Bringing 120V Heat Pump Water Heaters into Space-Constrained Housing: Addressing Up-Sizing Concerns Using Phase Change Material Heat Exchangers

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ABSTRACT

In the U.S., a majority of multifamily and manufactured housing units have domestic water heaters with capacities at or below 50 gallons. The small utility closets often present in these homes preclude installation of more energy-efficient and cost-saving heat pump water heaters (HPWHs), which are around 30% larger in size than their standard electric or gas counterparts. It is also often recommended to install a larger volume when replacing a standard water heater with a HPWH to minimize how often the backup elements need to run. This practice thus renders residents of space-constrained housing unable to take advantage of the 60%–70% energy savings associated with HPWHs when compared to electric resistance water heaters. To tackle this challenge, this study demonstrates how heat exchangers containing phase change materials (PCMs) can be integrated into water heaters to enhance hot water delivery. This technology opens new markets for HPWHs by providing up-sized performance in the volume of a smaller tank. We present numerical results that demonstrate how various PCM-integrated heat exchanger configurations could positively impact key performance indicators such as first hour rating while decreasing hot water unmet demand. Our results show that a 40-gallon HPWH with PCMs offers equivalent or elevated performance compared to that of a 50-gallon HPWH while improving hot water delivery without energy penalty. This study offers a novel solution for enhancing the adoption of high-performance equipment in a sector of the residential housing stock where HPWHs remain largely inaccessible. Future work includes developing prototypes based on these modeling results to validate the performance of this technology.

Introduction

Domestic water heating is a major source of energy consumption in U.S. households, constituting about 18% of total consumption (EIA 2020). Heat pump water heaters (HPWHs) can reduce this energy intensity significantly—when compared to electric resistance water heaters (ERWHs), HPWHs use 60%–70% less energy (Sparn and Maguire 2021). Nearly half of all homes in the U.S. currently have ERWHs (EIA 2020), so HPWHs represent a major opportunity for reducing sector- and household-wide energy consumption, peak demand, and utility bills.

Several regions of the U.S. have developed strategies to try to replace existing gas water heaters, including California and New England (TECH Clean California 2026, Mass Save 2025). Along with providing incentives for HPWHs, lower power 120V HPWHs have been developed to help facilitate this switch. 240V HPWHs have large backup electric resistance elements for periods of peak water heating demand but require a dedicated 30-amp circuit. In homes that currently use natural gas for water heating, this circuit is less common, and requiring a panel upgrade or running 240V power adds a substantial barrier to adoption owing to extra costs and installation complexity. Due to the lack of backup elements, 120V HPWHs may run out of hot water during periods of concentrated hot water use. To compensate for this, one solution is to overheat the tank and use a tempering valve. Many installers and decarbonization programs also recommend up-sizing of 120V HPWHs (PNNL 2026).

HPWHs are 30% larger in size than ERWHs and gas water heaters, presenting issues in homes that typically feature small utility closets such as manufactured homes or multifamily buildings with in-unit water heaters. 62% of these homes have water heaters smaller than 50 gallons (EIA 2020). Many of these units are "low boys"—a squat form factor designed specifically to fit into tighter spaces. Data on the typical closet size in manufactured and multifamily homes is not readily available, limiting an understanding of how many homes are space-limited. Widespread deployment of this technology requires better integration of system design with existing housing characteristics, such as utility closet size.

This work proposes the use of thermal energy storage via phase change materials (PCMs) as a solution for improving the performance of small-volume water heaters to meet up-sizing recommendations. PCMs with phase transition temperatures tailored to domestic hot water applications have a higher energy storage density than liquid water alone, thus allowing water heaters to achieve comparable performance with smaller tanks (Hirmiz et al. 2019). Several studies have investigated adding PCMs inside the tank of HPWHs as cylindrical or spherical capsules (Huang et al. 2025; Rendall et al. 2023; Sun et al. 2025). Huang et al. (2025) note up to 18.1% improvements in coefficient of performance (COP) and Rendall et al. (2023) cite 27.7% improvements in energy capacity. However, of the aforementioned studies, only Rendall et al. (2023) and Sun et al. (2025) address industry-standard performance metrics including first hour rating (FHR) and uniform energy factor (UEF) (DOE 2026), citing up to 26% increases in FHR (Sun et al. 2025) and 5.5% increases in UEF (Rendall et al. 2023). Zou et al. (2017) describe a configuration with PCM encased around the HPWH tank and report a 14% improvement in heat storage capacity and 4.5% improvement in COP. However, no studies directly quantify metrics such as unmet demand, which can indicate daily performance under realistic draw profiles.

PCMs suffer from low thermal conductivity, limiting heat transfer with water and PCM utilization. Studies have demonstrated the use of 3D printing to fabricate high-surface-area lattices such as triply periodic minimal surface (TPMS) containing PCMs (Ly et al. 2024; Troxler et al. 2026). This approach can boost heat transfer and conveniently divide space into two distinct domains, making them ideal for heat exchanger applications. Additionally, researchers have investigated the use of compressed expanded graphite as a shape-stabilization matrix and thermal conductivity enhancer for PCMs (Wang et al. 2021).

This study analyzes multiple options to increase the thermal capacitance of 120V HPWHs for space-constrained housing. In particular, we investigate (1) the use of TPMS lattices infiltrated with PCM as heat exchangers (HXs) inside the tank, and (2) an expanded graphite-PCM composite HX external to the tank.

