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Prepared for the U.S. Department of Energy
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Abstract

Heat pump water heaters (HPWH) provide a resource for increasing water heating efficiency in U.S. residences. Electric HPWHs have traditionally utilized R-134a as the refrigerant in the vapor-compression cycle; however, this refrigerant is undesirable long-term due to its high global warming potential. For HPWHs, low global warming potential refrigerants such as R-1234yf may offer comparable performance, but the evaluation of these systems has been limited to laboratory settings. This study provides field evaluations of off-the-shelf HPWHs that had their factory R-134a refrigerant replaced with an optimized charge of R-1234yf. The field evaluation consisted of R-1234yf HPWHs at two occupied field sites and two unoccupied, simulated lab homes. At the two residential field sites with occupants, the R-1234yf HPWHs operated issue-free for the 18-month field trial, and the home occupants perceived no change in HPWH performance relative to their prior R-134a HPWHs. At the lab homes, under simulated hot water draws, the average daily operating efficiency of the R-1234yf HPWH was within 2% of the baseline R-134a HPWHs.

Acknowledgments

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Acronyms and Abbreviations

COP	coefficient of performance
GWP	global warming potential
HPWH	heat pump water heaters
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
RH	Relative Humidity
UEF	uniform energy factor

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1.0 Introduction

Water heating consumes 173 billion kWh per year of site electricity in residential homes in the U.S. [1] Electric water heaters typically rely on resistance heating elements that directly convert electric energy to heat with a 1:1 ratio. To improve efficiency, heat pump technology has been integrated into water heaters to achieve over three times the efficiency of electric resistance water heaters. Heat pump water heaters (HPWHs) commonly use R-134a as the refrigerant in a vapor-compression cycle. While R-134a has zero ozone-depletion potential, it has a significant global warming potential (GWP), 1300 times that of CO2 [2]. It is therefore important to explore alternative low GWP refrigerants for the replacement of R-134a in HPWH applications. One candidate refrigerant for the replacement of R-134a is R-1234yf. R-1234yf possesses similar thermodynamic properties to R-134a and is being used in air conditioning systems in many new automobiles. R-1234yf has zero ozone-depletion potential and a 100-year GWP of less than one [2], making it an attractive option from an environmental perspective. Unlike R-134a, R-1234yf is classified as a mildly flammable refrigerant [3].

The use of R-1234yf as a replacement refrigerant for R-134a has been modeled in several studies. Several configurations of heat pump systems were simulated with both R-134a and R-1234yf working fluids and performance between the two fell within a ±2% range, with the R-1234yf performance typically being slightly lower than the R-134a performance [4]. An additional study specifically modeled the performance of R-1234yf as a drop-in replacement for an existing R-134a heat pump water heater. The results indicated that an optimized charge of R-1234yf as a drop-in replacement for R-134a in a heat pump water heater can achieve a uniform energy factor that is within 1% of the R-134a heat pump water heater with slightly lower capacity as indicated by slightly longer runtimes during the uniform energy factor simulations [5]. Laboratory testing has also been performed using R-1234yf as a drop-in replacement for R-134a in HPWHs. One study found a slight reduction in capacity and coefficient of performance (COP) with R-1234yf [6] and the other found matching capacity and slightly reduced, 6% lower, efficiency [7].

The consensus of prior research indicates that the use of R-1234yf results in a slight degradation of performance compared to an identical system charged with R-134a. However, no studies have evaluated the real-world performance of HPWHs charged with R-1234yf over an extended period. This study documents the measured performance of four HPWHs that were retrofitted with an optimized charge of R-1234yf refrigerant. No other modifications were made to the heat pump systems. Two systems were installed and tested in occupied homes, while the other two were tested in unoccupied lab homes.

2.0 Experimental Setup

Across the experimental platforms, a single off-the-shelf HPWH model was used to investigate R-1234yf HPWH performance. The HPWH model in the off-the-shelf condition served as a baseline, while the off-the-shelf model was modified with an R-1234yf charge to investigate field performance. Table 1 provides specifications for the off-the-shelf R-134a HPWH used in the study. The selected HPWH consisted of a 189 L (50 gallon) tank and dual 4,500 W backup electric-resistance heating elements. The refrigerant charge in the off-the-shelf HPWH was 0.65 kg (1.43 lb) of R-134a, while an optimized R-1234yf refrigerant charge of 0.60 kg (1.32 lb) was established in a prior effort [4] and utilized for the field evaluation.

