Field Study of 120-volt Heat Pump Water Heaters in the Big Easy

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ABSTRACT

To meet long-term goals for reducing carbon emissions and lessen the impacts of climate change, the U.S. plans to decarbonize its building stock, which includes the replacement of fossil fuel-burning end uses with energy efficient electric alternatives. As part of this strategy, the replacement of fossil fuel water heaters with heat pump water heaters (HPWH) has the potential to avoid substantial carbon emissions. An estimated 10-15 million single-family homes with fossil fuel water heaters do not have the electrical panel capacity to install a 240-volt HPWH designed to use a 30-amp circuit. For these homes, a technology recently introduced to the market, the 120-volt plug-in HPWH, can provide energy efficient electrification of water heating without an expensive panel and wiring retrofit.

This paper presents the results of an ongoing 120-volt HPWH field study conducted in 17 homes in New Orleans, LA. Key installation scenarios are profiled for retrofitting from gas-fired water heaters to 120-volt HPWHs, accounting for space, air volume, air temperature, condensate drainage, and electrical. Each HPWH had its surrounding air temperature, relative humidity, inlet and outlet water temperature, flow, and energy consumption monitored. Using these data, hot water delivery and energy efficiency performance were analyzed based on home characteristics. Hot water run outs were investigated to understand how hot water usage, inlet water temperature, and surrounding air temperature impact the HPWH's ability to meet load. From these results, best practices for 120-volt HPWH siting, sizing, and installation were developed.

Introduction

The U.S. is in the process of decarbonizing its economy, which includes integrating renewable sources of electricity generation into the grid, converting fossil fuel-fired end uses to efficient electric alternatives, and replacing inefficient electric end uses with energy efficient alternatives. As part of this strategy, heat pump water heaters (HPWH) are to replace fossil fuel burning water heaters and electric-resistance water heaters.

Currently, approximately 66 million, or 53%, of U.S. homes use fossil fuel (i.e., natural gas, propane, or fuel oil) for water heating, of which 50 million are single-family homes (EIA 2023). A subset of these homes, estimated at 10-15 million, lacks the electrical service and/or panel capacity to replace their fossil fuel water heater with a 240-volt HPWH without a substantial investment in the home's electrical infrastructure (Butzbaugh and Parsons 2023; Lindsey 2023). To address this problem, energy efficiency stakeholders and manufacturers met in 2018 to draw up the Retrofit-ready Heat Pump Water Heater Specification, and manufacturers set out to develop the 120-volt HPWH (120V HPWH), which can plug into the typical 120-volt outlet using a 15-amp circuit (Larson 2019). Currently, three water heater manufacturers have

120V HPWH models in the market, and other manufacturers have announced their intent to release new models (ENERGY STAR 2024).

The siting, sizing, and installation of water heaters is critical to meeting the hot water demand of households. HPWHs have certain dimensions, require a certain amount of air volume or airflow, operate in a certain range of surrounding air temperatures, produce condensate for drainage, and require certain electrical infrastructure. These distinctions are unfamiliar to many water heater installers. For the U.S. to transition its fossil fuel water heater stock to HPWH technology, it's important for industry, workforce, and energy efficiency programs to understand how to accommodate HPWHs in homes.

To understand the performance of 120V HPWH technology, the Advanced Water Heating Initiative (AWHI) launched a field study exclusively in California. The results of this research indicated that 120V HPWHs are an important water heating technology for decarbonizing the retrofit residential and small commercial market sectors. When sized appropriately, 120V HPWHs can electrify water heating adequately for an estimated 22-30% of the California housing stock (Khanolkar, Egolf, and Gabriel 2023).

The U.S. Department of Energy is complementing AWHI's research by investigating 120V HPWH performance in New Orleans, LA. This study aims to understand the installation and performance implications of replacing a gas-fired water heater with a 120V HPWH in a hot/warm climate.

Study Set-up

New Orleans has many attributes that are well-suited for the study's location. It is within IECC climate zone 2, which is within the recommended region for the first 120V HPWH model brought to market. New Orleans also separates the electric water heating-dominant Southeast from the gas water heating-dominant Southwest. More than half of the single-family homes in the state of Louisiana have gas-fired water heaters whereas in the neighboring state Mississippi and every other Southeastern state, more than half of single-family homes have electric water heaters (EIA 2023).

Of particular importance for understanding retrofits, New Orleans residential housing stock offers a wide variety of water heater locations within homes. Approximately 22% of homes in New Orleans were constructed before the widescale adoption of indoor plumbing (Census 2022; Census 1990). In addition, New Orleans is largely below sea level and surrounded by levees, making it vulnerable to flooding (Pistrika and Jonkman 2010). This has led to unconventional water heater locations in homes, including outdoor dedicated enclosures (typically metal boxes), detached sheds, outdoor closets, and attics. In addition, many homes in New Orleans are designed to reduce flood damage so water heaters are often installed in locations above base flood elevation within the home and exterior structures. These attributes can offer meaningful lessons learned and considerations for 120V HPWH installation and performance.

