thus, it is important to incorporate a grid's GHG condition into site-specific control strategies. The grid system-wide emission depends on the total power production rate from grid power generators, and other factors that affect system operating conditions, such as solar and wind availability. The marginal grid emissions rate (MGE) is the partial derivative of the systemwide emission rate with respect to the total production rate (Callaway, Fowlie, and McCormick 2018). It means the change of the emission rate in the grid region with respect to the last unit of electricity produced by dispatchable generators, in the unit of amount of CO2-equivalent per kWh. Intuitively, this indicates how much the carbon emission rate increases/decreases in a specific grid region when an appliance consumes one more/less unit of power. Therefore, MGE allows for the association of the power usage at a specific site with the carbon emission rate in that grid region by simply multiplying the on-site power consumption with the MGE signal. In this project, we used the MOER signal calculated by WattTime, based on a proprietary model that extends the basic methodology used by (Siler-Evans et al. 2013) and (Callaway, Fowlie, and McCormick 2018), but adapted for real-time use. WattTime calculates these marginal operating emission rates in real-time, every 5 min using a combination of grid data from the respective ISO and 5 years of historical Continuous Emissions Monitoring System data (Agency 2018). Figure 1 shows a demonstration of WattTime data on April 7th, 2023 for four major US grid balancing areas, i.e., California Independent System Operator (CAISO), The New York Independent System Operator (NYISO), Western Interconnection Balancing Authorities (WACM) and Southwest Power Pool (SPP).

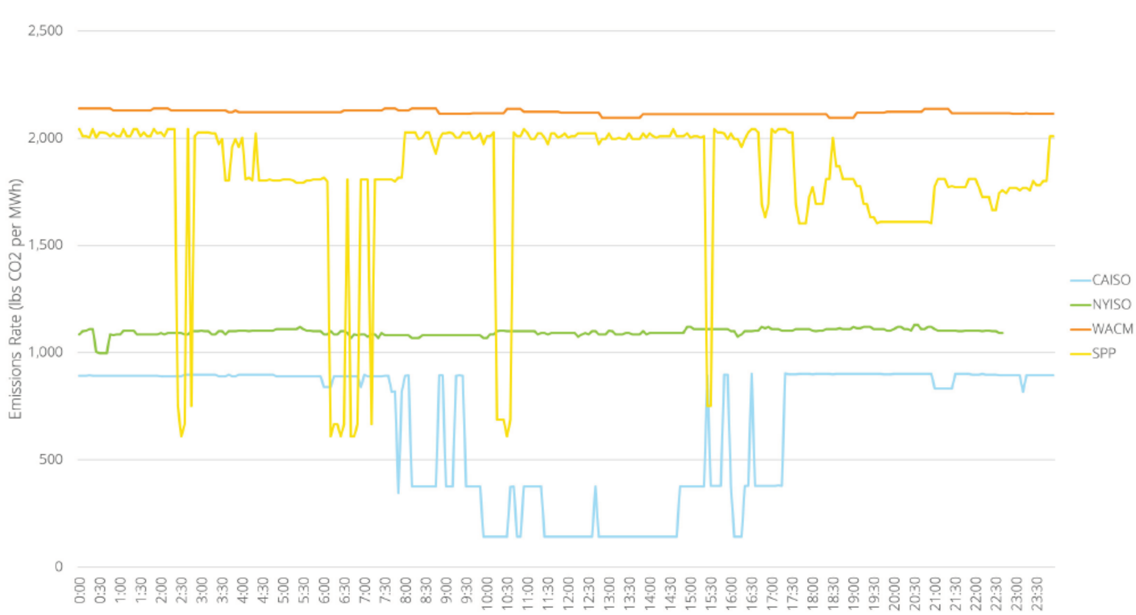



*Figure 1: Marginal Operating Emissions Rates for Four Representative US Grid Balancing Areas, April 7, 2023*

## 3. BENEFITS TO THE FUNDING DOE OFFICE'S MISSION

The project on centralized CO2 Heat Pump Water Heater (HPWH) systems with Thermal Energy Storage (TES) directly aligns with the U.S. Department of Energy's (DOE) mission to advance the national, economic, and energy security of the United States. By leveraging advanced thermal energy storage and CO2 heat pump technologies, this project enhances energy efficiency and promotes sustainable energy practices in multi-family buildings. The significant utility cost savings and emission reductions demonstrated through our simulations contribute to the DOE's goals of reducing energy consumption, lowering greenhouse gas emissions, and fostering innovation in clean energy technologies.