Table 1. Specifications of Baseline, R-134a Heat Pump Water Heater

Equipment Manufacturer	A.O. Smith
Equipment Model	HP10-50H45DV
Nominal Tank Size	189 L (50 gallon)
Off-the-Shelf R134a Charge	0.65 kg (1.43 lb)
Backup Electric Elements	Dual 4,500 W Elements
Manufacturer Warranty	10 Year

2.1 Lab Homes and Occupied Field Sites

Oak Ridge National Laboratory‘s (ORNL's) laboratory home is a two-story, 2,400 ft^2, single-family home located in Knoxville, TN. The home is unoccupied but has simulated occupancy using heaters, humidifiers, and hot water draw stations that are automatically controlled on a schedule. A baseline, unmodified heat pump water heater was installed alongside the R-1234yf-charged water heater in the 400 ft^2 garage. The two water heaters were installed approximately 6 ft apart and were oriented to prevent the discharge air from being blown in the direction of the other unit to maintain similar intake air temperatures. The HPWHs were not ducted and freely pulled and exhausted air from/to the garage. Two independent hot water draw stations were used to control the hot water usage of each water heater. These were programmed in the same fashion to provide consistent hot water usage for the two water heaters throughout the field test.

Pacific Northwest National Laboratory’s (PNNL's) laboratory homes consist of two identical side-by-side 1,500 ft^2 homes with three bedrooms and two bathrooms. Each lab home is instrumented for monitoring water heater performance and the water heater's impact on the surrounding indoor space. Automated hot water draws are controlled through the lab home's testing infrastructure, and the draw profiles were established from field data. The water heater is located within an interior closest at each home. Air vents are installed on the water heating closet and adjacent master bedroom closet to provide interior makeup air to the HPWH. The inlet air conditions to the HPWH are influenced by the home's indoor air conditions and the heat rejection of the HPWH. The home's indoor temperature was controlled by a centrally-located thermostat. During the experimental study, one home contained a R-1234yf HPWH, while the other home contained the baseline R-134a HPWH. Testing was conducted in a side-by-side manner under identical indoor temperature conditions and for identical hot water draw profiles.

Two occupied field sites were additionally utilized to investigate the performance of the R-1234yf HPWH. The selected field sites were both located in Portland, Oregon, but the field sites had differing home occupant counts and water heater locations. Both occupied field sites had an adult at home regularly during daytime hours on weekdays. Each occupied field site consumed hot water as desired with no restrictions or guidance from the research team. The R-1234yf HPWHs were utilized at the two occupied field sites for approximately 18 months without any operational issues. Both field sites previously contained a similarly sized R-134a HPWH, and the homeowners were surveyed as part of the study.

The lab homes both used the same set of hot water draw profiles for their testing, with profiles representing small, medium, and large hot water consumption. The cumulative hot water use for the day for each profile is shown in Figure 1. Each test site experienced different ranges of environmental conditions during the study. The conditions with the largest effect on efficiency are (1) daily hot water consumption and associated usage profile, (2) the hot water set point of the water heater, (3) the cold-water inlet temperature to the water heater, and (4) the inlet air wet-bulb temperature. The operating ranges for these parameters, along with general test site information, are shown in Table 2.

