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Plug-In Heat Pump Water Heaters: An Early Look to 120-Volt Products

Prepared For NEEA:
Geoff Wickes, Sr. Product Manager of Emerging Technologies

Prepared by:
Ben Larson, Principal Consultant
Sam Larson, Associate

Larson Energy Research
1932 Builder Drive
Menomonie, WI 54751

and

Cascade Engineering Services
6640 185th Avenue Northeast
Redmond, WA 98052

Northwest Energy Efficiency Alliance
PHONE
503-688-5400
EMAIL
info@neea.org

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Executive Summary

With a new class of heat pump water heaters (HPWHs) coming to market that can operate on a 15-Amp, 120-Volt circuit, this report seeks to answer questions about their performance capabilities using results from laboratory testing. It is intended to help identify the most appropriate installation locations for these “plug-in” water heaters.

Lab testing used two integrated style models: dedicated-circuit, with a maximum current of 12A, and shared-circuit, with a maximum current under 7.5A. Both models have a 50-gallon storage capacity, and neither has electric resistance elements. Each was tested using 125° F and 140° F water storage setpoints, with a mixing valve set to 120° F. Tests were performed in ambient air temperatures of 50° F, 67.5° F, and 95° F.

Tests measured supply (gallons of hot water delivered in the first hour), recovery efficiency (COP during full recovery from depletion), and recovery time (amount of time needed to reheat tank after depletion).

Primary Findings

- Raising the setpoint significantly increases supply (by 21%–45%). In each case, the increase crossed at least one sizing threshold from the Uniform Plumbing Code’s required minimum First Hour Rating (FHR).
- Raising the setpoint only slightly reduces efficiency (by 3%–8%).
- The shared-circuit model is slow to recover; reaching the 125° F setpoint took four hours. The tank is reheated mostly equally, meaning that the wait for any useful amount of hot water after a runout is substantial.
- The dedicated-circuit model recovers to 125° F in just over one hour.
- Recovery rates are correlated with ambient conditions, though the effect is not evident in first-hour performance. Compared to 67.5° F, output dropped as much as 17% when testing with 50° F ambient air and increased as much as 46% when testing with 95° F ambient air.
- Recovery efficiency is also correlated with ambient conditions. Compared to 67.5° F, efficiency dropped as much as 17% when testing with 50° F ambient air and increased as much as 25% when testing with 95° F ambient air.

Interpretive Findings

- On a 15-Amp, 120-Volt circuit, electric resistance would provide little advantage over heat pump-only operation in terms of recovery time.
- FHR might not provide enough information to size a lower output capacity water heater for installation. Alternate tests and outputs, such as the One-Plus test and the R_{105} metric used in the project, fill the information gap.
- The report includes a chart to illustrate how much hotter a smaller tank must be to provide the equivalent hot water resource as a larger tank (Figure 9). This is useful for sizing equipment, such as plug-ins, with an FHR dominated by the first draw volume.
- The report includes a HPWH selection guide (Section 4.3) that navigates the electrical supply circuit landscape to arrive at the best HPWH option for a given set of installation constraints.

Conclusions

- The low output capacity of the tested plug-in HPWHs leads to low First Hour Ratings and long recovery times. Using an elevated storage setpoint and a mixing valve is an effective strategy for preventing runouts and has only a small impact on energy efficiency.
- With their slower recoveries and without electric resistance, plug-in HPWH performance is more dependent on ambient conditions. For cool locations, greater energy storage capacity is recommended—through either a larger tank size, a higher setpoint, or both. For warmer locations, smaller tanks may be adequate.
- Where practical, a conventional 30-Amp, 240-Volt HPWH should be selected to achieve the greatest energy efficiency and ensure user satisfaction. In situations where electrical service upgrade costs are prohibitive, and the homeowner prefers a HPWH, plug-in models will often be able to meet demand. Informed caution is necessary to ensure the product is correctly sized for the specific situation.

While the conclusions of this report were based on just two designs from one manufacturer, the research team expects they will be broadly applicable to the plug-in HPWH category due to the common constraints imposed by a 15-Amp, 120-Volt circuit. Further, many of the findings—especially the ability of mixing valves to increase stored energy—are likely applicable to higher-output HPWHs.

1 Introduction

A new class of residential heat pump water heaters, “plug-in” models that operate on a 15-Amp, 120-Volt circuit, create the possibility of installing HPWHs in residences without the need to run a new electric circuit or make electric panel upgrades. These plug-in models operate at less total power than their traditional 30-Amp, 240-Volt HPWH counterparts. Those more traditional products generally use 4.5 kW resistance heating elements to improve hot water recovery time in some circumstances and provide backup heating in cold ambient conditions.[1] The plug-in designs may forego the resistance element to stay under the current/voltage cap of a 120-Volt circuit. This presents the design opportunity/challenge to mitigate what otherwise might be a longer recovery time and lower first-hour delivery. Hot water users and equipment installers may expect the delivery capability of a traditional product such as the 30-Amp, 240-Volt heat pump, electric resistance, or gas storage water heater.

This report explores the design challenge, approaches taken to address it, implications for product design, and where the plug-in products fit in the marketplace. It covers the issues in several ways, including generalized theoretical calculations and by lab testing two plug-in products that offer distinct approaches. A main goal of the report is to help determine the best potential uses of plug-in water heaters—the situations in which a higher current/voltage water heater is impractical.

Two observations informed the project approach. First, an obvious strategy to increase hot water delivery capability is to increase the water temperature inside the tank while connecting the hot water outlet to a thermostatic mixing valve. Second, the plug-in products rely entirely on heat pump operation, so ambient temperature matters more than with 30-Amp, 240-Volt equipment. Therefore, tests were designed to explore four primary questions:

- How does water **storage temperature** affect hot water **supply**?
- How does **ambient temperature** affect hot water **supply**?
- How does water **storage temperature** affect energy **efficiency**?
- How does **ambient temperature** affect energy **efficiency**?