Furthermore, this project supports the DOE's efforts to modernize the nation's energy infrastructure and increase the resilience of the energy grid. By enabling load shifting and reducing peak power consumption, our HPWH systems with TES help to balance the demand on the grid, particularly in cold climate regions where energy demand can be highly variable. This not only improves grid stability but also integrates seamlessly with the DOE's vision for a smarter, more flexible, and more sustainable energy system. Our collaboration with industry leaders and research institutions further amplifies these benefits, driving forward the DOE's mission to ensure America's security and prosperity through transformative science and technology solutions.

# 4. TECHNICAL DISCUSSION OF WORK PERFORMED BY ALL PARTIES

## 4.1 SAMPLE WATER DRAW PROFILE USED FOR SIMULATION.

For hot water usage, the DHW event schedule generator tool developed by U.S. Department of Energy (DOE) was used. Instead of inferring the draw profiles from statistical outputs, using the draw generator tool entails directly measuring the profiles. As shown in Figure 1, there are five identified hot water-related end uses: showers, faucets, and others not specified here. In this study, the seasonal variations in water consumption patterns are not considered. For instance, the study does not reflect changes in behavior, such as longer showers during colder months or increased laundry during warmer periods. It operates under the assumption that while daily water use at a fixture may fluctuate, it averages out to remain consistent throughout the year.

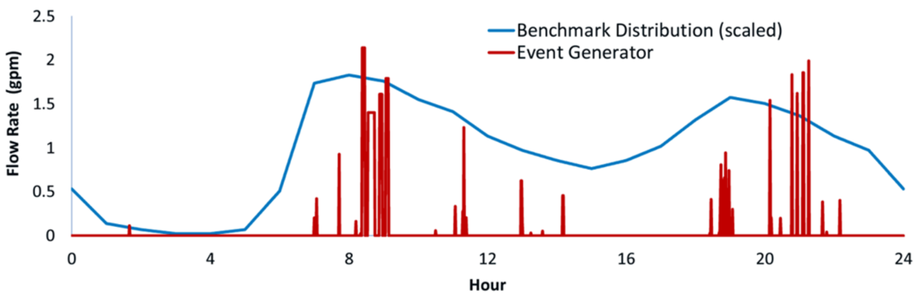


*Figure 2: Water draw profile from DOE event generator.*

## 4.2 SIZING OF THE CENTRAL HEAT PUMP WATER HEATER

When sizing a central heat pump water heater, we used a commercial tool, EcoSizer, which was developed by Southern California Edison (SCE), Sacramento Municipal Utility District (SMUD), Bonneville Power Administration (BPA), Northwest Energy Efficiency Alliance (NEEA), and Oak Ridge National Laboratory (ORNL). This sizing method accounts for hot water production during periods of peak demand from building occupants. The goal of water heating system sizing is to specify the heating capacity and hot water storage volume needed to meet peak hot water demand on the design day, which is usually the day with the coldest ambient conditions. By using the heat pump and water tank specifications, the minimum heating capacity and storage volume needed to meet this anticipated peak hot water demand is decided by a sizing curve under the design-day weather conditions.

For multifamily buildings, utilizing the EcoSizer's Low-Medium demand profile (25 gal/person/day) is typically adequate to meet water needs. The average daily consumption is 21.8 gal/person/day. To achieve effective load shifting, storage should cover the entire 4-hour peak demand, with heat pumps sized for recovery between peaks. Although heat pumps are typically sized for continuous operation on the coldest winter days, additional capacity may not be necessary in summer. However, for year-round load shifting, it's crucial to have sufficient storage and sufficient heat pump capacity to recharge more quickly between peaks during winter. After considering all these factors, the system was sized based on a 4-hour peak demand and has 500 gallons of water storage tank and 53kW heat pump capacity for a low-rise multi-family building.

Figure 3 shows a schematic diagram of the $CO_2$ HPWH system. Three primary water storage tanks and one swing tank are connected in series. Cold city water flows through the $CO_2$ heat pump gas cooler and its temperature is elevated to the set point. The storage tank in single-pass equipment is not mixed. It relies on tank stratification to ensure previously heated water does not re-enter the $CO_2$ heat pump gas cooler. Single-pass systems use a swing tank equipped with electric resistance for temperature maintenance.