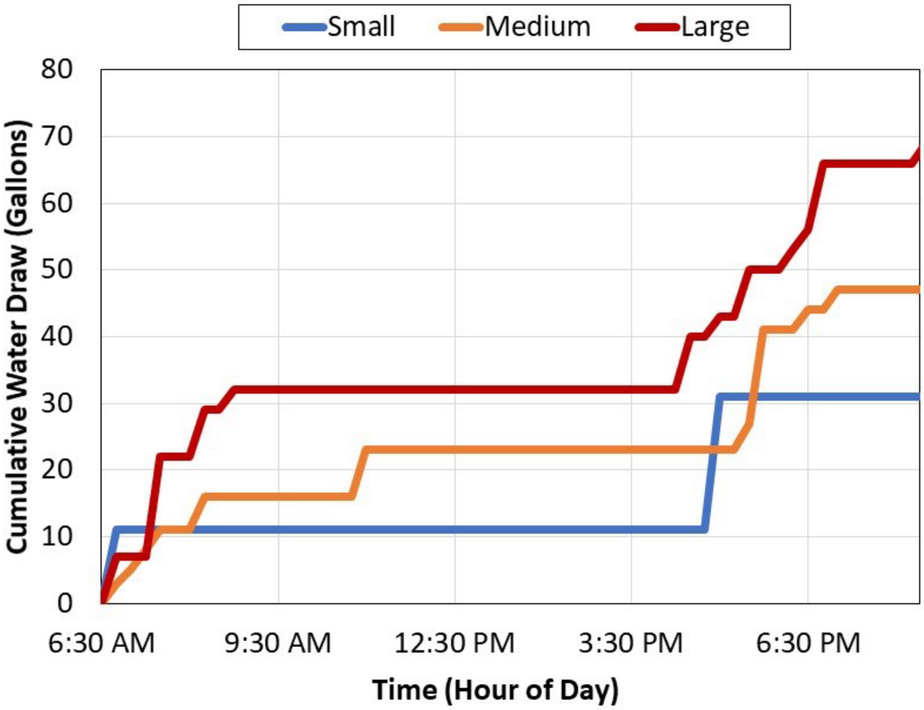


Figure 1. Hot Water Draw Profiles for Lab Home Testing

Table 2. Characteristics of HPWH Test Sites, Ranges of Operation, and Ranges of Environmental Conditions

	ORNL Lab Home	PNNL Lab Homes	Occupied Field Site 1	Occupied Field Site 2
Location of Field Site	Knoxville, TN	Richland, WA	Portland, OR	Portland, OR
Location of HPWH at Site	Garage	Interior Closet	Unconditioned Basement	Garage

	ORNL Lab Home	PNNL Lab Homes	Occupied Field Site 1	Occupied Field Site 2
Number of Home Occupants	NA	NA	3 Occupants	2 Occupants
At least one adult consistently home during weekdays, 8AM – 5PM?	NA	NA	Yes	Yes
Daily Hot Water Draw Profiles	Automated Schedule	Automated Schedule	Determined by Home Occupants	Determined by Home Occupants
Daily Hot Water Consumption Range (gallons)	31, 47, 69	47, 69	19 – 94	0 – 61
Hot Water Setpoint Temperature (°F)	120, 125, 130	125	~125	~130
Cold Water Inlet Temperature Range (°F)	58 – 78	47 – 74	44 – 59	47 – 60
Inlet Air Wet-bulb Temperature Range (°F)	50 – 62	41 – 57	48 – 58	44 – 57

2.2 Measurements and Performance Calculations

Additional refrigerant temperature measurements were taken on the refrigerant piping of the heat pump system, including compressor discharge temperature, compressor suction temperature, and evaporator inlet temperature. All four systems were instrumented similarly to measure their performance, as shown in Figure 2. The models and accuracies for the individual sensors that were used at each location are shown in Table 3, along with the resulting uncertainty estimate for the calculated COP.

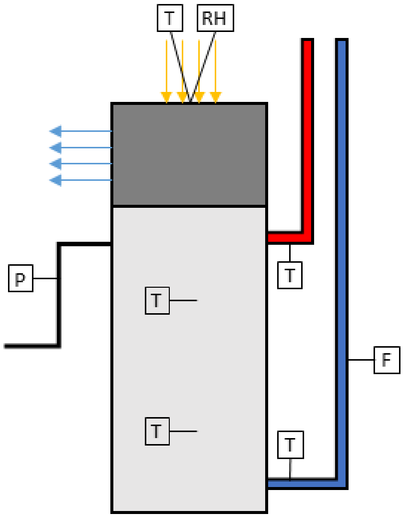


Figure 2. Diagram of Heat Pump Water Heater with Locations of Temperature (T), Relative Humidity (RH), Volume Flow (F), and Power Consumption (P) Marked