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[1] When the air around a HPWH is cooler it has less energy to draw from, slowing the rate of water heating and decreasing efficiency. Also, heat pump compressors have minimum operating temperatures, below which they cannot add any heat to the water.

The testing results, combined with existing information from other products, provide a larger picture of water heater characteristics, which can be used to inform water heater selection. Accordingly, the report surveys potential HPWH product offerings and distills a product selection guide from them. The guide also provides CO_2 emissions levels as another characteristic that is increasingly important in consumer product selection.

The project testing results are not intended to replace or compare with standardized Uniform Energy Factor (UEF) or First Hour Rating (FHR). Instead, the tests evaluate the equipment under different performance conditions to explore a range of approaches for creating successful plug-in products. The reader is encouraged to consider implications for the broader class of plug-in equipment and seek out general findings.

1.1 Sizing and First Hour Rating

When selecting a water heater for installation, the key criterion is the hot water supply. Storage-tank water heaters are designed to meet peak demands with stored hot water and then reheat the tank slowly. Plug-in water heaters are no different. However, the plug-ins are constrained to a much smaller electrical circuit than traditional products, which limits the heating rate and increases the recovery time to usable hot water. Sizing the water heater to the water heating load remains acutely important. Load profiles that would allow precise sizing for a specific dwelling, ones based on direct flow measurement, are rarely available. Actual hot water draws vary significantly house-to-house and day-to-day. Even if a water heater has a large enough delivery capability to meet the load on most days, the days when the occupant runs out of hot water are remembered most. Consequently, it is necessary to meet not only the typical load but even more than the 95% and 99% peak loads.

A method from the Uniform Plumbing Code (UPC) is traditionally used to determine the FHR requirement of a given dwelling (IAPMO 2020). The UPC provides a sizing table (see Table 1) based on bedroom and bathroom counts.

Table 1. UPC Water Heater Sizing

Room Count and FHR							
Number of Bathrooms	1–1½		2–2½			3–3½	
Number of Bedrooms	1	2–3	2	3–4	5	3	4–6
Minimum FHR (Gallons)	38	49	49	62	74	62	74

Note: Adapted from UPC 2021, Table 501.1(2)

Bedrooms and bathrooms do not use hot water; people do. Using a dwelling's maximum occupancy capacity as the basis for determining its FHR need can significantly overshoot the needs of the actual users. Actual peak load in a given dwelling may be significantly different from the requirement suggested by the UPC table. Some homes may have more time-dispersed water use, which would deemphasize the importance of a one-hour delivery rating.

Adding to sizing decision criteria, plug-in water heaters will have much smaller, or no, electric resistance heating elements compared to traditional 240-Volt water heaters. The higher-current electric resistance elements in 240-Volt HPWHs can add heat directly to the upper portion of the tank to quickly provide usable hot water. Without electric resistance backup, a HPWH's ability to meet demand is more dependent on ambient conditions. If the plug-in water heater is installed where the temperatures differ from standard testing conditions for some, or all, of the year, the effect on first-hour supply (both positive and negative) is an important consideration when selecting the water heater. Accordingly, the testing in this project explores the dependence on ambient conditions.

1.2 Generalizability and Comparisons Disclaimer

The report discusses findings for the specific equipment tested. However, the findings are not necessarily specific to this exact equipment and may be generalized to cover many models of plug-in HPWHs, assuming the others have similar enough characteristics. Other products may differ substantially enough to warrant additional calculations and estimates. The report does not exclusively endorse the specific products tested but rather seeks to provide information on the whole product category.

Throughout the report, the research team mentions characteristics of more conventional water heaters alongside the plug-ins. This provides a necessary frame of reference for understanding the new product type, but the team discourages directly comparing the suitability of plug-in water heaters against other types for identical purposes. It is the opinion of the authors that a 240-Volt HPWH should be selected over a plug-in wherever practical. This report is intended to help determine the best potential uses of plug-in water heaters—the situations in which a higher current/voltage water heater is impractical and these new products can fulfill the need.

2 Test Method

The research team created the “One-Plus” test to test these water heaters. The procedure is based on the U.S. Department of Energy (DOE) First Hour Rating test, but data are collected until the tank fully recovers from the final draw. The team also varied two factors beyond the standard test conditions: hot water storage setpoint and ambient conditions. Three aspects of each water heater’s performance are measured: first-hour hot water supply volume, recovery energy efficiency, and recovery time.

2.1 Procedure for One-Plus Test

1. Water is heated to the storage setpoint, and the water heater is idled for approximately one hour.
2. Water is drawn at a rate of three gallons per minute (measured at the mixing valve output), with the mixing valve calibrated to 120° F, until the water temperature falls below 105° F.
3. Each time the water heater recovers its setpoint, another three-gallon-per-minute draw is made until the temperature falls below 105° F. (This condition occurred in one of the 12 tests.)
4. Sixty minutes after the start of the initial draw, if the temperature at the top of the tank exceeds 105° F, another three-gallon-per-minute draw is made until the outlet temperature falls below 105° F.
5. The water heater is observed until the storage setpoint is satisfied and the compressor cuts out.

2.2 Independent Variables

2.2.1 Equipment

Tests were performed on two versions of plug-in HPWHs developed by Rheem. Both products are designed to be used on a 15-Amp, 120-Volt circuit. The first product draws enough current that it is intended for use only on a stand-alone, dedicated circuit. The second product is designed to draw less than 7.5 Amps, making it suitable for use on a circuit shared with other devices. This report refers to the first product as “dedicated-circuit” and the second as “shared-circuit.” Each unit takes a different approach to the plug-in HPWH current and voltage design constraints.