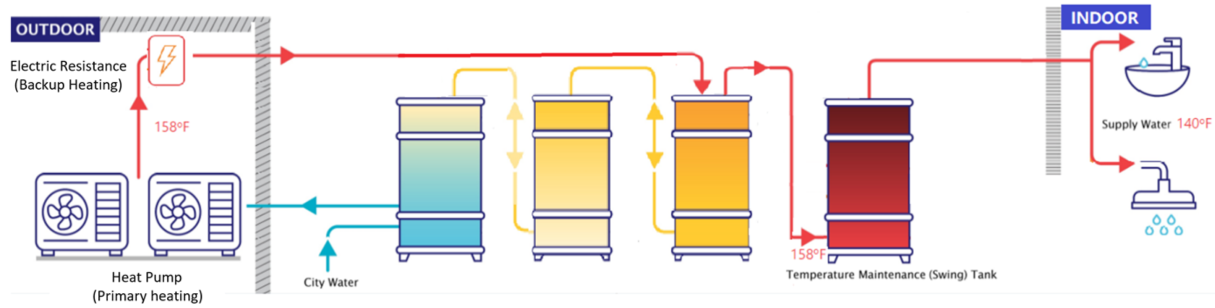



*Figure 3: Central CO2 HPWH without recirculation or mixing valve*

### 4.3 2.3 MODELING OF STRATIFIED WATER TANK

Due to the lower density of hot water, it naturally rises above colder water. Therefore, stratification happens. Stratification offers several advantages such as (1) it enables TES systems to meet building requirements with less storage efficiently, allows partially charged systems to deliver hot water, and enhances the efficiency of HPWH. The presence of a thermocline, where the temperature shifts between hot and cold water, is crucial. A smaller thermocline region indicates a tank closer to ideal stratification, which is essential for designing TES systems to minimize storage needs. For instance, experiments (Svarc et al. 2014) show that a well-stratified 500-gallon tank can provide approximately 300 gallons of usable hot water at 120°F, whereas a poorly designed, less stratified tank only supplies about 150 gallons. Therefore, it is important to model the water stratification correctly.

In order to model the stratified water tank equipped on cHPWH, a finite-element-based tank model developed by Boudreaux et al. (2014) for decentralized HPWH was modified. Figure 4 (a) shows the stratified water tank. Equation (1) shows the temperature calculation for a water layer, i.e. node. The model was validated against experiments on a small water tank with 55 gallon storage. When applied to centralized HPWH, since the hot water is added at the top of the tank and there is no heating source for other nodes, the fraction of energy added to node-1, $C_{hp}(1)$, is 1. For other nodes, $C_{hp}(n)$ is 0. When the heat pump capacity is sufficient, the electric resistance backup heating is off, so $C_e(n)$ is 0.
When the heat pump capacity is not sufficient to satisfy the water heating load, the electric resistance heating is on, the sum of $C_e(1)$ and $C_{hp}(1)$ is 1. Under these circumstances, the capacity of the heat pump is determined by the heat pump performance map as a function of ambient condition and the capacity of the electric resistance heating is the required water heating load minus the heat pump capacity.

$$\Delta T_w(n) = \frac{Q_{hp} \times C_{hp}(n) + Q_e \times C_e(n) - UA(n) \times (T_w(n) - T_{amb}) + \dot{m} \times c_w \times \big(T_w(n+1) - T_w(n)\big)}{c_p \times m(n)}$$

| | | | |
|---|---|---|---|
| $Q_e$ | = | Energy added to tank by the elements | |
| $Q_{hp}$ | = | the heats added by the heat pump | |
| $C(N)$ | = | fraction of energy added to node | |
| $UA(N)$ | = | standby heat loss coefficient of node N [Btu/min °F] | (1) |
| $T_w(N)$ | = | Water temperature of node N [°F], | |
| $T_{amb}$ | = | ambient temperature [°F], | |
| $\dot{m}$ | = | mass flow rate [lb/min], | |
| $c_p$ | = | Specific heat of water [Btu/lb °F], | |
| $T_w(N+1)$ | = | Water temperature of node N+1 [°F], | |
| $m(N)$ | = | mass of water in node N [lb]. | |

Figure 4 (b) shows a tank stratification test when turning the heat pump off first, but only pull hot water out of the tank. After a while, turn the heat pump on and continue to pull hot water from the tank.