Table 3. Sensor Models and Accuracies for All Four Test Sites

	ORNL Lab Home	PNNL Lab Homes	Occupied Field Sites (both)
HPWH inlet and outlet water temperature	Platinum RTD Class 1/10 DIN (±0.15°F)	Special Limits of Error T-Type Thermocouple (±1.0°F)	Platinum RTD Class 1/10 DIN (±0.15°F)
Hot water consumption	R1234yf - Badger M25-750PNPB-TJ-XXXX (±1.5% reading) R134a - Omega FTB4605 (±2% reading)	Dwyer DFMT (±0.12 GPM)	Badger M25-750PNPB-TJ-XXXX (±1.5% reading)
Inlet air temperature and humidity to HPWH	Campbell Scientific HC2S3 (±0.18°F, ±0.8% RH)	Dwyer RHP (±0.54°F; ±2% RH)	Campbell Scientific HC2S3 (±0.18°F, ±0.8% RH)
HPWH power consumption	WattNode Modbus (±0.5% reading)	Square D BCPM (±1% reading)	WattNode Modbus (±0.5% reading)
HPWH miscellaneous temperatures	Special Limits of Error T-Type Thermocouple (±1.0°F)	T-Type Thermocouple (±1.8°F)	Special Limits of Error T-Type Thermocouple (±1.0°F)
Typical uncertainty in COP calculation	R-1234yf ±1.6% R-134a ±2.1%	±8.5%	±1.6%

The performance of a storage-type heat pump water heater can be broken into two major buckets: the efficiency of the heat pump to transfer heat from the surrounding air to the stored water and the efficiency of the tank insulation to retain the heat of the hot water until it is used. It is challenging to measure the performance of these two parts of the system independently, so the combined performance of the system is measured instead. The stored hot water allows for the desynchronization of the heat pump operation and hot water usage, making it impossible to assess the instantaneous system performance. Accordingly, the efficiency has been calculated over the span of a day as shown in Equation 1,

$$\boldsymbol{COP_{daily}} = \frac{\sum \boldsymbol{V\rho c_p(T_{hot} - T_{cold})}}{\sum \boldsymbol{W_{electric}}} \tag{1}$$

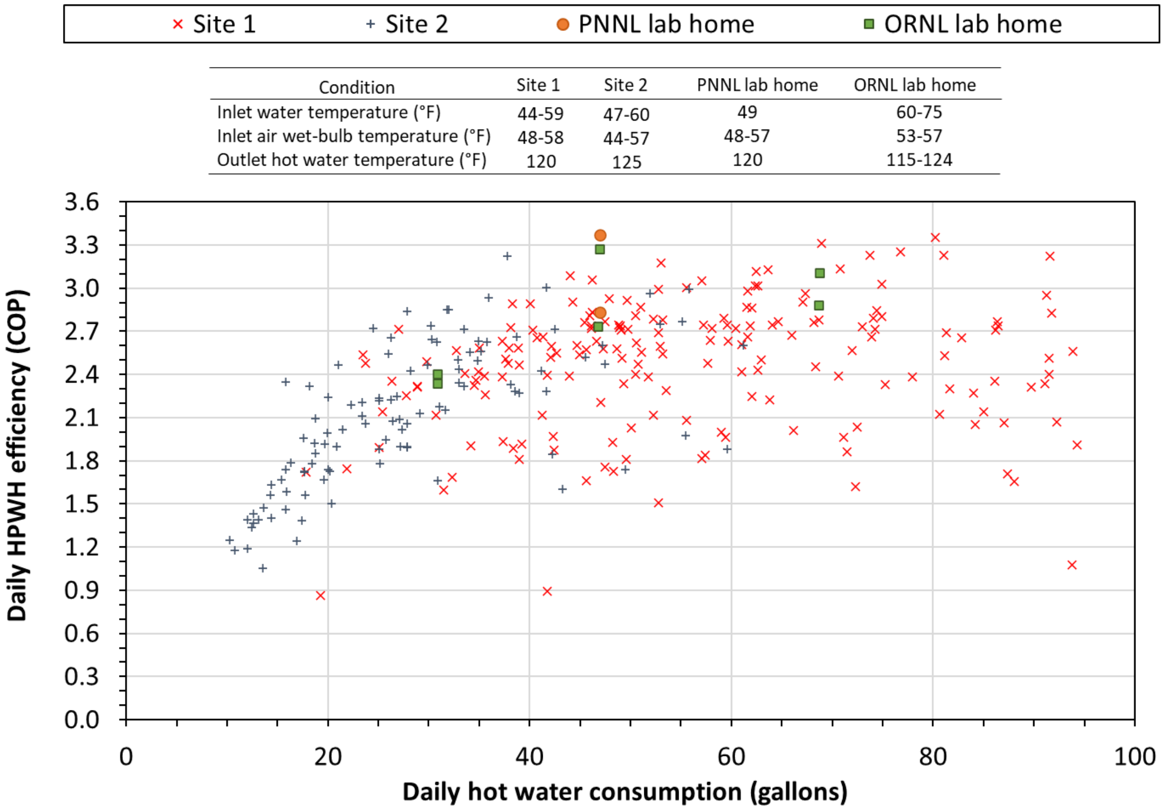
where:

COP_{daily} = coefficient of performance for the day
V = volume of hot water used during a timestep
ρ = density of the water
c_p = specific heat capacity of the water
T_{hot} = temperature of the water leaving the water heater
T_{cold} = temperature of the water entering the water heater
$W_{electric}$ = electric energy consumed by the water heater during the timestep

3.0 Experimental Results

The average daily COPs for the R-1234yf HPWHs installed at the two occupied field test sites are plotted in Figure 3. The HPWHs experienced a wide range of hot water usage that is expected in occupied homes. The average daily COP is dependent on the hot water delivered to the house, so it is expected to see lower COPs during days when there is lower hot water consumption. During these low hot water usage days, a higher fraction of heat pump heat is used to offset tank losses compared to heating cold water that has entered the tank because of hot water use, resulting in a lower daily COP as calculated in Equation 1. The large spread in daily COPs for a given daily hot water consumption can be attributed to differing environmental conditions (i.e., inlet water temperature, inlet air wet-bulb temperature) and differing hot water use profiles. The cold-water inlet temperature can influence the condensing temperature or condenser pressure during the start of the heating cycle. A lower inlet water temperature will lower condensing temperature and yield higher capacity and lower compressor power, both increasing the efficiency. Likewise, the inlet air wet-bulb temperature influences the evaporating temperature or evaporator pressure. A higher inlet wet-bulb temperature will increase the evaporating temperature and yield higher capacity and higher efficiency. The hot water consumption pattern can also influence efficiency. If a large amount of hot water, typically over 20 gallons, is consumed over a short period of time, then the HPWH may use the electric resistance heating elements to keep up with the demand. Using the electric resistance elements significantly lowers the heating efficiency. A hot water consumption profile that is more evenly spread throughout the day will result in higher daily COPs than profiles with large hot water usage over a short period in time. Additionally, hot water usage at the end of the day can skew that day's COP to be higher, and the following day's COP to be lower. This is due to the asynchronous nature of the delivery of stored hot water (the numerator of the daily COP calculation) and the energy used (the denominator of the daily COP calculation) to recover from the hot water usage that takes much longer. The average COP for the duration of the field test was 2.5 and 2.1 for sites 1 and 2, respectively.

In addition to the occupied field test site data, select data from the lab homes are plotted in Figure 3. The lab homes used 3 different hot water draw profiles, so the data points are all located around 31, 46, and 69 gallons with variations only due to different operating conditions. The lab home data points generally fall within the range of daily COPs experienced by the HPWHs installed at the occupied test sites.