The shared-circuit model uses a similar mechanical package to Rheem's ProTerra® [2] hybrid product but, crucially, eliminates the electric resistance elements. Lab measurements show the shared-circuit heat pump system uses ~260–500 Watts, depending on conditions, well within the limits of a single 120-Volt circuit. Full-size resistance elements would draw far too much current. To compensate for the slower reheating rate, the unit can increase stored energy via an integrated thermostatic mixing valve set to 120° F outlet, which allows the user to select a higher storage temperature but still deliver water at a safe temperature.

The dedicated-circuit model uses a completely new mechanical package that allows for a larger heat pump system and greater water heating capacity. Lab measurements show the heat pump draws 900–1,600 Watts depending on conditions. This translates to nearly 2.5 times the water heating capacity of the shared-circuit model. The unit achieves this partly through a unique split-evaporator design, effectively doubling the air-to-refrigerant heat transfer area, allowing for greater airflow and a larger compressor. Due to the faster heating rate compared to the shared-circuit model, the default storage tank temperatures are set at the typical 120° F, and a mixing valve is not included with the product. No resistance elements are used with this product.

For this project, a thermostatic mixing valve was added to the dedicated-circuit model to allow comparison of different water storage setpoints on both designs.

Table 2 provides a summary of the equipment characteristics. Some of the most notable impacts of the product design choices are clearly visible in the results of testing at DOE-standard conditions. The larger heat pump of the dedicated-circuit model can provide 2.5 times the water heating capacity of the shared-circuit model. In exchange, the efficiency is somewhat reduced; those implications are discussed later.

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[2] https://www.rheem.com/innovations/innovation_residential/hybridsavings/

Table 2. Equipment Characteristics Summary

	Dedicated-Circuit	Shared-Circuit
Make	Rheem	Rheem
Model	ProTerra Plug-In Heat Pump PROPH50 T0 RH120	Plug-In Heat Pump with HydroBoost XE50T10HM00U0
Nominal Storage Capacity	50 gal	50 gal
Supply Circuit Requirements	15A, 120V Dedicated	15A, 120V Shared
Max Amperage	≤12A	≤7.5A
UEF	3.0	3.0
FHR	51	55
Mixing Valve	Added for testing Set to deliver at 120° F	Integrated Set to deliver at 120° F
Default Storage Setpoint	120° F	125° F
Heat Pump Output Capacity, Input Power, and COP at 67.5F[3]	14,400 BTU/hr 1,180 Watts 3.6 COP	5,100 BTU/hr 364 Watts 4.2 COP
Electric Resistance Elements	None	None
Refrigerant	R-134a	R-134a
Airflow Path	Intake: Both left and right sides Exhaust: Top	Intake: Top Exhaust: Right side

2.2.2 *Ambient Conditions*

The lab tests explored a range of three sets of ambient conditions: those from the standard DOE tests and from NEEA's Advanced Water Heating Specification (AWHS) procedures (NEEA 2019) as shown in Table 3. The air temperatures are paired with inlet water temperatures to reflect seasonal changes.

Table 3. Ambient Test Conditions

Name	Air Temp	Air RH	Inlet Water Temp
50F	50° F	58%	50° F
68F	67.5° F	50%	58° F
95F	95° F	40%	67° F

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[3] As measured during recovery after first draw in One-Plus test at 68F ambient conditions.

2.2.3 Setpoint

The lab tests used two tank setpoints, shown in Table 4.

Table 4. Tank Setpoints

Name	Setpoint Selected in Controls
Lo	125° F
Hi	140° F

2.3 Metrics

2.3.1 Supply

“Supply” is measured as the gallons of water drawn through the mixing valve (both hot water from the tank and cool inlet water used to temper the heated water) during the procedure. The supply is akin to the FHR value. Note, however, that FHR is defined for a set of ambient conditions specified in DOE test procedures, whereas this testing explores a range of conditions. Therefore, this report uses the term “supply” for clarity, where one might find FHR if the tests were under standard conditions.

2.3.2 Recovery Efficiency

Recovery efficiency is measured as the coefficient of performance (COP) observed from the end of the final water draw to full recovery.

2.3.3 Recovery Time

Recovery time is measured as the number of minutes from the end of the last draw until…

- **R_{105}**: 15 gallons of water heated to at least 105° F
- **R_{125}**: Top quarter of tank heated to at least 125° F
- **R_{140}**: Satisfaction of 140° F storage setpoint control selection

3 Results and Analysis

3.1 Test Results

Results for all iterations of the One-Plus test are presented in Table 5. The table shows gallons supplied in the first hour, the recovery efficiency observed from the end of the final water draw to full recovery, and two different recovery times. All test data are graphed in Appendix A and the reader is encouraged to review those charts for further results insights.

Table 5. Test Results

Test	Supply (gal)	Recovery Efficiency	Recovery Time (min)		
			R_{105}	R_{125}[4]	R_{140}
Dedicated-50F-Lo	32.5	2.9	65	103	
Dedicated-50F-Hi	44.4	2.8	65		127
Dedicated-68F-Lo	61.1 1st draw: 30.7 2nd draw: 30.4	3.4	35	65	
Dedicated-68F-Hi	73.7 1st draw: 44.4 2nd draw: 29.3	3.3	35		81
Dedicated-95F-Lo	60.6 1st draw: 28.7 2nd draw: 32.0	4.0	18	41	
Dedicated-95F-Hi	87.6 1st draw: 46.4 2nd draw: 41.1	3.7	18		53
Shared-50F-Lo	42.2	3.3	215	336	
Shared-50F-Hi	55.5	3.1	309		433
Shared-68F-Lo	42.4	4.0	142	240	
Shared-68F-Hi	55.7	3.7	142		314
Shared-95F-Lo	42.9	4.9	76	146	
Shared-95F-Hi	57.3	4.6	76		195

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[4] Because the R_{125} metric is defined differently than the water heater controls' criteria for satisfying a 125° F setpoint selection, the water heaters did not always meet the R_{125} definition in Lo tests. In these cases, data from Hi tests were used to determine the R_{125} value.