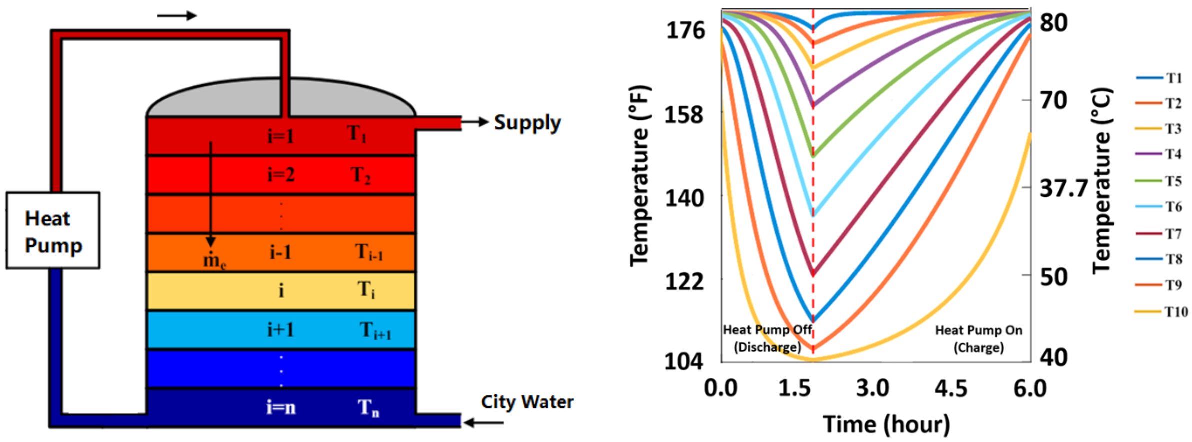



*Figure 4: (a) Stratified water tank illustration; (b) Water layer temperature when the heat pump is off and on*

The performance of the heat pump is modeled using a performance map provided by the $CO_2$ central heat pump manufacturer. Figure 5 shows the heat pump COP as a function of outdoor temperature and water inlet temperature.

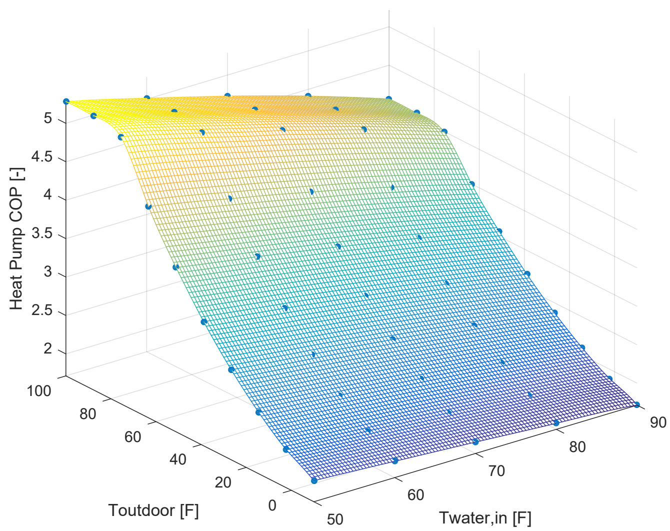
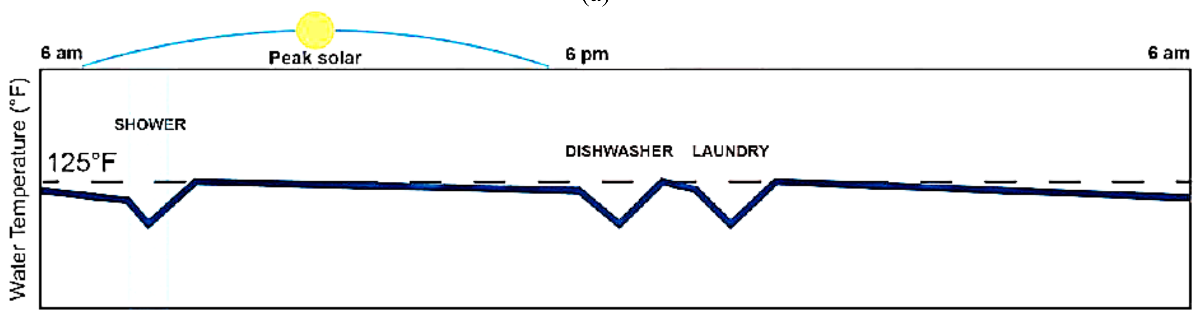



*Figure 5: Heat pump performance map as a function of outdoor temperature and inlet water temperature.*

## 4.4 2.4 LOAD SHIFTING BY PREHEATING THE WATER

The idea behind shifting the operation schedule is to preheating the water heater tank during the hours when the electricity rate is low, or when the heat pump efficiency is high due to warm outdoor temperature, or when the grid emission intensity is low, i.e. preheat the water when there is an excess of renewable power generation to avoid curtailment. Effective load shifting reduces HPWH operation during peak grid hours, the load-shifting goals include reducing peak demand (kW) during grid peak hours, lowering energy usage (kWh) in peak periods, reducing utility costs ($) and decreasing carbon emissions (MTCO2). This project aims at balancing these objectives, focusing on reducing utility costs while minimizing CO2 emissions. In this study, the load shifting is realized by a preheating strategy, i.e., preheating water during off-peak hours to reduce the energy required during peak times, as demonstrated in Figure 6.