Methodology

This paper seeks to compare the performance of a 40-gal HPWH with various energy storage-enhancing configurations to that of the up-sized 50-gal HPWH. We use the National Laboratory of the Rockies' (NLR) OCHRE™ tool (Maguire and Blonsky 2025) to simulate FHR for 40-gal

HPWHs containing PCMs and verify the ability to achieve equivalent hot water delivery to an up-sized tank without increasing physical footprint. Additionally, we use OCHRE to conduct annual simulations of a full dwelling with realistic water draw profiles based on varying occupancies. These simulations allow us to compare the energy consumption and unmet demand impacts of a PCM-integrated HPWH with a baseline HPWH that has both standard and elevated setpoints. In addition, this study includes quantitative and qualitative data that elucidates the prevalence of HPWH-limiting space constraints in manufacturing housing.

Water Heater Closet Dimensions Survey

To understand the challenges associated with replacing gas water heaters with HPWHs, this study collects water heater closet data from four different sources:

1. An online survey targeted at manufactured home parks distributed through Colorado School of Mines and conducted from December 2024 to March 2025, which required participants to measure the actual closet dimensions and take a photo with a numeric password for verification.
2. An online survey sent by QuitCarbon to their 6,000 clients and subscribers in California, where residents submitted self-reported dimensions of the utility closet present in their homes.
3. Dimensions measured and provided by a general contractor performing a community-scale electrification project of 12 manufactured homes in Colorado (Saeidi et al. 2026).
4. Dimensions provided by Slipstream Inc. measured during energy assessment in a manufactured housing community retrofit of 24 homes in Minnesota.

Given the small sample size, the closet-dimension dataset collected as part of this study is not necessarily representative of national manufactured-housing stock, particularly regions with different vintages and HUD code compliance histories. Nonetheless, this study provides preliminary data on a metric that is not widely reported across the industry. To bolster the data collection, qualitative validation was included via interviews with the following manufactured housing companies and contractors that have experience replacing water heaters:

- Two leading manufactured home companies with over 4 million homes across the US.
- A non-profit in Colorado working on an ~80 manufactured housing community that has electrified about 30 homes.
- An electric cooperative in Colorado that installed 20 HPWHs in 2022 (Moorefield 2023).

Water Heater Model Description & PCM Implementation

OCHRE is a tool developed at NLR to model residential buildings, with a focus on modeling buildings in co-simulation with the local distribution grid and advanced control strategies (Blonsky et al. 2021). OCHRE is open source with a relatively small code base compared to other tools, making it ideal for prototyping the unique equipment and combinations of technologies. In this study, we add new capabilities in OCHRE to model a water heater integrated with PCMs. This new model allows for both internal and external PCM integration strategies, enabling analysis and comparison of PCM-integrated HPWH performance to the baseline HPWH model. OCHRE and other tools like EnergyPlus (DOE 2025) use a 1D model for the water heater with vertical isothermal nodes. The model uses 12 nodes at different heights in the tank and accounts for conduction between nodes, heat transfer due to fluid flow, heat added due to the heat pump or backup element, convection between water and the immersed heat exchanger, and an inversion mixing algorithm. The inversion mixing algorithm ensures that bouyancy effects where warmer less dense water rises above colder water are captured, with temperature inversions resolved instantaneously (Maguire 2018).

Figure 1 shows the two PCM integration strategies in the OCHRE HPWH model, as well as diagrams showing the components of the RC network. At a specified flow rate, cold mains water enters the bottom of tank and travels through the 12 nodes before exiting as hot water. Heat pump condenser coils are adjacent to the bottom half of the tank as denoted by the diagonal lines in nodes 7–12. For both configurations, conduction occurs between PCM nodes and between water nodes, while convection occurs between water nodes based on the geometry of the HX. Heat from the condenser coil is injected directly into the water nodes and charges the PCM through the RC network pictured in Figure 1. Similarly, heat from the discharged PCM travels through the RC network to be injected into the water nodes, calculated based on enthalpy vs. temperature data collected via differential scanning calorimetry.