Knowing the number and timing of the draws in the One-Plus test helps understand the results. Each test reflects the unit's heating capacity and ability to heat the upper portion of the tank; more draws and shorter spacing between them indicate more capacity. Table 5 shows the shared-circuit unit produced one draw per test, at the start of the test. At the 60-minute mark, the water had not crossed the 105° F threshold. Likewise, the dedicated-circuit 50F tests produced single draws. The dedicated-circuit 68F and 95F tests produced two draws. The 95F Lo test triggered the second draw at 45 minutes, while the others were triggered at 60 minutes.

Testing revealed that the first-hour supply provides only one piece of the hot water availability puzzle. It is also useful to know how soon hot water will again be available, especially if the initial supply is relatively low. For example, the dedicated-circuit model at 50F / Lo setpoint has a supply of 32.5 gallons, which is much lower than the shared-circuit model's 42.2 gallons at the same conditions. Yet, the dedicated-circuit product makes hot water available much more quickly: It achieves full recovery in 1 hour 40 minutes, compared to 5 hours 34 minutes for the shared-circuit. Consequently, the research team introduced the different recovery time metrics: R_{105}, R_{125}, and R_{140}.

The noticeably lower supply of the dedicated-circuit unit at 50F is due entirely to a particularity of the two water heater designs. The dedicated-circuit unit begins the tests with the lower third of the tank at about 90° F, while the shared-circuit unit begins the tests with the lower third of the tank at about 106° F. The tanks were pre-conditioned in the same way, so the difference is due to the water heater operation and the time at which each ends its reheating cycle. This particular dedicated-circuit tank stores less water above 105° F than the shared-circuit model.

Further, at the end of the first draw, the shared-circuit tank temperatures are uniformly lower. This suggests that more stored heat is usefully extracted than from the dedicated-circuit tank. The cause is likely different water mixing/stratification profiles. The two effects combine to produce a lower first draw volume in the dedicated-circuit tank even though both tanks have the same water storage volume. In terms of supply, the shared-circuit model has a greater reservoir of usefully heated water, which helps explain why it outperforms the dedicated-circuit tank for all the initial draws.

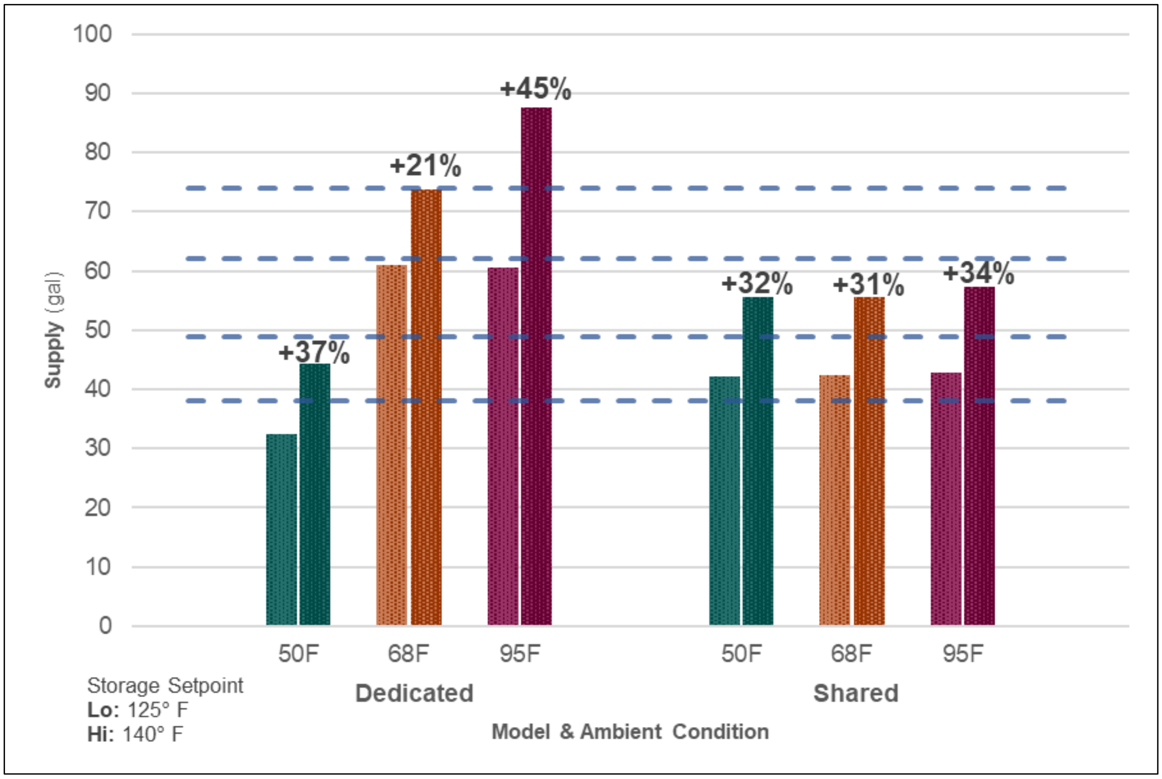
3.2 Setpoint Effects

3.2.1 Setpoint and Supply

Changing the water storage setpoint from Lo to Hi increased the supply by 21% to 45%, depending on test conditions. In each case, the increase crossed at least one threshold in the UPC water heater sizing requirements.