(a)




(b)

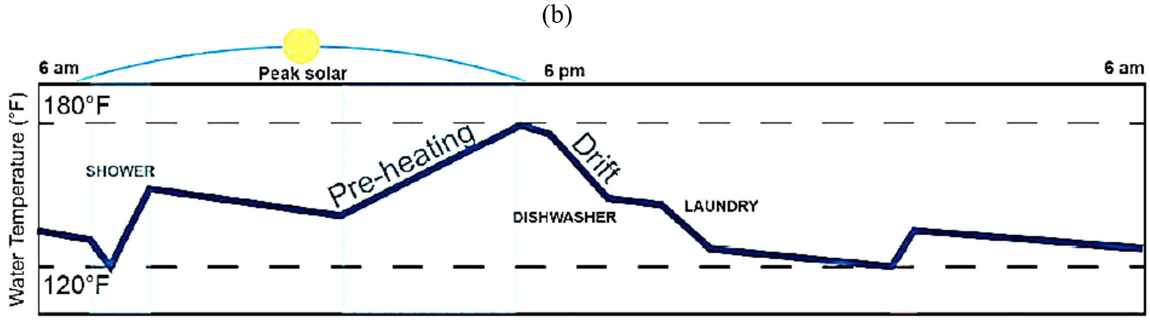



*Figure 6: Illustration of load-shifting of central HPWH through preheating water tank (a) Average water tank temperature with fixed set point; (b) Average water tank temperature with preheating*

## 2 CASE STUDY

The load shifting performance of cHPWH is evaluated using Los Angeles and Chicago, using the Time-of-Use scheme and marginal grid emission signal for 2022, i.e. 8766 hours. Figure 6 shows dry bulb temperature for Los Angeles and Chicago.

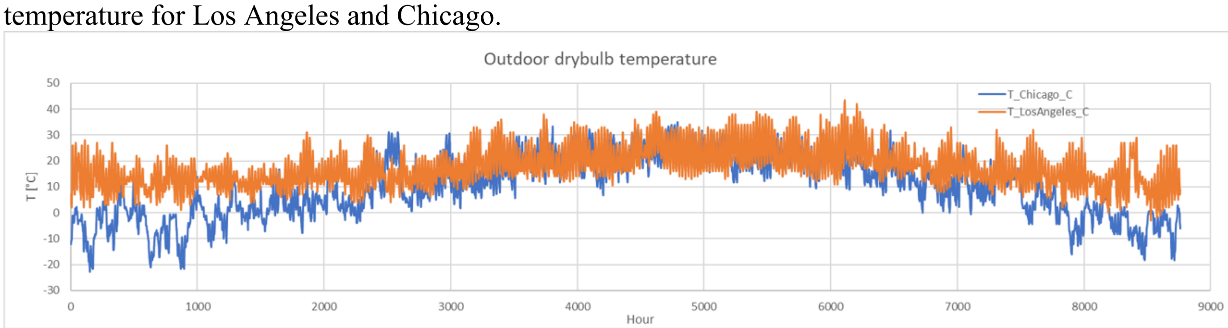



*Figure 7: Hourly Dry Bulb Temperature for Los Angeles and Chicago from 1/1/2022 to 12/31/2022*

Figure 7 shows the marginal grid emission (MGE) data Los Angeles and Chicago in 1/1/2022. The grid in Los Angeles has more renewable mix, and thus cleaner. Both MGE signal shows significant peak and unpeak periodic patterns which are easier for load shifting implementation compared with MGE signal in Southwest Power Administration with smaller variation of MGE.