The study has two manufacturer partners, designated as Manufacturer A and Manufacturer B, which capture the highest and second highest share of the U.S. water heater market. Manufacturer A was first to release a product line of drop-in 120V HPWHs into the market in July 2022. It offers two 120V HPWH designs, one for a dedicated 15-amp circuit and one for a shared 15-amp circuit. This study is researching both types. The shared circuit model uses a 365-watt compressor, comes equipped with an integrated thermostatic mixing valve, and is available in 50-, 65-, and 80-gallon nominal capacities (measured volumes of 46, 59, and 72 gallons, respectively) (ENERGY STAR 2024).

Manufacturer A's dedicated-circuit design uses a 1,200-watt compressor, does not have a thermostatic mixing valve, and is available in 40- and 50-gallon nominal capacities (measured volumes of 37 and 46, respectively) (Larson and Larson 2022). Manufacturer A does not include back-up electric resistance in its 120V HPWH product line. This is an important consideration for siting since the compressor has an operating inlet-air-temperature range of 37-145 °F. Manufacturer A recommends that its 120V HPWHs are only installed in U.S. climate zones 1-3.

Manufacturer B is the other manufacturer partner with a drop-in 120V HPWH product line, released to the market in July 2023. This manufacturer promotes its 120V HPWH design as suitable for a shared 15-amp circuit for homes in all U.S. climate zones. This model has a compressor input of approximately 375 watts and operating inlet-air-temperature of 40-120 °F. Manufacturer B's 120V HPWH is equipped with 900 watts (W) of back-up electric-resistance heating, which only activates if the air temperature falls outside of the compressor operating range or if the heat pump itself fails. Manufacturer B offers 66- and 80-gallon models (measured volumes of 68 and 82 gallons, respectively) for its 120V HPWH product line.

The pursuit of an installer partner ran parallel to participant recruitment beginning in the spring of 2022. A one-page summary/factsheet for the study was prepared to help explain the study to potential installers. An initial list of potential partners was generated from the ENERGY STAR installer list for Louisiana (ENERGY STAR 2022). Securing an installer partner was an underestimated challenge, requiring a considerable amount of outreach. Many installers had never heard of a HPWH, and of those who had, most hadn't seen one in person. Installers were reluctant to commit to installing an unfamiliar technology. Nearly all had never installed a HPWH with exception of one, which was primarily an HVAC installer. This company initially committed to become the installer partner for the study for about a month, and then withdrew during the planning process due to high HVAC business volume.

After the initial installer partner withdrew, all potential installer partners were exhausted from the ENERGY STAR list. To find new prospects, a list of licensed plumbers in the New Orleans area was acquired, which led to finding a partner. The study's installer partner had never installed a HPWH prior to working on the study but was eager to learn. Prior to scheduling participant installations, the research team held meetings with the installer partner and each manufacturer individually to discuss 120V HPWH installation considerations and review site selection. In addition, Manufacturer A provided an installation expert on its staff to accompany the installer for the first two installations, which the installer found helpful.

Recruitment

As this study involves homeowner participants and includes the collection of personally identifiable information (PII), the team was required to submit all relevant material to the Pacific Northwest National Laboratory's (PNNL) Institutional Review Board (IRB). In accordance with Federal law, DOE policy, and PNNL policy, the IRB evaluates and authorizes research involving humans. An IRB application, which includes all material relevant to human subjects, was submitted for this project and received initial approval of materials in March 2022. Outreach materials were developed by the team to aid in study recruitment and protect participants, including a recruitment postcard, one-page summary of the study for participants, pre-installation questionnaire, and informed consent.

Following IRB approval, recruitment began with postcard mailings to properties identified in Attom's Property Navigator (formerly GeoData), a property data service. Properties were filtered by zip code, building type (single-family), and occupancy status (owner-occupied). Once the property data was exported, it was cleaned of all corporate, business, trust, and municipality owned properties and reformatted for mass outreach mailing. A map of the targeted properties in New Orleans, LA is shown in Figure .

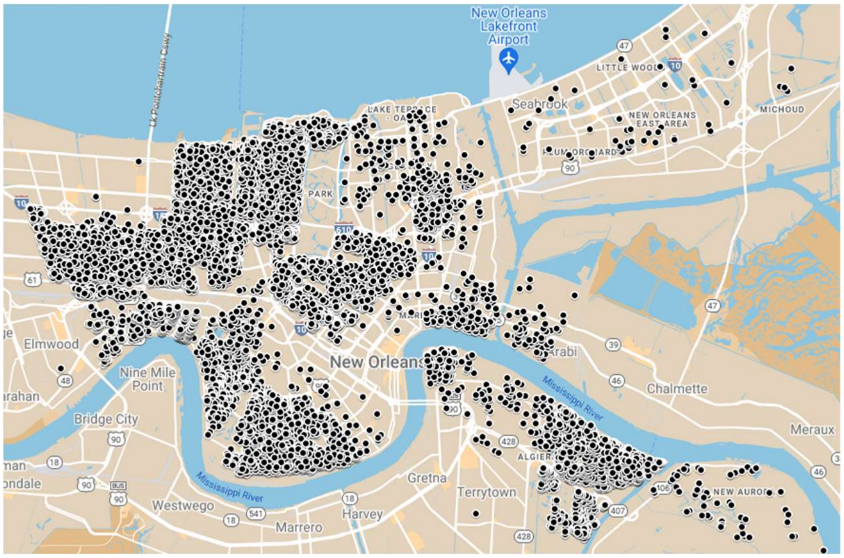


Figure 1. A map of mailer outreach in New Orleans, LA for this study.