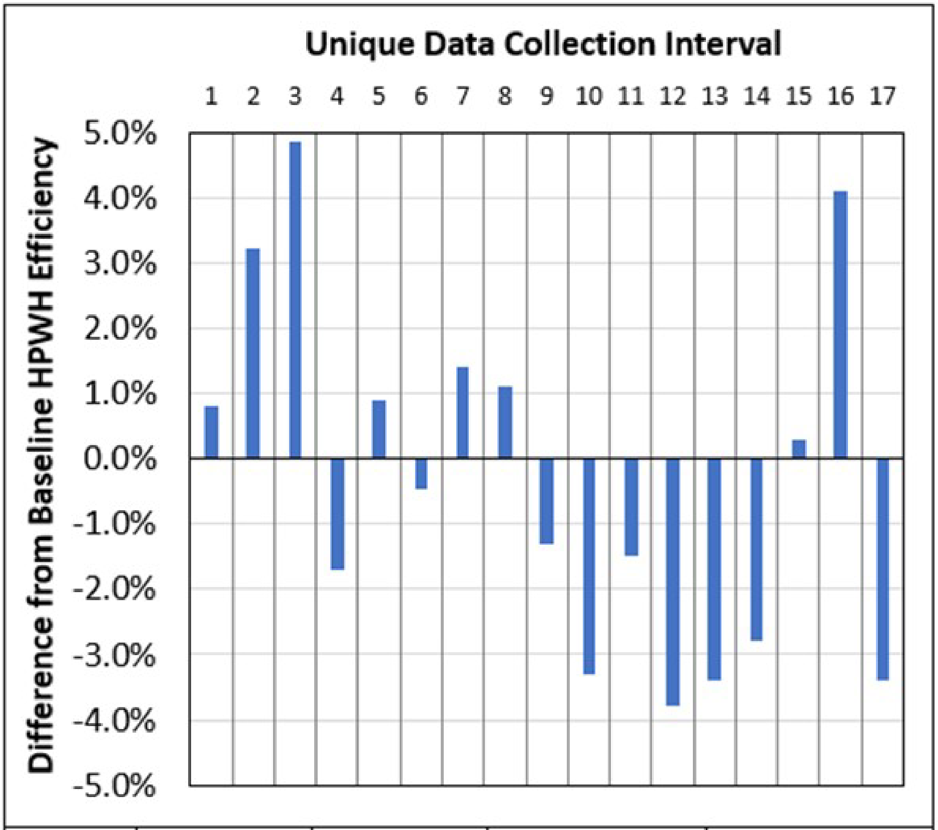


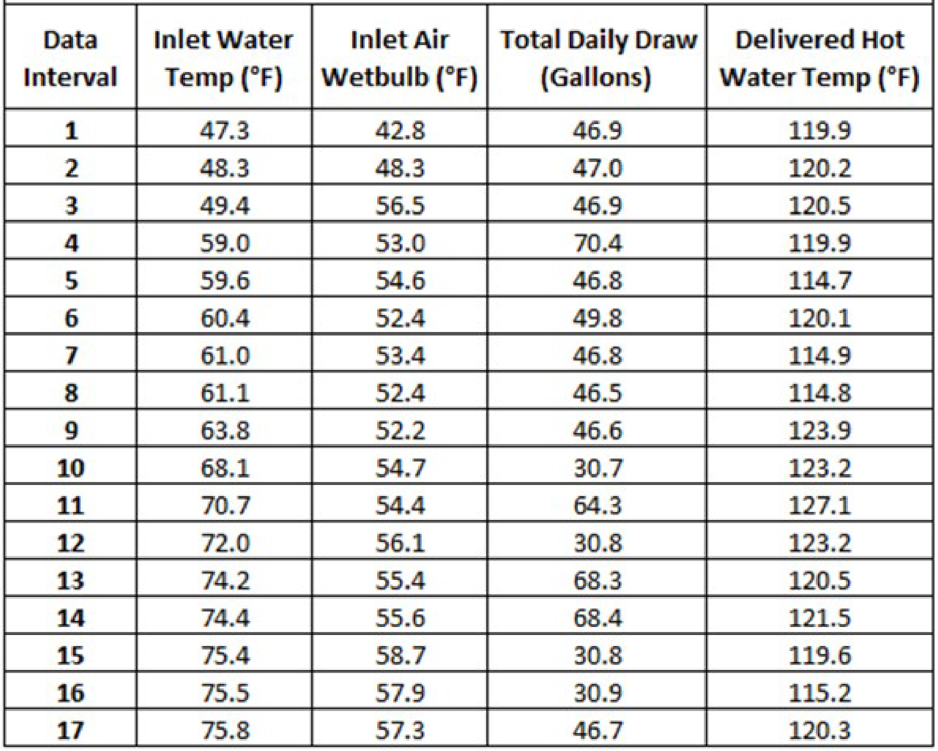
Condition	Site 1	Site 2	PNNL lab home	ORNL lab home
Inlet water temperature (°F)	44-59	47-60	49	60-75
Inlet air wet-bulb temperature (°F)	48-58	44-57	48-57	53-57
Outlet hot water temperature (°F)	120	125	120	115-124