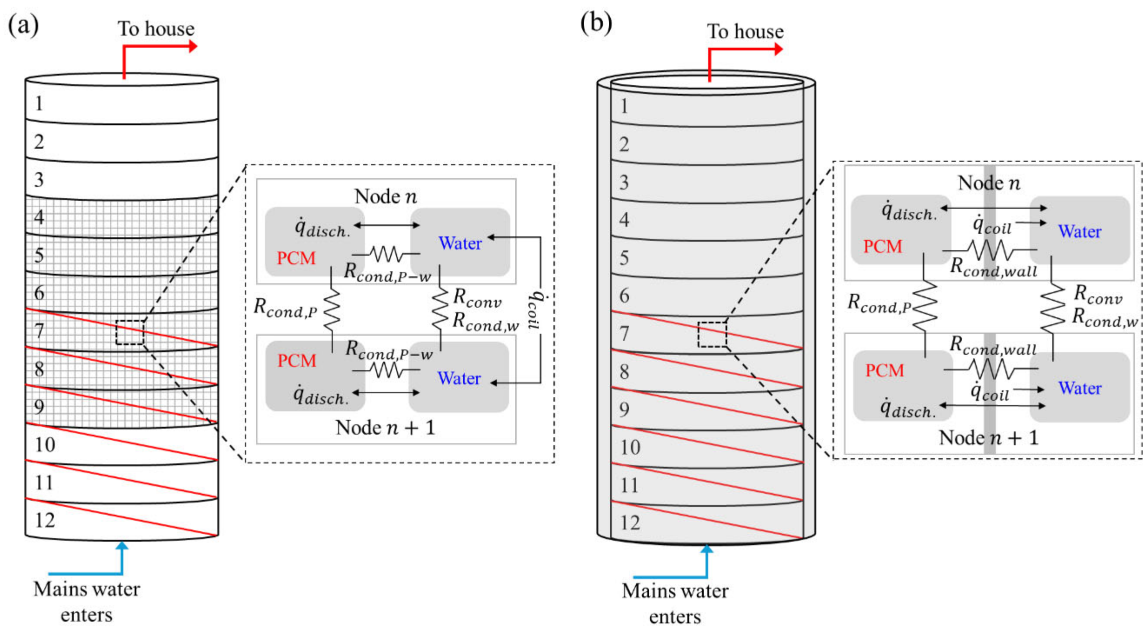

Figure 1. OCHRE heat pump water heater model setup with (a) PCM inside tank and (b) PCMs outside tank

In Figure 1a (internal HX), nodes 4–9 contain PCM and water at a specified fraction corresponding to the vol% of the HX in the tank. The lattice geometry is represented as a ratio between the HX surface area and the PCM volume (SA/V ratio), which is used to calculate relative resistance and capacitance within and between nodes. Conduction occurs directly between PCM and water within the same node, and convection in the water is determined based on the provided SA/V ratio and a specified convective coefficient (h_{conv}), described further below. Losses to the ambient occur largely through the water nodes as part of a resistor network including the tank wall and insulation (not pictured in Figure 1a). Figure 2 shows an example of a printed HX module with an internal TPMS lattice, along with renderings to visualize the water and PCM channels contained within the HX. The lattice is a 3D printed scaffold consisting of photopolymer resin, where the SA/V ratio is represented by the surface area of the blue region (water) relative to the volume of the red region (PCM).

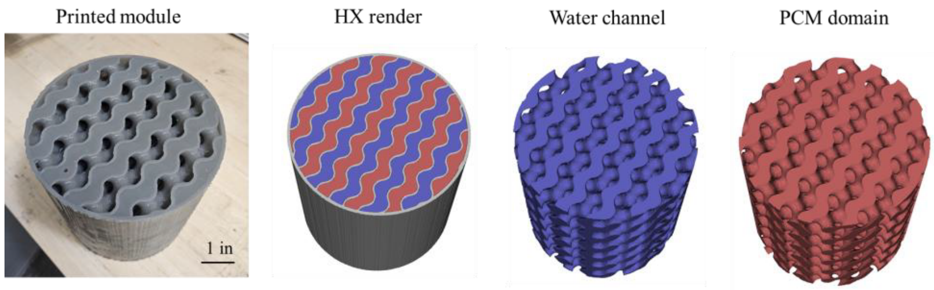

Figure 2. Printed internal HX with visualizations of TPMS lattice HX components.

In Figure 1b (external HX), each vertical node contains water and PCM at a specified thickness, separated by the tank wall. The PCM exists as part of an expanded graphite composite in an annular wrap around the tank wall, between the condenser coils and the insulation. Conduction between the PCM and water within the same node is dominated by conduction through the tank wall, while the convective resistance is based on the film heat transfer at the wall interface. To avoid increasing the diameter of the tank, the thickness of the insulation is adjusted based on the thickness of the PCM annulus. Losses to the ambient are adjusted based on the resulting thickness of the PCM and insulation layers.

The PCM for both configurations is based on PureTemp 48X (PureTemp 2025), a bio-based organic PCM. The primary inputs for the internal HX case are the convective coefficient of water through the lattice ($h_{conv,TPMS}$) and SA/V ratio. The primary inputs for the external HX are annulus thickness and the convective film coefficient at the tank wall ($h_{conv,film}$). Table 1 lists these and other relevant material properties for both configurations.

Table 1. PCM heat exchanger properties used in simulations

	Internal HX	External HX
PCM melting temperature (°C)	48	48
Total composite enthalpy (J/g)	178	180
Avg. composite specific heat capacity (J/g-K)	1.95	1.85
Avg. composite thermal conductivity (W/m-K)	0.2	10
Water convection coefficient (W/m^2-K)	2,000	250
SA/V ratio range	3 – 7	-
PCM annulus thickness range (in)	-	0.2 – 1.2

The composite properties and SA/V ratios used for the internal HX are based on a methodology developed in Blackley et al. (2026). A thermodynamic model is used to assess the minimum PCM content required to increase the total energy storage capacity of a 40-gal HPWH to that of a 50-gal HPWH (both with setpoint and cutoff temperatures of 125°F and 105°F, respectively) without exceeding the weight of an 80-gal HPWH. Additionally, the methodology includes a parametric study in OCHRE that assesses the SA/V ratio and $h_{conv,TPMS}$ that result in maximized FHR. To determine the maximum and minimum thickness of the external PCM layer, we conducted the same thermodynamic assessment. The procedure to determine the h_{conv} values listed in Table 1 is described below.