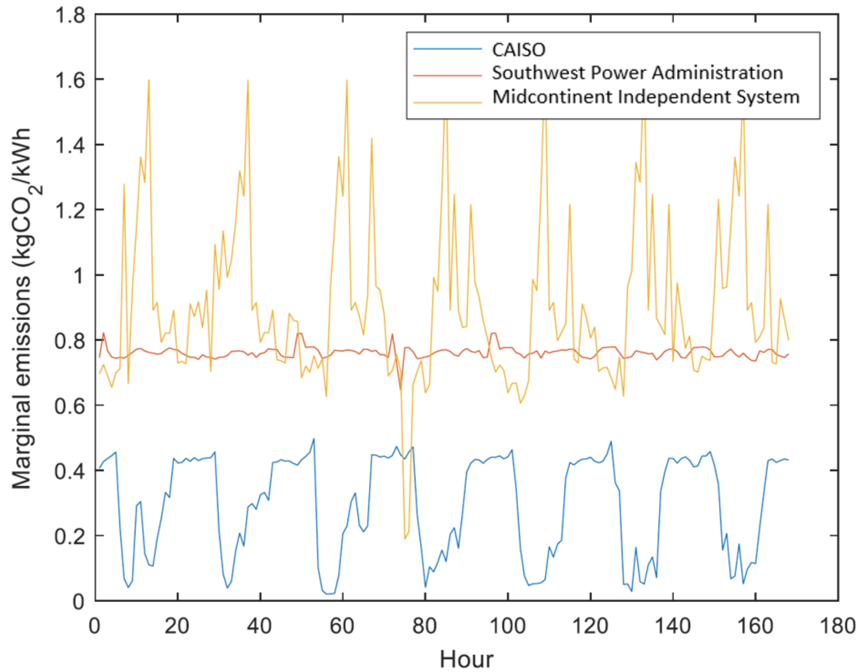



*Figure 8: Marginal Grid $CO_2$ Emission for CAISO (used in Los Angeles), SPA and MIS (used in Chicago).*

For Los Angeles (Figure 9 (a)), the Time-of-Use utility rate is adopted from Southern California Edison (SCE) and the natural gas price is adopted from SoCalGas. The electricity price ranges from 25 to 44 cents per kWh. For Chicago (Figure 9 (b)), the Time-of-Use utility rate is from ComEd company.

(a)

(b)

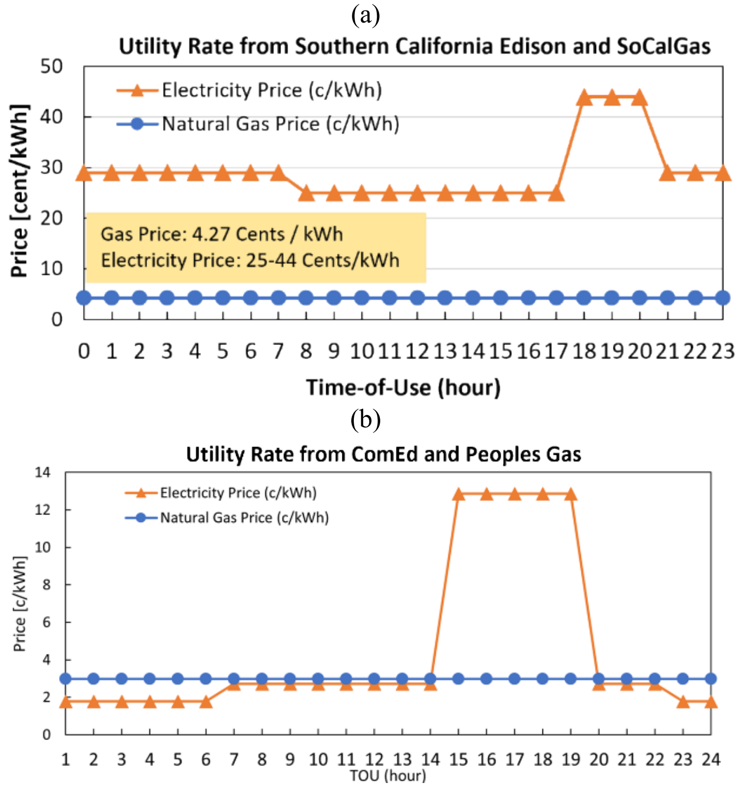



*Figure 9: (a) Time-of-Use Utility Rate from Southern California Edison in Los Angeles; (b) Time-of-Use Utility Rate from ComEd in Chicago.*

In this project, two HPWH operation scenarios are modeled, i.e., a baseline case without preheating water and a load-shifting case with preheating under a specified schedule. The preheating schedule for Los Angeles and Chicago are shown below:

- Los Angeles: 10 am – 1pm (stacked benefits for non-peak TOU and low MGE)
- Chicago: 3 am-6 am (non-peak TOU) or 10 am – 1 pm (high heat pump COP due to warm ambient)

Figure 10 and Figure 11 show the HPWH electricity consumption for 1/1/2022 in Los Angeles and Chicago with and without preheating, respectively. And Table 1 and Table 2 show the comparison of annual energy consumption.