Increasing the tank setpoint increases the amount of stored heat at the beginning of the test. In turn, this stored heat is available to increase the volume used in the first hot water draw. This setpoint increase is almost exclusively responsible for delivering more hot water since changing the tank setpoint does not directly change the tank heating rate. Table 6 shows that the setpoint increase adds significantly to the first draws (the only draw in the case of the shared-circuit tests). Of the two sets of test conditions that produced a second draw (dedicated-circuit 68F and 95F), the setpoint only increased the second draw volume in 95F conditions. In that case, the higher setpoint allowed the heat pump to take advantage of the warmer air for a longer time and store more heat. Refer to Section 4.1.1 for further discussion of the change in stored energy with a change in setpoint.

Figure 1. Setpoint Effect on Supply



Note: Dashed lines show First Hour Rating thresholds from UPC water heater sizing guidelines.

Table 6. Average First-Draw Volumes

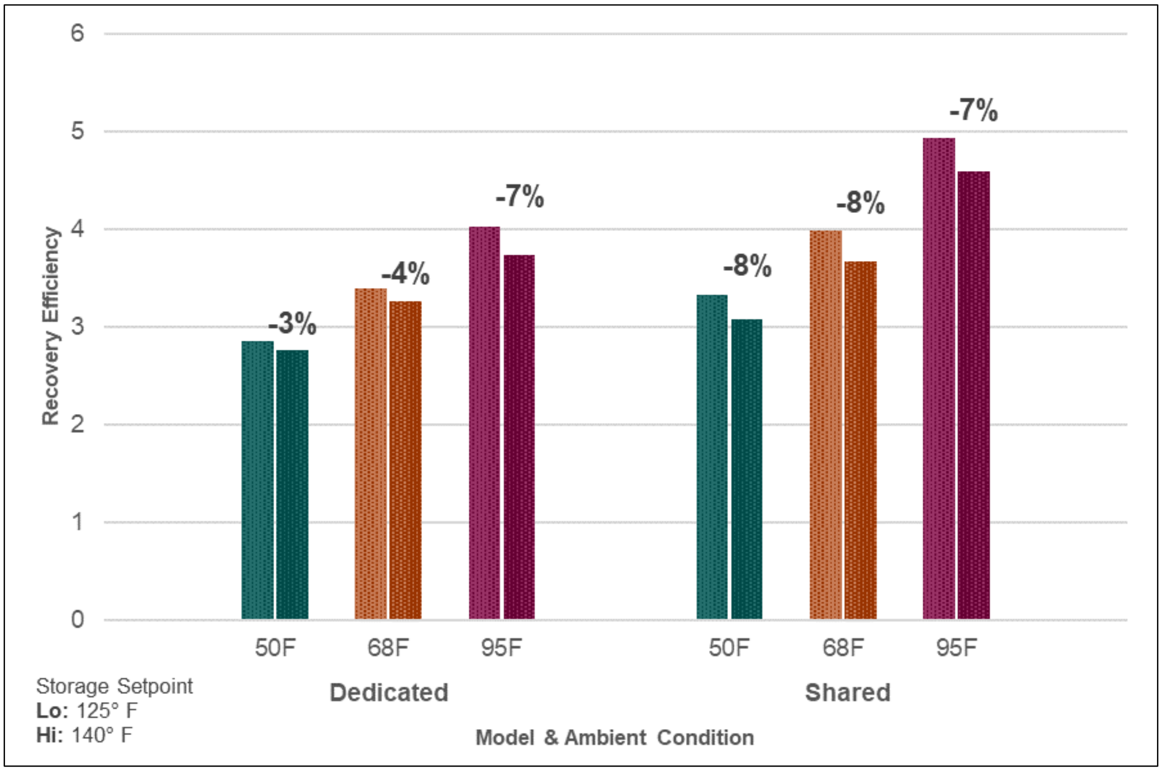
Setpoint	Dedicated	Shared
Lo	**30.6 gal**	**42.5 gal**
Hi	**45.1 gal**	**56.2 gal**

Setpoint and Efficiency

Increasing the water storage setpoint from Lo to Hi reduced the recovery efficiency by 3% to 8%. The reduction is expected since the heat pump must move energy farther "uphill" to the 140° F water compared to 125° F water.

Note that a higher setpoint will also increase standby losses.[5] A 24-hour UEF-style test, because it includes idle periods, would likely show a greater decrease in energy efficiency from higher storage temperatures. This might also explain why the shared-circuit model lost more efficiency—its longer recovery time would increase total heat loss from the tank compared to total heat input.

Figure 2. Setpoint Effect on Recovery Efficiency



3.2.2 Setpoint Cost / Benefit

Overall, the increase in setpoint temperature resulted in a marginal reduction in energy efficiency compared to the increase in hot water supply, as Table 7 shows. The tradeoff is better with the dedicated-circuit model compared to the shared-circuit model, and more so at the 50F

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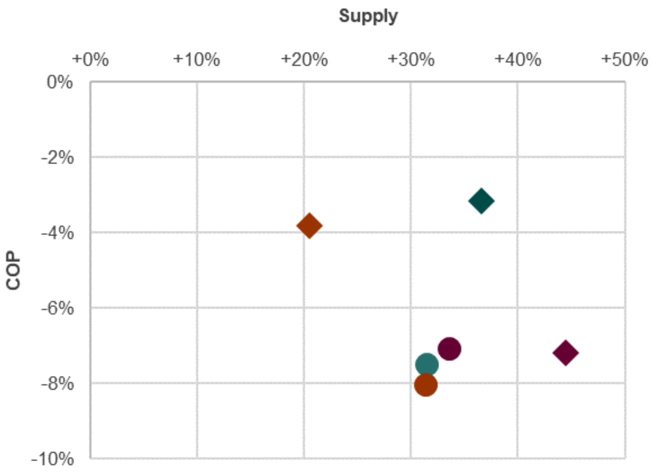
[5] At 67.5° F ambient air, an increase from the 125° F Lo to the 140° F Hi setpoint will increase standby losses 25%. Standby loss energy use, however, is a small fraction of the energy compared to the hot water use.

ambient condition compared to the other test conditions. The supply increases 21%–45% (12–27 gallons) for a decrease in recovery efficiency of 3%–8%.