Tank Convection Coefficient Calculations

The calculation procedure for determining $h_{conv,TPMS}$ in the internal case is outlined in Blackley et al. (2026). The hydraulic diameter (D_h) of the lattice is determined via Equation 1, where V_w and SA_w correspond to the volume and surface area of the water channel, respectively.

$$D_h = \frac{4V_w}{SA_w} \tag{1}$$

The range of D_h observed across all lattice geometries is between 0.087 and 1.63 inches with a median of 0.52 inches. We calculate Reynolds number (Re) for each lattice as a function of D_h, where fluid properties such as density and dynamic viscosity are based on water at 105°F, the approximate temperature at which the water is no longer considered hot. The fluid velocity is equivalent to the superficial velocity through the tank, which is based here on a volumetric flowrate of 3 gpm (corresponding to the FHR test procedure) and a tank diameter of 15 inches.

The observed Re range is between 6.52 and 120 with a median of 38. Several studies in literature have experimentally investigated the Nusselt number (Nu) of water in TPMS lattices with similar D_h and Re values, reporting Nu values between 2 and 100 for the range of Re above (Saghir et al. 2024; Femmer et al. 2015; Yan et al. 2023). We calculate a range of $h_{conv,TPMS}$ corresponding to this Nu range using the median D_h as the characteristic length and the thermal conductivity of water at 105°F.

The resulting range of $h_{conv,TPMS}$ is between 50 and 5,000 W/m^2-K, which is used in Blackley et al. (2026) to conduct a parametric analysis coupled with SA/V ratios observed in the lattices. The results showed that for the range of SA/V ratios listed in Table 1, an $h_{conv,TPMS}$ of 2,000 W/m^2-K consistently results in a maximized FHR. Laboratory testing of HX prototypes in later phases of this project will determine the actual value of $h_{conv,TPMS}$ for selected geometries.

We determine $h_{conv,film}$ for the external HX based on an approximation of laminar natural convection from a heated vertical plate (Nellis and Klein 2009). We calculate the Rayleigh number (Ra) using the height of the tank (about 47 inches), a surface temperature of 48°C (PCM transition temperature), and a bulk fluid temperature of 105°F. Fluid properties including thermal expansion coefficient, kinematic viscosity, and thermal diffusivity are based on water at 105°F. We then calculate the average Nusselt number ($\overline{Nu}$) using Equation 2, where C_{lam} is defined in Equation 3, and Pr_w is the Prandtl number of water at 105°F.

$$\overline{Nu} = \frac{2.0}{\ln\left(1 + \frac{2.0}{C_{lam} Ra^{0.25}}\right)} \tag{2}$$

$$C_{lam} = \frac{0.671}{\left[1 + \left(\frac{0.492}{Pr_w}\right)^{9/16}\right]^{4/9}} \tag{3}$$

The resulting $\overline{Nu}$ is equivalent to 508 and can be used to solve for $h_{conv,film}$, where the characteristic length is equivalent to the height of the tank. The resulting $h_{conv,film}$ value is 268 W/m^2-K, which we approximate as 250 W/m^2-K to maintain a more conservative estimate.

Dwelling Simulation Procedure

The simulations conducted in OCHRE consist of the FHR simulation and full dwelling simulation. The FHR simulation is equipment-specific and follows the DOE standard for FHR test procedures, outlined by DOE (2026b). FHR provides consumers with information on the maximum volume of hot water that can be delivered in an hour. Due to the 1D approach used in OCHRE, current FHR simulations do not necessarily capture the complex mixing dynamics seen during large water draws such as those in the FHR test. Therefore, these simulations seek to provide early-stage guidance on design decisions based on relative performance, and laboratory testing during future phases of this effort will confirm actual FHR. For the dwelling simulation, OCHRE is configured to use HPXML files, a standardized format developed to allow for interoperable descriptions of the features of residential buildings (BPA 2026). BEopt (NLR 2026) provides an interface for quickly creating residential building models and allows for cost optimization of different common technologies.

The BEopt model used in this work is based on a manufactured house located in Lake County, CO (Munz and Tabares-Velasco 2024), though the weather file is from Golden, CO. The BEopt model consists of a 1,040 ft^2, 3-bed, 2-bath manufactured house built in 2009. We investigate an occupancy of 4 or 6 people, with the latter representing less common but plausible higher water usage homes. We use BEopt to generate HPXML files and hot water usage schedules for each occupant configuration. Hot water usage schedules are based on the Building America Domestic Hot Water Event Schedule Generator, which uses probability distributions of hot water use by end use to determine realistic discrete usage events (Hendron et al. 2010).

Since the house was built after 2009 and to generalize the construction for Golden, CO, we adjusted existing envelope construction values based on the HUD standard for Climate Zone 3 outlined in DOE (2026a). Existing system specifications include 14 ACH, SEER2 12.4 air conditioner, 86% AFUE gas furnace, 15% leakage ducts, and 20% LED lighting. A custom water heater option was created for this work, consisting of a 40-gal HPWH with 4.9 UEF located in the living space and a 125°F setpoint.

Annual simulations were performed in OCHRE to determine energy consumption of the whole home, including a baseline 120V HPWH and different PCM-integrated 120V HPWH designs. OCHRE accounts for all energy usage in the home and any interaction between equipment, such as how the HPWH may cool the space during operation (which can affect HVAC energy usage). Along with calculating energy consumption, OCHRE also tracks the outlet temperature of any water heater and calculates unmet load. Unmet loads are calculated using an unmet fixtures metric (Maguire 2020), which calculates the energy deficit in providing water hot enough for occupants during shower, sink, and bath draws. It is assumed that occupants require a minimum temperature of 105°F.