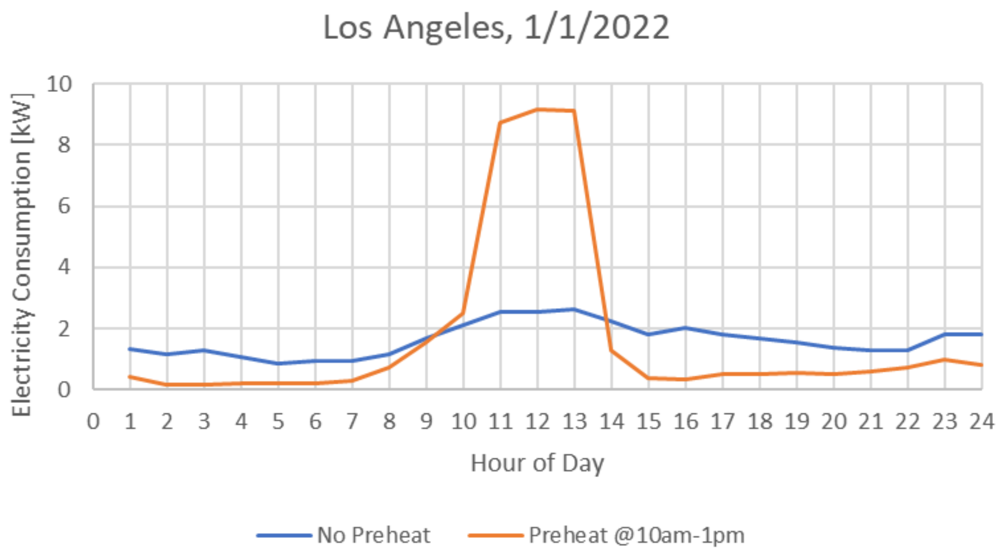



*Figure 10: Central HPWH Electricity Consumption for 1/1/2022 in Los Angeles*

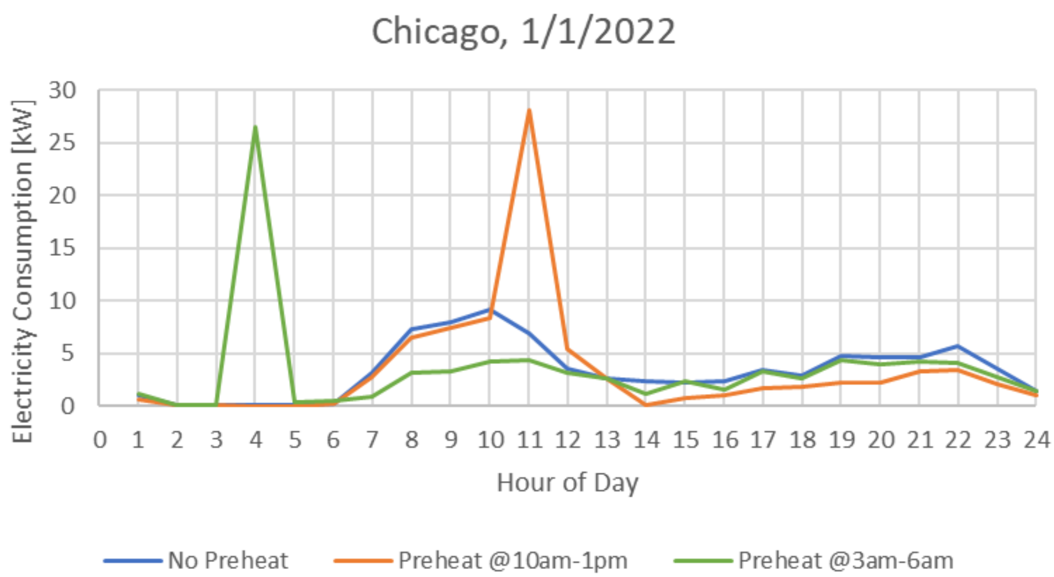



*Figure 11: Central HPWH Electricity Consumption for 1/1/2022 in Los Angeles*

*Table 1: HPWH operation cost comparison in Los Angeles*

| | No Preheat Baseline | Preheat @10am-1pm |
|---|---|---|
| **Annual total utility cost [$]** | 6471 | 5994 (7.4% ↓) |
| **GHG Emission [lbCO2/year]** | 15900 | 14286 (10.2% ↓) |

*Table 2: HPWH operation cost comparison in Chicago*

| | No Preheat Baseline | Preheat @10am-1pm | Preheat @3am-6am |
|---|---|---|---|
| **Annual total utility cost [$]** | 5479 | 4681 (15%↓) | 5727 (4.5%↑) |
| **GHG Emission [lbCO2/year]** | 63030 | 55025 (13%↓) | 65902 (4.6%↑ ) |

In Los Angeles, due to the non-peak TOU period coinciding with the grid emission and warm outdoor temperature, both utility saving and CO2 reduction are achieved simultaneously. However, in Chicago, preheating water at higher ambient temperatures can reduce the utility cost and CO2 emission because it reduces the time to run a heat pump at low efficiency. In addition, the demand reduction benefits are more significant in Chicago with colder climates than in Los Angeles, especially in terms of utility cost saving.