Outreach postcards promoted the opportunity to receive a free 120V HPWH installation. They were mailed in ten batches to approximately 19,700 homes across 20 zip codes, generating 192 initial responses. Of those responses, 102 simply dropped communication despite continued outreach efforts. Of the 90 who engaged with PNNL, 55 either did not meet the eligibility requirements for the study (e.g., possessed electric-resistance water heater, not owner-occupied, not a single-family home) or were disqualified due to installation circumstances (discussed further in the Installation Scenarios section). In addition to outreach mailers, potential participants were also encouraged to share the opportunity with friends, family, and neighbors, which captured a handful of potential participants. Table 1 provides further information on the recruitment outreach mailings.

Table 1. Summary of Recruitment Outreach

Date	Quantity	Contacted	Eligible	Ineligible	No Response
5/3/2022	1,080	8	1	2	5
6/1/2022	1,575	22	4	8	10
7/14/2022	1,251	14	4	4	6
9/7/2022	1,639	19	5	5	9

Date	Quantity	Contacted	Eligible	Ineligible	No Response
10/6/2022	2,441	25	7	6	12
2/14/2023	1,248	17	4	5	8
5/4/2023	2,998	10	3	7	0
6/8/2023	3,430	31	3	4	24
8/29/2023	925	11	3	4	4

Once potential participants were identified through various outreach efforts, pre-installation questionnaires and site photos were collected from each potential participant to determine preliminary eligibility. When the information provided by the potential participant was too ambiguous to determine qualification, a site visit was conducted. Following preliminary site selection, the team met with the manufacturers and installer partner to discuss the eligible sites and make a final decision on 120V HPWH design, tank size, and installation circumstances. Of the 34 respondents that were initially deemed eligible to participate, the team selected 19 participants that met the qualification criteria and represented a range of installation scenarios.

Monitoring Equipment

Each of the participating homes had a data monitoring system installed at the same time as the 120V HPWH. To align with the AWHI California study, the same monitoring equipment and sensor package was chosen with the goal of collecting data that can be compiled and compared consistently. Monitoring platforms were chosen by kW Engineering, AWHI's California study partner, taking into consideration the budget, availability of platform-compatible plug-load meters, and California's rules and regulations surrounding custom/fabricated equipment. To work within these constraints and monitor all sensors at the appropriate sampling rates, two data acquisition platforms were chosen: Obvius and InfiSense.

Obvius is a bespoke hardwired setup that includes a cellular router and data logger contained in an outdoor-rated enclosure. This platform was initially used to monitor water flow and temperature. It was chosen because of the cloud-upload capabilities, local backup storage, and support of a sampling rate of five seconds, which is required to monitor short hot water draws. InfiSense was initially used to wirelessly monitor plug-load, ambient air temperature, and relative humidity. The sensors were chosen because of the ability to use a wireless, off-the-shelf plug-load meter. In November 2022, InfiSense announced their dissolution and the impending shutdown of the API used for data acquisition. kW Engineering worked with Senet, a LoRaWAN network provider, to replace the InfiSense API prior to a loss of data access.

Installation Scenarios

Water heater siting, sizing, and installation affect the ability to meet household hot water demand. For the U.S. to transition its water heater stock to HPWH technology, the water heater installer workforce, supply chain, and energy efficiency programs benefit from understanding how to accommodate HPWHs in homes.

For this study, nearly all participants had the typical gas storage water heater, which has 40,000 Btu/hour of input capacity firing at an 80% thermal efficiency coupled with 40 gallons of storage. This water heater provides 32,000 Btu/hour of useful thermal input. The dimensions are typically 60 inches tall by 20 inches in diameter with additional clearance needed for the flue to vent combustion gases. Some of the gas storage water heaters in this study were installed on small metal or cement platforms.

To augment recovery, typical 240V HPWHs are equipped with two 4.5 kW back-up electric-resistance heating elements and larger tank sizes (typically 50 gallons and larger). In contrast, 120V HPWHs are not equipped with electric-resistance back-up for the purpose of supplementing heat pump heating. This is due to the limitations of a 15-amp circuit, which would trip in the event of both heat pump and electric resistance operating simultaneously.

For sizing, installers often use a rule-of-thumb of increasing the tank size at least one level when replacing a gas storage water heater with a 240V HPWH (A. Gianni, personal communication, December 8 and 12, 2023). For instance, an installer replacing a 40-gallon gas storage water heater with a 240V HPWH may choose to install a 50-gallon 240V HPWH. For 120V HPWHs, California installers are finding that tank size should be increased two levels, meaning a 40-gallon gas storage water heater should be replaced by a 65-gallon 120V HPWH (B. Foster, personal communication, June 6, 2023 and September 20, 2023). For this study, PNNL developed its own sizing methodology that accounts for the number of bedrooms, number of bathrooms, water heater location, and climate zone. This methodology adapts the Uniform Plumbing Code's recommended first-hour rating for home size (i.e., number of bedrooms and bathrooms) by accounting for the 120V HPWH's expected COP and one-hour delivery capability during peak load conditions, given the expected surrounding air temperature and inlet water temperature.