Results

Water Heater Closet Survey

The 230 submissions collected in the Colorado School of Mines survey resulted in 70 authentic submissions. The survey distributed via QuitCarbon received 170 total responses, 28 of which are considered space-constrained homes. The remaining 9 responses are from the Colorado and Minnesota communities. Submissions included 19 condos, 67 manufactured homes, 16 multifamily units, and 5 townhouses. For this analysis, we defined the minimum closet dimensions as 26-in. depth and 26-in. width (26" x 26"). This is based on a 3-in. clearance between the HPWH tank and closet walls (to facilitate maintenance and installation), assuming a 40-gallon HPWH diameter of 20 inches, which is commonly installed in manufactured homes.

Table 2 shows the number of homes with water closet dimensions equal to or above 26" x 26" and smaller than 26" x 26". Of the 67 manufactured homes surveyed, 75% had closets that fell below the threshold, and among all respondents, 83% of all houses with closets below the threshold are manufactured homes. This result highlights the importance of addressing space concerns, particularly in manufactured housing.

Table 2. Number of households with water closets under or over the threshold for four space-constrained housing types

	Condo	Manufactured Housing	Multi-Family	Townhouse
Over or Equal to 26"x26"	11	17	15	4
Under 26"x26"	8	50	1	1

A more granular look at the manufactured housing closet dimensions reveals that the limiting factor in meeting the threshold is closet width, as the majority of the households fall below the 26-in. threshold in width, but above the threshold in depth. To compare the survey data to our qualitative interviews, we clustered the data based on when the house was built, corresponding roughly to when various housing codes were passed: before 1976 (pre-HUD), between 1977 and 1994, and after 1994. Information from the two nonprofits that have installed more than 200 HPWHs in Colorado aligned with our findings: manufactured homes built after 2000 may have closets up to 30" x 30", but the majority had dimensions between 20" x 20" and 24" x 24". The two leading manufactured housing companies which have built over 4 million manufactured homes across the U.S. also stated that before 2012–2015, most utility closets were designed to accommodate 40-gal water heaters with dimensions around 24" x 24". New house models use 28" x 28" or 32" x 32", depending on whether the water heater is gas or electric. In general, closet width and depth posed more challenges than closet height, suggesting a "skinny" HPWH with a smaller diameter and greater height may be ideal.

Tank Up-Sizing

Figure 3 shows the results of the FHR simulations for the (a) internal HX and (b) external HX, where we evaluate the impact of design factors such as SA/V ratio and PCM layer thickness, respectively. The left y-axis (in blue) shows the FHR in gallons resulting from the corresponding design parameter on the x-axis, while the right y-axis (in red) shows the PCM utilization percentage. Here, a PCM utilization of 100% signifies that all the PCM discharged during the test, while a PCM utilization of 50% signifies that half of the PCM remains in the liquid state at the end of the test. The SA/V ratios investigated in Figure 3a correspond to designs identified in Blackley et al. (2026), with a HX that composes 31 vol% of the tank and consists of 81 vol% PCM. The minimum and maximum PCM layer thicknesses shown in Figure 3b come from the parametric analysis described at the end of the PCM Implementation section above.

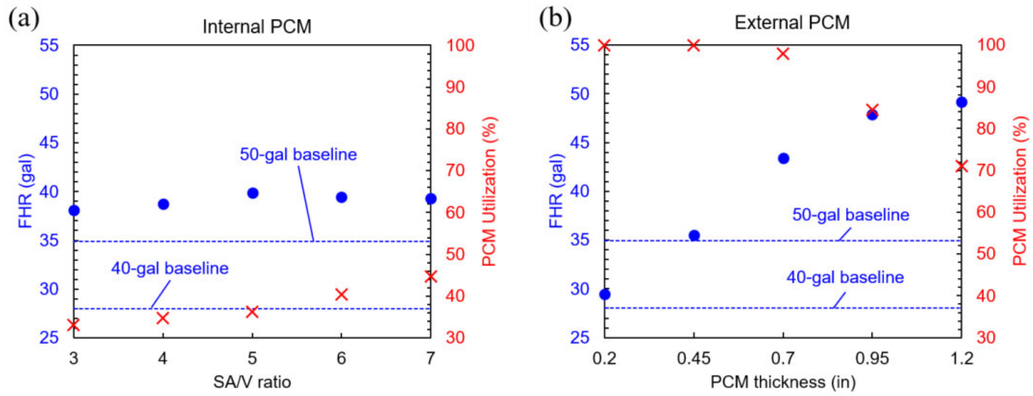

Figure 3. First hour rating (blue circle) and PCM utilization percent (red X) as a function of design parameters for (a) internal PCM HX and (b) external PCM HX

For the internal HX in Figure 3a, FHR remains nearly constant while PCM utilization increases with increasing SA/V ratio. The larger surface area available for heat transfer increases PCM utilization, but since each SA/V ratio design has the same amount of PCM (32.5 kg), FHR gains are limited. All SA/V ratio designs exceed the FHR of the 50-gal baseline, with the SA/V ratio of 5 achieving 14% higher FHR relative to the up-sized tank at a PCM utilization of 36%.