## 5. COMMUNICATIONS

The following conference paper was published and presented to disseminate the findings of this work:

Li, Z., Bush, J., Gluesenkamp, K.. 2024. Assessment of Centralized Domestic Hot Water Systems as An Electrification Option for Multi-Family Water Heating in Cold Climates. 20th International Refrigeration and Air Conditioning Conference Purdue. Paper # 2508.

## 6. COMMERCIALIZATION POSSIBILITIES

The TES enabled centralized HPWH systems technology offers a transformative solution for multi-family residential buildings. By utilizing large water storage tanks as thermal batteries, these systems significantly reduce peak power consumption and provide substantial load-shifting benefits. With proven utility cost savings and emission reductions demonstrated through simulations in cities like Los Angeles and Chicago, this project is poised to make a significant impact in the energy efficiency market. The target market for this technology includes multi-family residential buildings in urban areas, particularly those in regions with high energy costs and stringent emission reduction regulations. The multi-family housing market is substantial, with a consistent demand for new units in major cities across the United States. Moreover, the growing emphasis on energy efficiency and sustainability in building practices presents a significant opportunity for our technology to thrive. Trends such as the adoption of smart grid technologies, rising utility costs, and regulatory pressure to reduce greenhouse gas emissions further bolster the market potential for our HPWH systems.

The project’s unique selling propositions lie in its ability to deliver significant utility cost savings and emission reduction. The integration of advanced CO2 heat pump technology, combined with finite-element-based stratified tank models, ensures optimized performance and efficiency. To effectively market the central HPWH systems, in future, the project team will involve more stake holders by including utility companies, building owners, and property management companies.

Partnerships will play a crucial role in our commercialization plan. Collaborating with industry leaders like Steffes and other technology providers will enhance our product's capabilities and market reach. We will also work with utilities to offer incentive programs for adopting HPWH systems with TES and engage with regulatory bodies to promote favorable policies and incentives for energy-efficient technologies.

## 7. FUTURE COLLABORATION

As the project team continues to advance our research on grid-interactive heat-pump water heating technology, we recognize the immense potential for future collaboration with industry leaders and innovative partners. Our ongoing partnership with Electrification Strategies and Steffes has laid a strong foundation, and we are eager to explore further opportunities with industry partners. Steffes’ expertise in electric thermal storage and smart grid solutions aligns seamlessly with our objectives. Future collaboration will not only optimize energy consumption but also provide consumers with greater control over their energy usage, ultimately leading to cost savings and reduced environmental impact.

Furthermore, the future joint efforts will focus on developing scalable models that can be applied across various types of multifamily housing units. By combining our research insights with Steffes' practical experience in deploying thermal storage solutions, we can create adaptable and customizable systems that meet the diverse needs of different residential settings and pave the way for broader adoption of electrification strategies in the housing sector. ORNL team is excited about the potential for these collaborations to drive significant advancements in our research and in the broader field of electrification. Together with Steffes, Electrification Strategies and other key partners, the team aims to create sustainable, efficient, and resilient energy solutions that will benefit both consumers and the environment.

## 8. CONCLUSIONS

This project evaluates the performance of a centralized DHW system equipped with a $CO_2$ heat pump water heater in multi-family buildings through simulation. The heat pump system and water storage tank are sized using design-day sizing. A generic stratified tank model is used and performance data from a commercial DHW product are used to simulate the central HPWH system. To assess the potential of the centralized DHW system for energy efficiency improvements, load-shifting, and emission reductions, annual simulations are conducted. These simulations incorporate utility tariffs and marginal grid emission data from Los Angeles and Chicago. Simulation results show the feasibility to use central $CO_2$ HPWHs as thermal battery for demand response management. Preheating water at higher ambient temperature (or low utility or low grid emission hours) can reduce the time to run heat pump at low efficiency and reduce the need for electric resistance in peak hours. The case study demonstrates that the demand reduction potential of central $CO_2$ HPWHs is significant in cold climates regions.

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