An initial step of replacing a water heater within a home or on the property is approximating the physical dimensions of the water heater location and the route to reach this location. The typical 120V HPWH is 72 inches tall and 26 inches in diameter and may require additional clearance for accessing the air filter and/or side-mounted inlet/outlet water connections (depending on the manufacturer). In this study, narrow doorways and hallways were sometimes difficult to navigate. Through the participant recruitment process, the following water heater locations were identified as unique challenges for this study and thus considered a lower priority: crawl spaces, unfinished basements with narrow or spiral staircases, cramped indoor closets, and attics with narrow or pulldown staircases.

HPWHs have air volume requirements because HPWHs transfer heat from the surrounding air to water in the storage tank. This process requires a certain amount of airflow at a temperature within the compressor's operating range for the HPWH to extract heat. The cool air exhaust of a HPWH can quickly cool a confined space, reducing COP and eventually causing compressor shutdown. According to Northwest Energy Efficiency Alliance research, water heater locations with less than 450 cubic feet of surrounding air volume call for retrofit alterations to accommodate the HPWH's airflow requirements (Larson and Larson 2022).

The replacement of gas tankless water heaters with 120V HPWHs is a unique retrofit scenario. In warm climates, gas tankless water heaters are often installed outside of the home's envelope on an exterior wall (EIA 2023). This study includes one participant where the existing gas tankless water heater was installed along an exterior wall with only 2-3 feet of separation from the wall of the neighboring home. In this case, replacing the existing gas tankless water heater with the 120V HPWH required careful planning to size and site the 120V HPWH installation.

Water heater locations in unconditioned spaces also run into the issue of air temperatures falling below the compressor's operating range. To date, New Orleans has had two three-day stretches of sub-40 °F air temperatures from December 2022 through January 2024 (i.e., 14-month period). Similar to confined spaces, these water heater locations may call for retrofit interventions to accommodate the 120V HPWH's need for 40 °F or greater air temperatures, if possible. For this study, outdoor water heater enclosures, detached sheds, and detached garages were the locations that had the highest risk of facing sub-40 °F air temperatures.

As a product of the heat transfer process, HPWHs generate condensate, or pH-neutral water, which must be drained. Condensate drainage can become a challenge for water heater locations without a nearby drain line or floor drain. Water heaters located in indoor closets near living spaces may not have immediate access to a drain. In addition, outdoor enclosures, detached sheds, detached garages, and attics have the potential to hinder draining condensate in subfreezing outdoor air temperatures.

Even for shared-circuit 120V HPWHs, a home's electrical infrastructure can pose issues. This study encountered candidate homes with unsafe wiring (e.g., cloth wiring and knob-and-tube wiring in poor condition), circuits at amperage capacity, and water heater locations that lacked electrical outlets. In these instances, accommodating a 120V HPWH would call for electrical upgrades and/or water heater relocation. The fundamental reason for the development of the 120V HPWH design was to avoid electrical upgrades, so an objective of the study was to use the home's existing electrical infrastructure even if it meant water heater relocation. When electrical upgrades were required for an existing water heater location, study candidates were given the option of relocating the water heater. In these instances, space constraints and potential concerns with noise or vibration deterred study candidates from agreeing to relocation.

Installation Best Practices and Retrofits

Multiple retrofits were implemented to resolve specific installation challenges encountered in this study. One of the objectives of the research was to avoid electrical infrastructure upgrades, including adding or replacing circuits in the panel, running new conduit and wiring, and installing new outlets and receptacles. For this study, none of the 120V HPWH installations required changes to the electrical infrastructure.

When necessary, adjustments were made to the water heater location to accommodate the 120V HPWH. For two installations in utility/laundry rooms, both the clothes washer and dryer were moved to provide the needed space (one was moved within the utility room, and another was relocated to an adjacent closet). Shelving and pedestals were removed for multiple sites. Every existing outdoor enclosure was too small to fit a 120V HPWH and therefore was replaced with a new enclosure that required special order through the wholesaler. These orders needed 2-4 weeks between placement and enclosure delivery.

When relocation was necessary, PNNL met with the study candidate to identify the new site for the water heater. The key considerations in this process were identifying a location with: (1) a reasonable route to and enough space to site a 120V HPWH, (2) sufficient air temperature at the water heater location, (3) nearby electrical outlet on a 15-amp circuit with 7.5 amps of available current, and (4) nearby drain line for condensate. Given that candidate homes had walls that could undergo a wall penetration for ducting, air volume and airflow were a secondary consideration. As mentioned previously, a gas tankless water heater located on an exterior wall required relocation of the water heater due to space. In this case, an indoor closet near a clothes washer was the chosen relocation site. A key consideration for relocating the water heater is the added cost due to labor time and materials.

When a location's air volume or potential surrounding air temperature was considered inadequate for 120V HPWH operation, airflow interventions were implemented. Nine of the 17 installations had either exhaust, intake, or dual ducting (i.e., both exhaust and intake) installed. When one-directional exhaust or intake ducting were installed, the location was reviewed to determine whether enough intake airflow was available. When airflow appeared restricted, a grill or louvered door were installed to improve flow. The three outdoor enclosures had exhaust ducts, vent hoods, and insulated flex duct installed, and came equipped with louvers on the door. This prevented the cool exhaust air from pooling within the enclosure and decreasing enclosure air temperatures below the outdoor air temperature. A utility/laundry room installation only required the replacement of the solid door with a louvered door since it had approximately 500 cubic feet of space.