Figure 3. Average Daily Efficiency of R-1234yf HPWHs at Four Different Test Sites for the Range of Conditions Specified

A baseline R-134a HPWH was run side-by-side the R-1234yf HPWH at the ORNL lab home. The water heaters experienced the same hot water draw profiles, shared the same feed for cold water to their inlets, were set at the same hot water setpoint temperatures, and shared the same ambient air as a heat source. This allows for direct comparison between the two systems with minimal differences in their operating conditions. The average efficiency of the two systems is compared for a variety of conditions in Figure 4. Overall, the R-1234yf HPWH had an average COP that was 1.3% less than the R-134a system over the span of 138 days. However, this difference falls within the ±2.7% measurement uncertainty estimated for the percent difference in COP between the two systems. A sample plot of the power profile for the two systems is shown in Figure 5. The R-1234yf HPWH has slightly lower instantaneous power use, particularly during the end of the heating cycle. The R-1234yf HPWH runs slightly longer than the baseline unit, though, indicating slightly lower heating capacity, and off-setting the lower instantaneous power use to consume slightly more energy for the day.

The side-by-side PNNL lab homes also collected data for a R-1234yf and a R-134a HPWH under similar conditions. During the winter evaluation period the R-1234yf HPWH was 0.9% more efficient than the R-134a HPWH and during the summer evaluation period it was 2.2% more efficient. Both of these differences fall within the measurement uncertainty of the test setup.





Data Interval	Inlet Water Temp (°F)	Inlet Air Wetbulb (°F)	Total Daily Draw (Gallons)	Delivered Hot Water Temp (°F)
1	47.3	42.8	46.9	119.9
2	48.3	48.3	47.0	120.2
3	49.4	56.5	46.9	120.5
4	59.0	53.0	70.4	119.9
5	59.6	54.6	46.8	114.7
6	60.4	52.4	49.8	120.1
7	61.0	53.4	46.8	114.9
8	61.1	52.4	46.5	114.8
9	63.8	52.2	46.6	123.9
10	68.1	54.7	30.7	123.2
11	70.7	54.4	64.3	127.1
12	72.0	56.1	30.8	123.2
13	74.2	55.4	68.3	120.5
14	74.4	55.6	68.4	121.5
15	75.4	58.7	30.8	119.6
16	75.5	57.9	30.9	115.2
17	75.8	57.3	46.7	120.3

Figure 4. Average COP Comparison between R-1234yf and R-134a Charged HPWHs Operated Side-by-Side at ORNL and PNNL Lab Homes for Unique Data Collection Intervals