The external HX in Figure 3b shows that as the thickness of the PCM increases, FHR increases but PCM utilization decreases. This reveals that the PCM discharge rate is limited by $h_{conv,film}$ and the surface area at the tank wall. While PCM thicknesses between 0.2 and 0.7 inches fully deplete over the course of the FHR test, the 1.2-in. thickness sees utilization drop to about 71%. Nonetheless, the larger relative mass of PCM in the 1.2-in case (50.5 kg) results in a 41% improvement in FHR relative to the 50-gal baseline, while the 0.2-in case shows improvement over the 40-gal baseline but does not meet the 50-gal baseline. While PCM utilization is an important metric for thermal energy storage performance, maximizing FHR remains the most salient factor in technology deployment. Therefore, we select the 1.2-in thickness for the annual simulations. Future efforts will explore alternative methods for thermal conductivity enhancement such as fins to improve PCM utilization even for high PCM thickness.

The FHR estimated by the model differs from the rated FHR for 40- and 50-gal HPWH products. The 1D approach used in the OCHRE model captures general water heater dynamics based on inversion mixing, making it computationally efficient and ideal for annual energy simulations. However, periods of concentrated hot water draw such as in the FHR test may introduce convection loops and mixing phenomena beyond just preserving thermal stratification, which is not currently accounted for in the model. Nonetheless, the absolute difference between the 40- and 50-gal baseline FHR values reflects that seen in commercial products, so the relative performance of PCM-integrated HPWHs remains relevant at this phase of the project. This performance primarily depends on how much heat can be stored in the PCM and how quickly it can be discharged to the water, and future benchtop testing will test the dynamics predicted by the model. To better support FHR simulations, efforts are underway to integrate a more complex 1D flow-dependent mixing model that includes additional terms that capture the more detailed physical phenomena in scenarios like the FHR test (Rendall et al. 2021).

Energy Usage and Unmet Demand

On average, water consumption remains consistent throughout the year, with 4 occupants averaging 35.8 gal/day and 6 occupants averaging 53.1 gal/day. Instances of unmet demand increase in winter months when the mains temperature is lower, as the average temperature of the water tank drops with the lower temperature of water entering the tank.

Unmet demand is calculated as the energy required to heat the water to the required temperature (105°F for fixtures such as showers) any time the outlet water temperature dips below the required temperature (Maguire 2020). In real usage, occupants are likely to change their behavior in the event of a cold shower but may choose different responses. In modeling, it is difficult to pick one representative behavioral strategy; therefore, the model continues the hot water usage even when temperatures drop, then calculates the unmet demand. This makes unmet demand a useful comparison metric when looking at different tank designs and setpoints. One kWh of unmet demand is equivalent to an 8-minute shower with a flowrate of 2 gpm at about 80°F, or 25°F below the desired temperature. Large unmet demand can indicate that a tank is undersized for the usage it is experiencing.

Table 3 shows the results of the annual simulation for the modeled household with either 6 or 4 occupants. This table lists the unmet demand of the baseline 40-gal HPWH without PCMs at both the 125°F setpoint and an elevated setpoint of 140°F, 50-gal HPWH without PCMs, 40-gal HPWH with internal PCMs (HX parameters of a SA/V ratio of 5, containing 32.5 kg of PCM), and 40-gal HPWH with external PCMs (HX parameters of a 1.2-in. PCM layer, containing 50.5 kg of PCM). Table 3 also includes total electric energy to demonstrate the impact of both PCM configurations on overall energy consumption (and thus, costs).

Table 3. Annual simulation results for baseline 40-gal HPWH (125°F setpoint), 40-gal HPWH with elevated (140°F) setpoint, baseline 50-gal HPWH, and both PCM configurations in 40-gal HPWHs for both 6 and 4 occupants

	6 Occupants					4 Occupants				
	No PCM – 40 gal (125°F)	No PCM – 40 gal (140°F)	No PCM – 50 gal	Int. PCM	Ext. PCM	No PCM – 40 gal (125°F)	No PCM – 40 gal (140°F)	No PCM – 50 gal	Int. PCM	Ext. PCM
Total household electric energy (kWh)	7,910	8,120	7,930	7,970	8,010	6,840	6,990	6,840	6,870	6,930
Total hot water unmet demand (kWh)	36.6	4.88	19.1	3.51	18.1	3.24	0.647	1.84	0.56	1.15

Across all configurations, we find that adding PCMs to a 40-gal HPWH increases total household energy consumption, though only by a maximum of a 1.32% for the 4-occupant home with external PCMs. Both PCM configurations are successful in decreasing total unmet demand from both 40-gal and 50-gal HPWHs—the internal configuration reduces unmet demand up to 90.4% for an occupancy of 6, and the external configuration does so up to 64.5% for an occupancy of 4. The internal PCM configuration is more successful in reducing unmet demand than the external PCM since the internal PCMs more directly interface with the water as a part of a high surface area structure that improves heat transfer between the two materials. The external PCMs, however, are limited by the low relative flow within the tank, and thus, heat transfer rate.

When the setpoint of the 40-gal tank is increased to 140°F, the unmet demand decreases relative to the 125°F setpoint by 86.7% for 6 occupants and 80.0% for 4 occupants, outperforming the 50-gal tank at 125°F in both cases. However, the internal PCM still results in a lower unmet demand than raising the setpoint alone. While the increase in energy usage associated with the higher setpoint is still marginal (up to 2.65% in the 6-occupant case), it does so to a greater extent than adding either internal or external PCMs. Existing HPWH products with tempering valves that allow for elevated setpoints may provide similar benefits to PCMs, and additional work is underway to develop controls to modulate tank setpoints based on hot water demand (Domantay et al. 2026). This control attempts to learn occupant behavior and preheat only when necessary, thus increasing hot water delivery while minimizing additional energy input. In future phases of this project, this controls work will be combined with the current analysis to understand how to maximize the combined benefits of an elevated setpoint with PCMs while minimizing energy usage.