For one participant, a dual-ducting configuration was installed. In this case, the 120V HPWH was installed in February 2023 in an unconditioned, attached shed that shared a wall with the home's kitchen. The initial installation did not involve ducting. During the three-day stretch of sub-40 °F temperatures in January 2024, the participant reported running out of hot water. To remedy the lack of hot water, two wall penetrations were inserted and both the intake and exhaust were ducted from the attached shed to the kitchen. To date, this has allowed the 120V HPWH to operate continuously, relieving the lack of hot water without causing discomfort to occupants in the kitchen.

Even though all 120V HPWHs located in outdoor enclosures were ducted, sub-40 °F outdoor air temperatures caused compressor cutoff on occasion. During the study, New Orleans has had two, three-day periods with such air temperatures. One participant ran out of hot water and notified the research team. To remedy the lack of hot water, a 250-watt dimmable heat lamp was added to the enclosure near the 120V HPWH's intake grill and turned on during the three-day stretch of sub-40 °F air temperatures. The heat lamp kept the air temperature at 60 °F near the top of the enclosure, allowing the 120V HPWH to operate. In December 2022, the 120V HPWH provided enough hot water to meet the home's load with help from the heat lamp. However, in January 2024, this was not the case, and the 120V HPWH was unable to meet load. The participant requested the replacement of the 120V HPWH with a gas storage water heater and exited the study. In climates with sub-40 °F air temperatures, it's best practice to relocate 120V HPWHs without electric-resistance back-up into the conditioned space rather than using a heat source (e.g., dimmable heat lamp) to facilitate operation.

Identifying a solution for condensate drainage was a relatively minor challenge. Of the 17 installations to date, nine had condensate drainage tied into the clothes washer drain line. Two of those nine required wall penetrations for the condensate drain line to reach the clothes washer drain line. Four installations in unconditioned spaces had condensate drainage tied into downspouts. In these instances, the drain lines had ample slope to prevent residual condensate from remaining in the drain lines and potentially freezing. The remaining four had condensate drainage directed to either a floor drain, utility sink, or HVAC drain line. For this study, none of the installations required condensate pumps since they didn't call for elevated drain lines or reaching elevated drainage sites.

Even though electrical infrastructure was not upgraded, electrical assessments were necessary to ensure the 120V HPWH would have enough available amperage on the circuit to fulfill power demand without tripping the breaker. This meant using a circuit finder tool to identify the other electrical receptacles and end uses sharing the same circuit, ensuring no large loads would share the same circuit as the 120V HPWH. For utility/laundry room installations, 120V HPWHs often shared circuits with the clothes washer. In this study, clothes washers were 120 volts and used a dedicated 15- or 20-amp circuit. Clothes washers less than 10-years old should have a peak operating current less than 10 amps, which means the 120V HPWH can typically share the same circuit as the clothes washer without tripping the circuit breaker.

While installer rules-of-thumb for HPWH sizing are helpful, this study indicates that additional information can help with 120V HPWH sizing. If the home has an indoor jacuzzi or soaker tub, children who take consecutive baths, or had regular hot water run outs during the winter or throughout the year, then a larger (i.e., 80-gallon 120V HPWH) may be the appropriate option to replace the gas water heater to reduce the risk of running out of hot water. For this study, two homes had their gas storage water heaters replaced with 80-gallon 120V HPWHs based on these additional home characteristics.

The conversion of a home's water heater from gas to a 120V HPWH adds two additional steps. The installer needs to valve off the gas line, remove any fittings, and seal and cap it. The installer also must remove the exhaust vent and seal the vent chimney. In combination with other installation tasks, every installation has taken four to eight hours for the homes in this study.

Analysis

Each of the 17 installed 120V HPWHs had sensors installed to monitor electric current, electric voltage, ambient air temperature, ambient air relative humidity, cold water inlet temperature, hot water outlet temperature, and water usage. These measurements are logged on set intervals ranging from 5- to 60-seconds. Using this data, research was conducted on hot water consumption, energy use, and hot water delivery.

Analysis Methodology

Energy usage calculation. For this study, energy usage was logged by plug load monitors in the form of separate alternating current (AC) and AC voltage at each timestep. AC power was computed at each recorded timestep utilizing the following equation:

$$P = I * V * F_P \qquad (1)$$

Where P is AC power in watts, I is AC current in amps, V is AC voltage in volts, and F_P is the power factor. For this study, the power calculation assumes a power factor of 1, which was selected in the absence of more granular electric measurements (e.g., oscilloscope) which was impractical for this study, and may mean calculated energy consumption is slightly higher.

Utilizing the computed time series power data, power was integrated to calculate the energy usage between each time step in the data series. Power was computed via the midpoint rule, which was implemented as the following:

$$\mathrm{E}_n = (t_{n+1} - t_n)\frac{P_{n+1} + P_n}{2} \qquad (2)$$

Where E is the calculated energy in joules, P is the previously computed power in watts, t is the timestamp, and n is the index of a value in the recorded time series data. Energy was computed between each data point in the recorded data, and then summed to variable energy use intervals of interest (i.e., hourly, daily, monthly, and annual energy usage).