Table 7. Setpoint Cost/Benefit Comparison

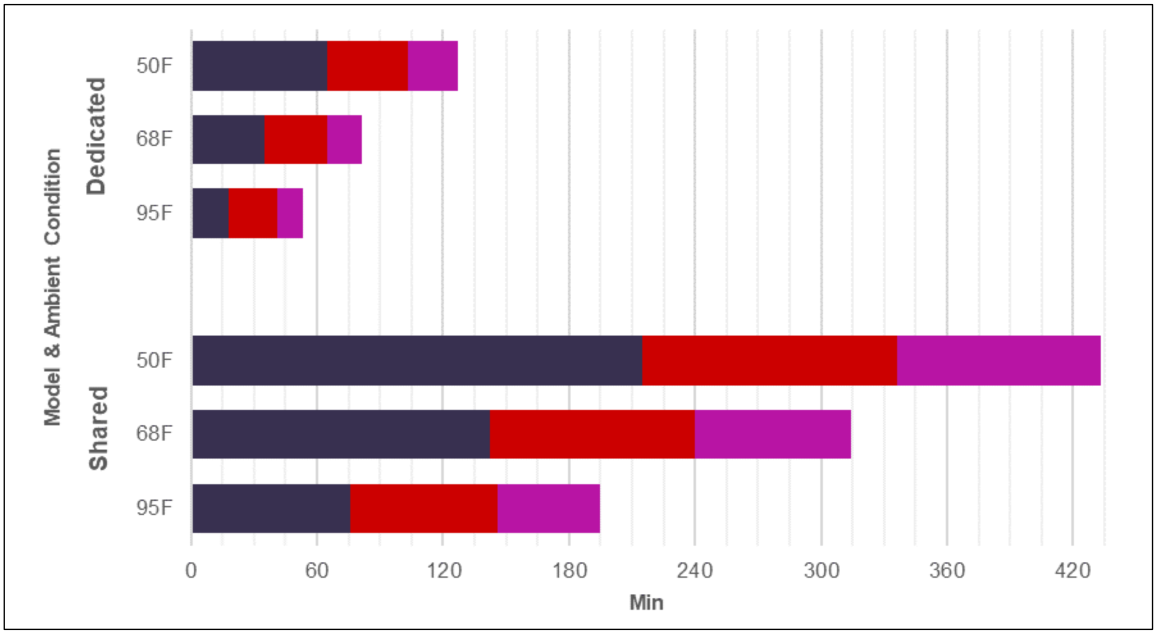
Model & Ambient Condition	Supply Increase	COP Decrease
◆ Dedicated-50F	11.9 gal	0.09
◆ Dedicated-68F	12.6 gal	0.13
◆ Dedicated-95F	27.0 gal	0.29
● Shared-50F	13.3 gal	0.25
● Shared-68F	13.3 gal	0.32
● Shared-95F	14.4 gal	0.35



3.3 Recovery Times

In addition to knowing how much water can be drawn from a fully heated tank in one hour, it is also important to understand how long a user will be left waiting before a useful amount of hot water is again available. The recovery time is more useful when distilled into milestones, such as when at least 15 gallons are heated to 105° F or higher, enough for a shower. Figure 3 graphs the recovery times to three milestones, as observed in the One-Plus tests.

Figure 3. Recovery Times



■ **R_{105}** 15 gal of water heated to at least 105° F

🟥 **R_{125}** Top quarter of tank heated to at least 125° F

🟪 **R_{140}** Satisfaction of 140° F storage setpoint control selection

3.4 Ambient Condition Effects

3.4.1 Ambient Conditions and Supply

As expected, warmer ambient conditions increase supply (shown in Figure 4), though not uniformly over the first hour.

The short test duration combined with the relatively low-capacity heat pumps disguises the benefit of warmer ambient conditions. For example, all three Shared-Hi supply results are approximately equal. This is because the tests included only one draw each, and the supply therefore depended on the amount of energy stored in the tank at the beginning of the test. While recovery rates were quicker in warmer ambient conditions, those recoveries did not contribute to measured supply since the threshold for a second draw was not met within 60 minutes. The recovery times (as discussed above), rather than first-hour supply, better describe the effects of ambient conditions on water sufficiency.