Figure 4a shows the daily total unmet demand for the month with the highest occurrences of unmet demand (March) along with the daily total volume of water drawn for the 6-occupant household and all three 40-gal HPWH scenarios. Figure 4b shows the net heat transferred to the water along with hot water draw flowrate for the 5-hour period within the day with the highest number of water draws for 6 occupants. The model accounts for the energy required to charge the PCM, represented as a negative heat injection from the PCM. The data in Figure 4b represents the sum of the heat injection from the heat pump and the heat injection from the PCM, thus representing only the heat injected directly to the water. For example, when the PCM is discharging and the heat pump is on, the water receives heat from both sources. However, when the PCM is being charged, the water receives a lower relative amount of heat from the heat pump. Therefore, Figure 4b contains an instance of negative heat delivered to the water, indicating that only the PCM (and not the water) is receiving heat from the heat pump.

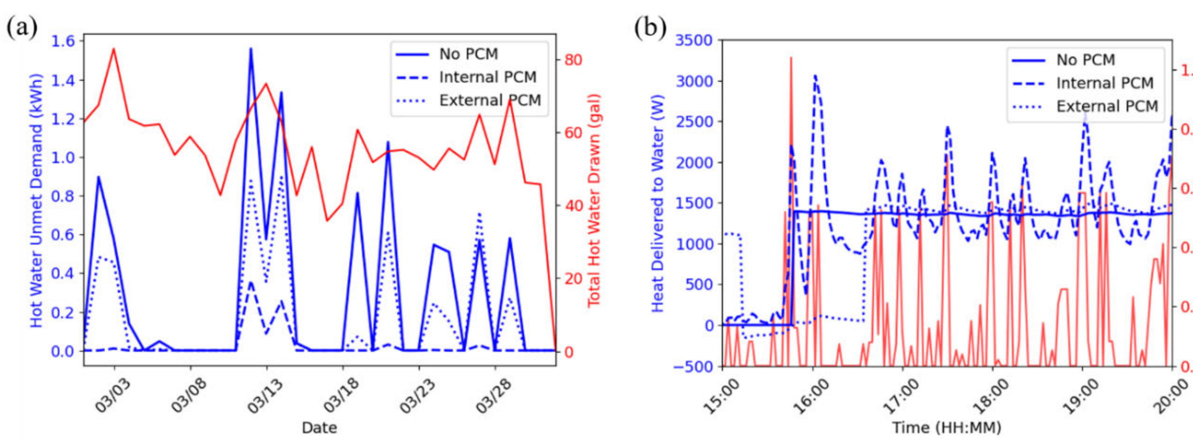

Figure 4. (a) Daily unmet demand and water drawn over month with highest unmet demand and (b) net heat delivered to water and water draw flowrate for 5-hr period in day with highest number of draws

Figure 4a exemplifies the effectiveness of the internal PCM in avoiding unmet demand—during days with large unmet demand in the baseline case, the internal PCM configuration results in zero or very low unmet demand, with only a few exceptions. The peaks of unmet demand remain largely consistent between the baseline and the external PCM case, but in general, the external PCM results in a lower magnitude of unmet demand. Figure 4b shows that internal PCMs are much more effective in delivering heat quickly during instances of high-flowrate water draws, exemplified in the number of large peaks compared to the more constant heat input from the baseline and external PCMs. The external PCM provides supplementary heat but to a lesser degree due to the conduction-limited heat transfer.

Unmet Demand Sensitivity Analysis

The convection coefficients chosen for each HX configuration in the above simulations may play a significant role in the performance of the water heater and unmet demand outcomes, as this metric is largely responsible for determining the interactions between the PCM and water. Due to the complex geometries used in this project, the convection coefficient is a substantial source of uncertainty until future laboratory testing can determine what is actually achievable. To determine how large a role it plays in each scenario, we conduct a sensitivity analysis on unmet demand, varying values of $h_{conv,TPMS}$ and $h_{conv,film}$ for the internal and external HXs, respectively. We chose values lower than those listed in Table 1 to account for fouling over time and provide conservative estimates. Figure 5 shows the results of this analysis, where the y-axis shows the percent improvement in unmet demand relative to the 40- and 50-gal baseline values (listed in Table 3). In both cases, the maximum h_{conv} value corresponds to one listed in Table 1 and used in the above simulations. The blue circle markers correspond to the 6-occupant household, while the red triangle markers correspond to the 4-occupant household. The solid lines show the percent improvement relative to the 50-gal baseline, and the dashed lines show the percent improvement relative to the 40-gal baseline.