Water consumption calculation. Water usage was measured via a positive displacement flow meter, which measures cumulative water usage from the time of its installation onwards. Data was output from the flow meter and was automatically processed to compute usage between measurement points. This was done with the following equation:

$$\mathrm{V}_n = V_{lifetime,n} - V_{lifetime,n-1} \qquad (3)$$

Where V is the volume of water consumption in gallons, n is a specific index of a timestep in the data series, and the $lifetime$ subscript corresponds with the cumulative measured volume of water flowing through the flow meter over its installed lifetime. Since water consumption was computed between timesteps in the data series, water consumption was also summed over variable time intervals of interest for analysis.

Hot water run out identification. For homeowners, running out of hot water is frustrating and can lead to animosity toward a water heating technology. A hot water run out occurs when most of a water heater's storage volume is consumed, and the temperature of water exiting the water heater (referred to as outlet temperature) and delivered at fixtures falls below expectations. These events are potentially problematic for 120V HPWHs, since this technology has lower heat input rate compared to gas storage water heaters, and thus requires additional time to heat water to setpoint.

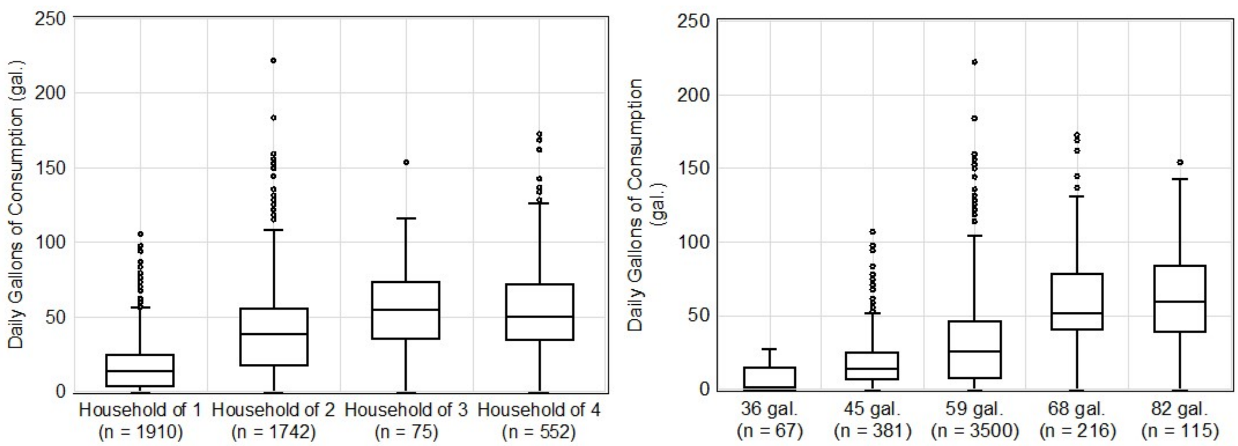
When reviewing charted time series data, it can be difficult to identify when a water heater begins to run out of hot water, short of full depletion of the hot water tank. Since hot water runouts are of particular concern for 120V HPWHs, an algorithmic methodology for determining hot water runout events was developed as a part of this study. This methodology balances proper identification of runouts with the possibility of identifying false positive runout events.

The first step in identifying hot water runouts was to isolate hot water draws. For the purposes of this analysis, hot water draw events were characterized as a flow event for which hot water is drawn from the tank, preceded and succeeded by no water drawn for a minimum of 60 seconds (i.e., downtime). After applying this method to the hot water flow data, individual hot water events were identified and analyzed to determine if they led to a hot water runout event.

The criteria for identification of a hot water runout event were developed to identify runouts under the constraints of thermistor lag, flow-induced mixing in the pipe, and indirect measurement of outlet water temperatures (as hot water temperatures were measured via a thermistor in the piping approximately one foot from the water heater's outlet). Each of the comparisons in the algorithm is designed to address these issues and verify that measured hot water temperatures are dropping well after the flow event is established, rather than incorrectly identifying runouts when water is stationary at ambient temperatures in the piping before the flow event begins.

Hot Water Use Analysis

Utilizing the water consumption calculated in Eq. 3, daily gallons of hot water consumption (GPD) were calculated for each participant or site. This data is visualized on a household occupancy and water heater size basis in Figure 2.



(a) Consumption on per-household occupancy basis

(b) Consumption on an installed tank size basis

Figure 1. Box and whisker plots displaying daily hot water consumption (gallons) on a household occupancy basis (a) and daily hot water consumption (gallons) compared to installed 120V HPWH tank sizes (b).