Figure 4. Ambient Condition Effect on Supply

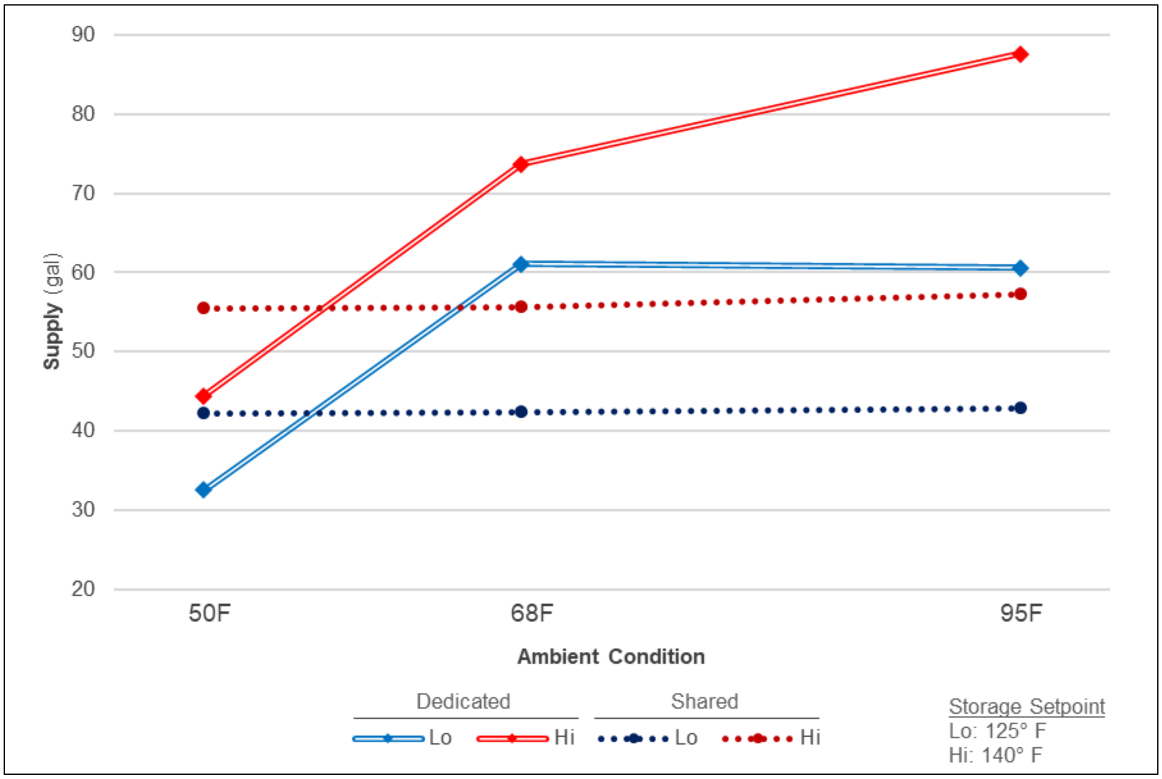
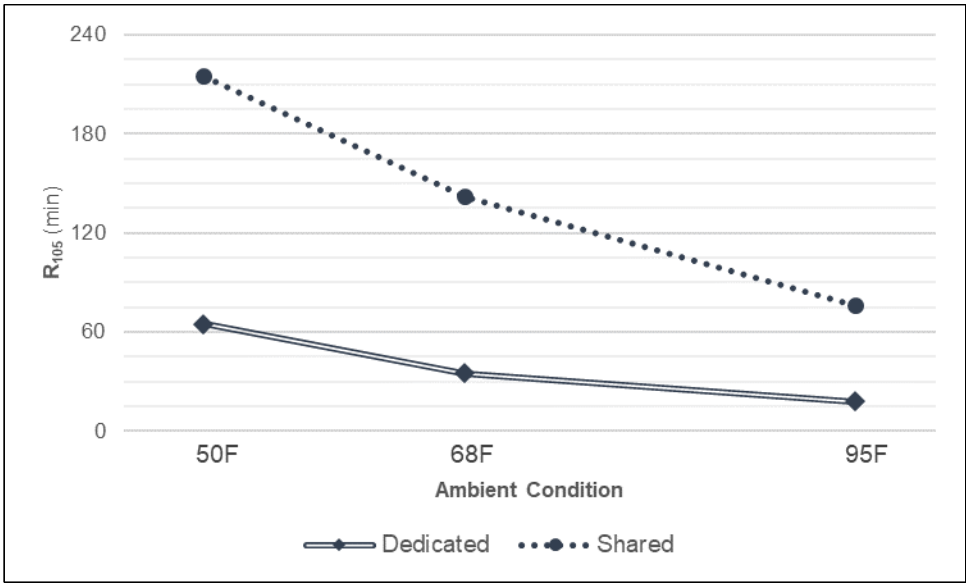


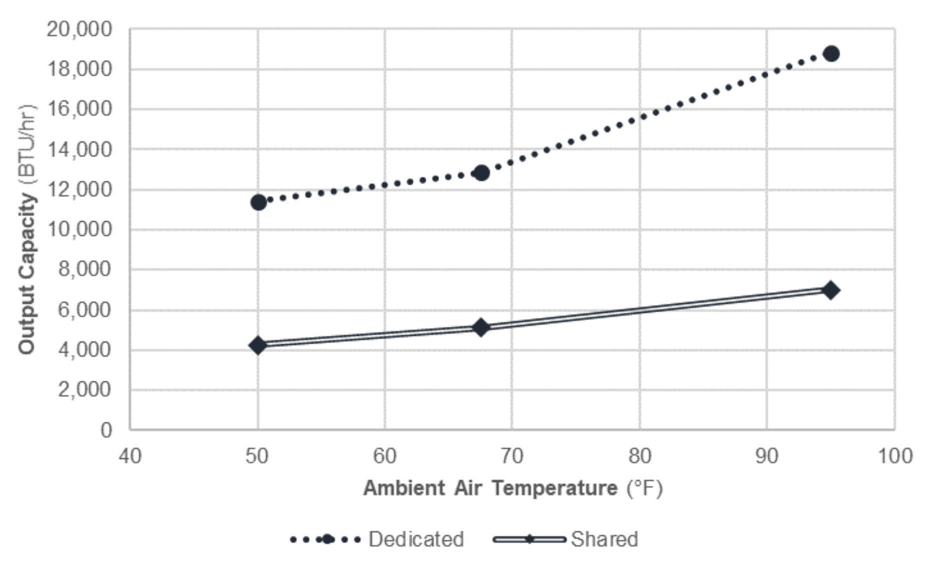
Figure 5 shows the benefit of ambient temperature on recovery time and illustrates the supplementary value of examining a metric other than first-hour supply. In this specific case, the metric is the time to recover to 15 gallons of usable hot water, R_{105}. The time ranges by factors of two to four, spanning the 50F to 95F ambient range and depending on the product. Interestingly, the figure also reveals nonlinearity in recovery time, despite linearity in COP. At the colder temperatures, both units take longer and longer to reheat. This holds for the R_{125} and R_{140} metrics as well.