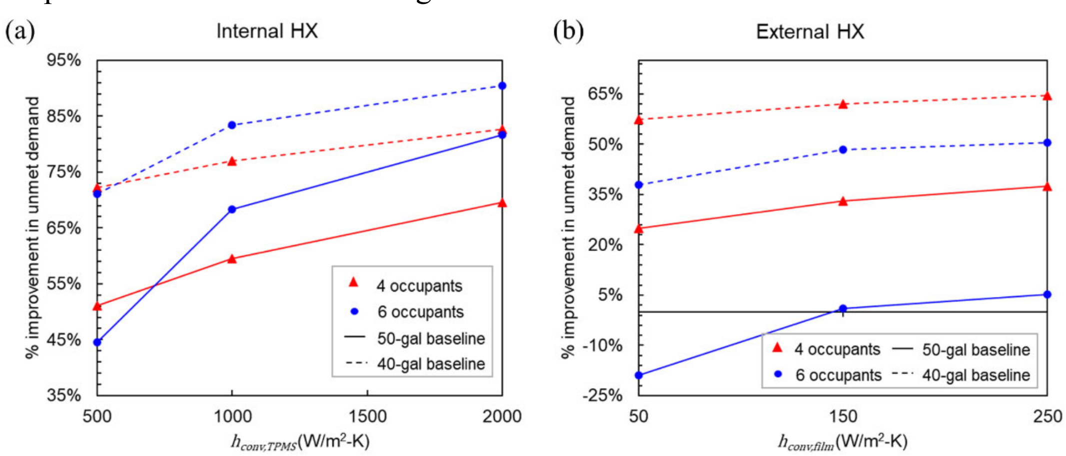

Figure 5: Convection coefficient sensitivity analysis results for the (a) internal HX and (b) external HX

Figure 5a shows that for 4 occupants, the percent improvement in unmet demand increases nearly linearly with $h_{conv,TPMS}$, whereas increases in $h_{conv,TPMS}$ for the 6-occupant household experience diminishing returns in unmet demand abatement. This suggests that for scenarios with a larger number of water draws, there are additional limiting factors such as PCM thermal conductivity that affect how quickly the PCM can discharge into the water. Regardless, Figure 5a shows that even when reducing $h_{conv,TPMS}$ by 75%, adding PCMs still improves unmet demand relative to both baseline cases.

Figure 5b shows similar trends regarding the impact of increasing $h_{conv,film}$ on improvements in unmet demand, though the diminishing returns are less pronounced. Notably, however, an $h_{conv,film}$ of 50 W/m^2-K results in a negative percent improvement for the 6-occupant case relative to the 50-gal baseline, meaning the unmet demand is higher than that of the baseline. All other cases consistently show improvements upon the baseline, but the difference between the maximum and minimum $h_{conv,film}$ investigated are much less impactful than the internal HX, suggesting factors such as PCM thermal conductivity play a larger role.

Conclusion

Heat pump water heaters are a highly efficient solution for domestic water heating, but their larger size and frequent up-sizing make them impractical for space-constrained housing including multifamily and manufactured homes. However, more data revealing the extent of this challenge in such homes is essential. Additionally, creative solutions for managing sizing concerns while maintaining hot water delivery performance is necessary.

To tackle these challenges, this study details the results of surveys conducted across several space-constrained housing communities in Colorado, California, and Minnesota and interviews with two major manufactured housing companies and contractors, highlighting the need for small-volume HPWHs in manufactured housing. Based on simulations conducted in OCHRE, we illuminate how optimized design parameters allow two different PCM integration strategies to effectively increase the FHR of a 40-gal tank to that of a 50-gal tank, thus eliminating the need for up-sizing. While the OCHRE FHR simulations may be improved by adding more robust stratification and mixing effects, the relative improvement observed in FHR due to the addition of PCMs is noteworthy and can function as a valuable early-stage design tool.

Our simulations reveal that the FHR-maximized internal PCM configuration can reduce unmet demand by up to 90.4% (for 6 occupants), while the optimized external configuration does so more modestly (up to 64.5% for 4 occupants). These cases can abate unmet demand better than an up-sized 50-gal tank without significantly increasing energy consumption. The internal case can decrease unmet demand even more than a 40-gal HPWH with an elevated setpoint. A sensitivity analysis on the impact of convection coefficient on unmet demand shows that even when reducing h_{conv} between 75%–80% from current best estimates, adding PCMs still shows decreased unmet demand except in the 6-occupant case for the external HX.

Future work includes analysis of other climate zones, experimental work to validate PCM HX design decisions and actual heat transfer coefficients, and a sensitivity analysis on additional HX parameters such as thermal conductivity and PCM mass. Additionally, we will expand our investigation of combining the novel PCM-integrated HPWH with existing products that may achieve similar goals, such as those with an elevated setpoint and integrated tempering valve.

Acknowledgments

This research was performed under an appointment to the Building Technologies Office (BTO) IBUILD- Graduate Research Fellowship administered by the Oak Ridge Institute for

Science and Education (ORISE) and managed by Oak Ridge National Laboratory (ORNL) for the U.S. Department of Energy (DOE). ORISE is managed by Oak Ridge Associated Universities (ORAU), and ORNL is managed by UT-Battelle LLC. All opinions expressed in this paper are the author's and do not necessarily reflect the policies and views of DOE, CMEI, BTO, ORISE, ORAU, ORNL or UT-Battelle. ORISE is managed by ORAU under DOE contract number DE-SC0014664, and ORNL is managed by UT-Battelle LLC under DOE contract number DE-AC05-00OR22725.

This work was authored in part by the National Laboratory of the Rockies for the U.S. Department of Energy (DOE), operated under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Building Technologies Office under Contract No. DE-EE00010912. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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Disclosures

AI-assisted tools used: ChatGPT, NLR Simple Chat.
Used for: code debugging.
Extent: generating code/figures.
Human review: The authors reviewed and verified all content, calculations, and citations.