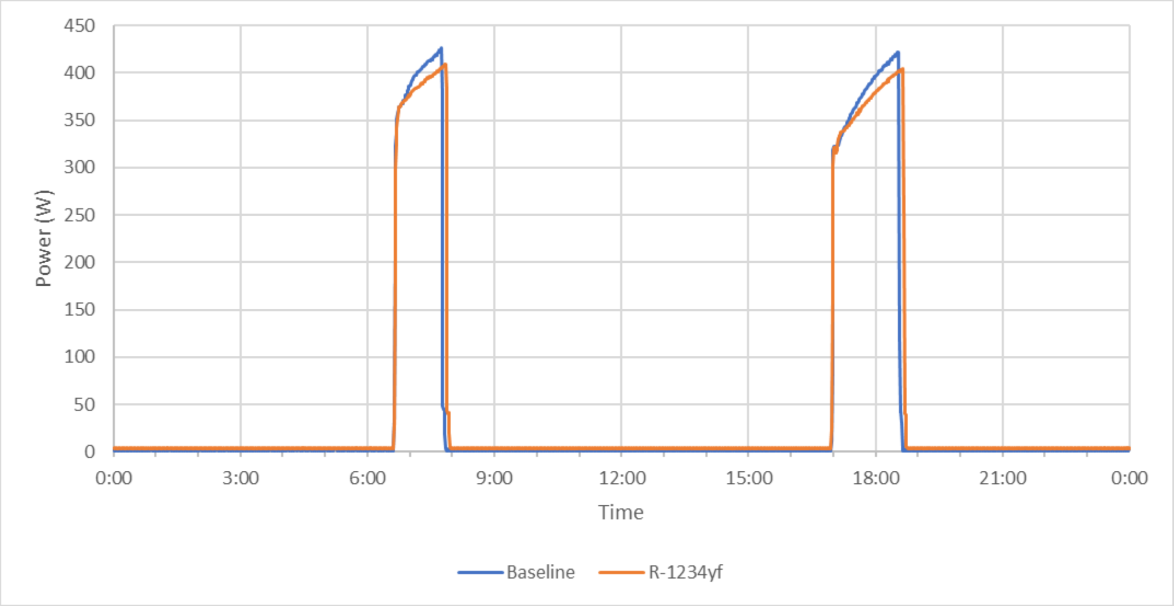


Figure 5. Comparison of Power Profile for Baseline, R-134a, Unit and R-1234yf Unit for Small Hot Water Draw Profile

A two-round homeowner survey was conducted after each homeowner had utilized a R-1234yf HPWH. Round one occurred approximately six months after installation around the end of summer data collection. Round two occurred approximately 12 months after installation around the end of winter data collection. The homeowners were asked an identical set of questions for both rounds. Both occupied field sites had similar 50-gallon R-134a HPWHs from the same manufacturer prior to this R-1234yf HPWH field study. Table 4 provides a summary of the survey questions and homeowner responses for each site for both summer and winter seasons. Both homeowners were satisfied with their R-1234yf HPWHs and observed no change from their previous R-134a HPWH. Both homeowners stated that they "never" run out of hot water, and the availability of hot water was like their previous R-134a HPWH of similar tank size.

Table 4. Survey Responses for the Two Occupied Field Test Sites

	Field Site 1 3-Occupant, Basement		Field Site 2 2-Occupant, Garage	
	End of Summer Data Collection	End of Winter Data Collection	End of Summer Data Collection	End of Winter Data Collection
How often did you notice that you run out of hot water while using the R-1234yf HPWH?	Never	Never	Never	Never
Are you generally satisfied with your Optimized Charge R-1234yf HPWH?	Yes	Yes	Yes	Yes
In comparison to your previous R-134a HPWH, have you noticed a change in Availability of Hot Water?	No change	No change	No change	No change
Would you recommend the R-1234yf HPWH to friends and family?	Yes	Yes	Yes	Yes

4.0 Conclusions

The refrigerant in four off-the-shelf, R-134a-charged HPWHs was replaced with R-1234yf, an alternative low GWP refrigerant. Two of these systems were installed and tested in occupied homes, while the other two units were tested in unoccupied lab homes. The R-1234yf installed in the occupied homes had average COPs of 2.1 and 2.5 respectively over the duration of the field test. Surveys of the home occupants did not indicate any complaints related to the performance or operation of the R-1234yf HPWH. All four test sites showed daily COPs that fell within similar ranges, despite some variations in environmental conditions.

The side-by-side operation of an R-123yf HPWH and a baseline, R-134a HPWH of the same model showed minimal efficiency difference at both the ORNL lab home and PNNL lab homes, 1.3% lower for the R-1234yf HPWH at the ORNL lab home and 0.9% and 2.2% higher for winter and summer periods at the PNNL lab homes. These differences fall within the measurement uncertainty range for both test sites. Overall, the results indicate that R-1234yf is a viable low GWP replacement for R-134a in HPWHs that will provide similar levels of performance that are not noticeably different to building occupants.

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