From Figure 1a, measured GPD values are shown on a household occupancy basis. Median GPD increases with occupancy with exception of the four-person home, which had similar hot water usage as the three-person home. This could be due to the low sample size of the bin for the lone three-person home in the study. Comparing average GPD by home occupancy can offer context for energy use: one-person households had an average GPD of 16, two-person households had an average GPD of 39, three-person households had an average GPD of 56, and four-person households had an average GPD of 54. For comparison, the DOE residential water heater test procedure uses GPD bins of 38 for low usage, 55 for medium usage, and 84 for high usage (DOE 2023, Tables III.2-4). The maximum plot values, represented by the upper whiskers, may provide insight for sizing considerations. They represented the 97^{th} percentile for one- and four-person homes (56 and 127 GPD, respectively), and 99^{th} percentile for two- and three-person homes (109 and 116 GPD, respectively). Maximum outlier GPD values were 100 gallons or greater for all household bins.

From Figure 1b, GPD values are shown across the measured tank volumes of 120V HPWH models included in the study: 36-, 45-, 59-, 68-, and 82-gallons. The average GPD increased with measured volume size, from 7 GPD for the 36-gallon 120V HPWH up to a GPD of 62 for the 82-gallon model. The maximum plot values represented the 100th percentile for the 36-gallon 120V HPWH, 90th percentile for the 45-gallon 120V HPWH, 99th percentile for the 59-gallon 120V HPWH, 95th percentile for the 68-gallon 120V HPWH, and 98th percentile for the 82-gallon 120V HPWH. Given the sample sizes by measured tank volume bin, the 59-gallon 120V HPWH is well represented whereas other bins may benefit from increased sample size while the study continues.

Energy Use Analysis

Utilizing the computed energy usage of each site, energy usage values were aggregated to analyze annual consumption of sites which were in service for at least one full calendar year. These results are displayed in Table 2.

Table 2. Summary of annual energy use for each of the sites that have been in service for at least one year.

Site ID	Household occupancy	Average hot water GPD (gal.)	Annual energy usage (kWh)	# of days in year 1 with valid energy data (Days)	Number of days with <1 gal. of usage (Days)
Site 01	1	17.3	317	361	37
Site 02	1	13.4	326	361	80
Site 03	2	48.1	941	357	6
Site 04	1	11.1	252	361	153
Site 05	4	45.6	624	364	32
Site 06	2	44.0	865	364	43
Site 07	2	25.2	448	310	69
Site 08	1	20.2	321	358	17
Site 10	2	30.8	434	352	18

Participant annual energy use ranged from 252 kWh to 941 kWh for 120V HPWH installations. A Pearson correlation coefficient was calculated to determine the correlation between occupancy and daily hot water consumption (R=0.87, p=2.4e-06), occupancy and daily energy consumption (R=0.8, p=5.7e-05), and daily hot water consumption and daily energy consumption (R=0.83, p=1.6e-05). These tests all returned correlation coefficients at or above 0.8, accompanied by strong p-values, indicating a strong positive correlation. The average occupancy per participant home was 1.8 people, and average energy use was 503 kWh per year.

The annual energy use calculations were initially computed to represent a full calendar year following the date of each site's HPWH install. However, due to the complexities of conducting data acquisition in occupied field sites, some data was lost or unmeasured due to sensor, communications, and/or power outages. This resulted in seven of the nine sites losing approximately 1% of annual data, and two sites losing approximately 4% and 5% of annual data, respectively. In most sites, these outages were randomly distributed throughout the year. However, an undiagnosed power sensor failure at Site 07 resulted in approximately 14 days of missing data during May 2023.

In addition to data loss, participants had many days with little to no hot water usage on a per-site basis. For the sake of this analysis, this was characterized as days with less than one gallon of hot water usage. Site 04 had the lowest annual energy usage with just 252 kWh/year, which resulted from low HPWH operation for nearly 40% of the year due to days with low or no hot water usage. These days of low hot water utilization are likely the result of vacations, or days when participants occupied their homes and chose to not use hot water. For example, based on participant feedback and reviewing when low usage days occurred, many participants ceased to use hot water from late July to late August 2024 during a drought and heat wave in the New Orleans, LA area.

Hot Water Delivery Analysis

The ability of 120V HPWHs to deliver hot water to occupants is critical to market adoption. After removing incomplete or invalid data, the hot water delivery analysis contained an aggregate 4,216 days of hot water use data among 16 participants. For these days, there were 116 instances in which the hot water outlet temperature decreased down to 100 °F. Of these instances, 71 reached an outlet temperature of 95 °F or lower.

More than half of the study's participants rarely, if ever, lacked hot water. Three participants, representing an aggregate 1,039 days of hot water use, never had their hot water outlet temperature run down to 100 °F or lower. Six participants, representing an aggregate 1,338 days of hot water use, had only one or two instances in which their hot water outlet temperature ran down to 100 °F or lower (eight instances total).

The remaining seven participants represented 108 of the 116 instances of hot water outlet temperatures reaching 100 °F, and 67 of the 71 instances in which outlet temperatures reached 95 °F or lower. These participants accounted for 1,839 days of hot water use in the sample. Of these seven participants, five had their 120V HPWH located in unconditioned spaces (i.e., outdoor enclosure, attached shed, or detached garage). These participants had six instances in which the hot water outlet temperature reached 100 °F or lower when the surrounding air temperature fell below the compressor cutoff temperature. At the beginning of the study, they reported never running out of hot water with their previous gas storage water heaters.

Two of the seven participants had their 120V HPWHs installed in conditioned spaces (i.e., indoor closet and utility/laundry room). The participant with four occupants previously had a gas tankless water heater and reported never running out of hot water before. This two-bedroom, two-bathroom home (originally with three occupants when joining the study) was sized for a 65-gallon 120V HPWH (measured volume of 59 gallons). The other participant had three occupants in the home and previously had a 38-gallon, 40,000 Btu/h gas storage water heater, which reportedly ran out of hot water 12 or more times per year. This three-bedroom, two-bathroom home was sized for an 80-gallon 120V HPWH (measured volume of 82).

Whether the 120V HPWH was in unconditioned or conditioned space, high hot water usage within a two-hour window was the primary reason for running out of hot water. Table 3 provides the average hot water usage that occurred during the runout event, over the hour prior to the beginning of the runout event, and over the second hour prior to the beginning of the runout event for each of the measured volumes (gallons) of 120V HPWH models in the study with exception to the 36-gallon, dedicated-circuit 120V HPWH, which did not have a hot water run out (installed in a one-person household).

Table 3. Average hot water usage leading to a 95 °F hot water runout by measured volume of 120V HPWH.

Measured Tank volume (Gal)	Average usage during runout event (Gal)	Average use during hour prior to event (Gal)	Average use during second hour prior to event (Gal)	Average total (Gal)
45 (*n* = 13, 3.4%)	25	27	15	66
59 (*n* = 41, 1.2%)	30	32	10	72
68 (*n* = 9, 4.2%)	35	26	20	80
82 (*n* = 3, 2.6%)	27	22	17	66

All values were rounded to the nearest gallon. The number of run outs by measured tank volume are represented by *n*, followed by the bin percentage. Table omits four hot water runout outliers for which occupants ran hot water continuously to prevent pipes from freezing.

Across the four different measured volumes, the hot water consumption during the runout event and two hours prior totaled 66-80 gallons. Analyzing hot water runouts by occupancy produced similar results. Table 4 provides the average hot water usage that occurred during the runout event, one hour prior to the beginning of the runout event, and second hour prior to the beginning of the runout event based on participant occupancy.

Table 44. Average hot water usage leading to a 95 °F hot water runout by home occupancy.

Occupancy	Average usage during runout event (Gal)	Average use during hour prior to event (Gal)	Average use during second hour prior to event (Gal)	Average total (Gal)
1 (*n* = 14, 0.7%)	26	28	14	68
2 (*n* = 33, 1.9%)	32	33	8	73
3 (*n* = 3, 4%)	27	22	17	66
4 (*n* = 16, 2.9%)	29	25	20	74

All values were rounded to the nearest gallon. The number of run outs by occupancy are represented by *n*, followed by the bin percentage. Table omits four hot water runout outliers for which occupants ran hot water continuously to prevent pipes from freezing.

Hot water consumption during the runout event and two hours prior totaled 66-74 gallons across the four occupancy bins. When hot water run outs occurred, participants often would wait a half hour to check for hot water, only to find that they were still lacking. In some instances, participants made multiple attempts, which were recorded as one hot water runout.

Conclusions

The 120V HPWH was developed with the objective of electrifying fossil fuel-fired water heating in absence of upgrading the home's electrical panel. This study completed 17 installations of 120V HPWHs without upgrading the home's electrical infrastructure. However, in many cases, electrical assessments were necessary to ensure the 120V HPWH had enough available amperage on the circuit to fulfill power demand without tripping the breaker. This meant identifying the other electrical receptacles and end uses sharing the same circuit. In addition, participant recruitment indicated that some homes may require water heater relocation to avoid electrical upgrades.

In this study, certain water heater locations were avoided since they required additional retrofit measures, including crawl spaces, unfinished basements with narrow or spiral staircases, attics with narrow or pulldown staircases, cramped closet installations, and exterior spaces near property lines. Airflow interventions were implemented in nine installations where air volume or surrounding air temperature was considered insufficient. Even in IECC climate zone 2, unconditioned water heater locations such as outdoor water heater enclosures, detached sheds, and detached garages run the risk of compressor lockout due to sub-40 °F air temperatures. In these instances, it's best practice to relocate 120V HPWHs into the conditioned space rather than use a heat source (e.g., dimmable heat lamp) to facilitate operation during cold temperature periods. Resolving condensate drainage was a relatively minor challenge in this study, requiring wall penetrations in just two installations. The replacement of gas water heaters with 120V HPWHs required four or more hours for every installation.

Given the average occupancy of 1.8 people per participant home in combination with the number of participant days with low hot water usage, annual average energy consumption of 503 kWh met expectations for New Orleans, LA. However, participant homes had days of high hot water usage of 100 gallons or greater, which is an important consideration for sizing. Nine participants rarely, if ever, ran out of hot water. Seven participants ran out of hot water at a per-day rate of 6% over 1,839 participant days. High hot water usage, rather than air or inlet water temperature conditions, was the primary factor. Six of these participants reported never running out of hot water with their previous gas storage water heaters. This indicates that 120V HPWHs may struggle to meet load for households acclimated to consuming large amounts of hot water in short timeframes by virtue of the high input rates of gas water heating technology. The ability of 120V HPWHs to deliver hot water to occupants is important for customer satisfaction, and thus market adoption. Continued research and development into streamlining installation and improving the hot water delivery of 120V HPWHs is warranted.

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