Figure 5. Ambient Condition Effect on R_{105}



Another clear indicator of hot water supply and recovery time is the equipment output capacity, as shown in Figure 6. Capacity increases as the ambient air temperature and humidity increase, leading to shorter recovery times. The values plotted are the average heating capacity for each One-Plus test over the final recovery period at the Lo tank setpoint. The output capacity for the Hi tank setpoint tests is slightly lower, but the trend is the same (not shown). As with Figure 5, these show the nonlinearity with temperature.

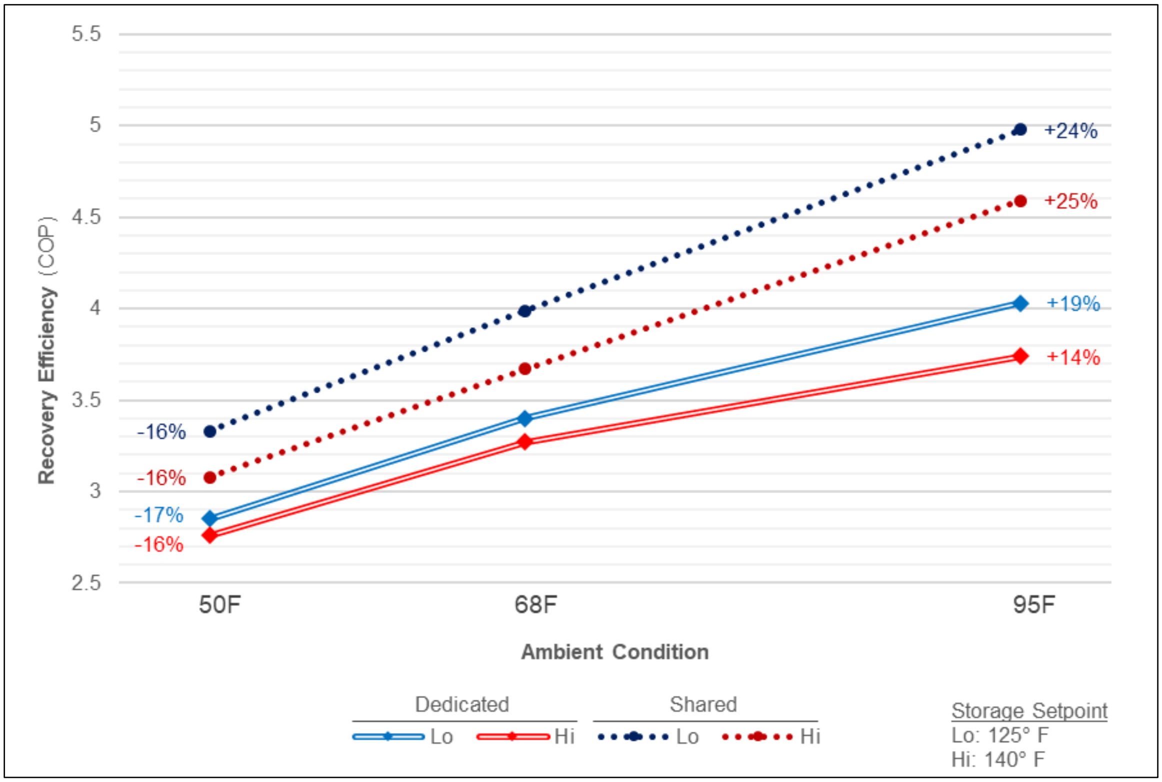
Figure 6. Output Capacity by Ambient Air Temperature—Lo Tank Setpoint



3.4.2 Ambient Conditions and Recovery Efficiency

Also, as expected, warmer ambient conditions improve recovery efficiency. The percentages in Figure 7 show relative differences in recovery efficiency for the same model and setpoint compared to the 68F condition. The setpoint has only a small effect on that relative efficiency difference, as expected from the results of Section 0

Figure 7. Ambient Condition Effect on Recovery Efficiency



4 Discussion

4.1 Test Interpretations

4.1.1 Recovery Time

The lab testing results highlight a clear challenge for plug-in HPWHs: recovery time to usable hot water after large draw events. When the tank is depleted of all hot water, as with the One-Plus test, it can take several hours to make usable hot water (defined as ≥105° F). 240-Volt water heaters will typically employ a resistance heating element in the upper part of the tank, allowing them to bring a smaller volume of water to useful temperature quickly. For integrated HPWHs (both plug-in and 240-Volt), the condensing heat exchanger is typically wrapped around the lower portion of the tank. The compressor provides heat to the whole tank, albeit via the bottom; the whole tank must be heated to heat the water at the top of the tank.

Figure 8 depicts heat distribution within the tank throughout recovery from a large draw event. The figure shows results from One-Plus tests of the shared-circuit and dedicated-circuit plug-in models as well as those from an FHR test of a conventional 240-Volt HPWH with an upper electric resistance element.[6] [7] The figure shows that at just 10 minutes after the end of the first draw, the conventional 240-Volt water heater already has 7.5 gallons of water at 105° F at the tank top, while neither of the plug-in water heaters has produced useful hot water. The dedicated-circuit product mean tank temperature is greater than the 240-Volt's, but because it cannot concentrate heat in the upper portion of the tank, none of the water is usefully hot (i.e., ≥105° F). At 20 minutes, the 240-Volt water heater has heated the upper quarter to 125° F while the other two remain below the 105° F threshold. The dedicated-circuit product has the same mean tank temperature as the 240-Volt HPWH, suggesting similar recovery rates but different heat distributions. The final figure facet shows the two plug-in tanks at full recovery, 240 (shared-circuit) and 65 minutes (dedicated-circuit) after the end of the draw.

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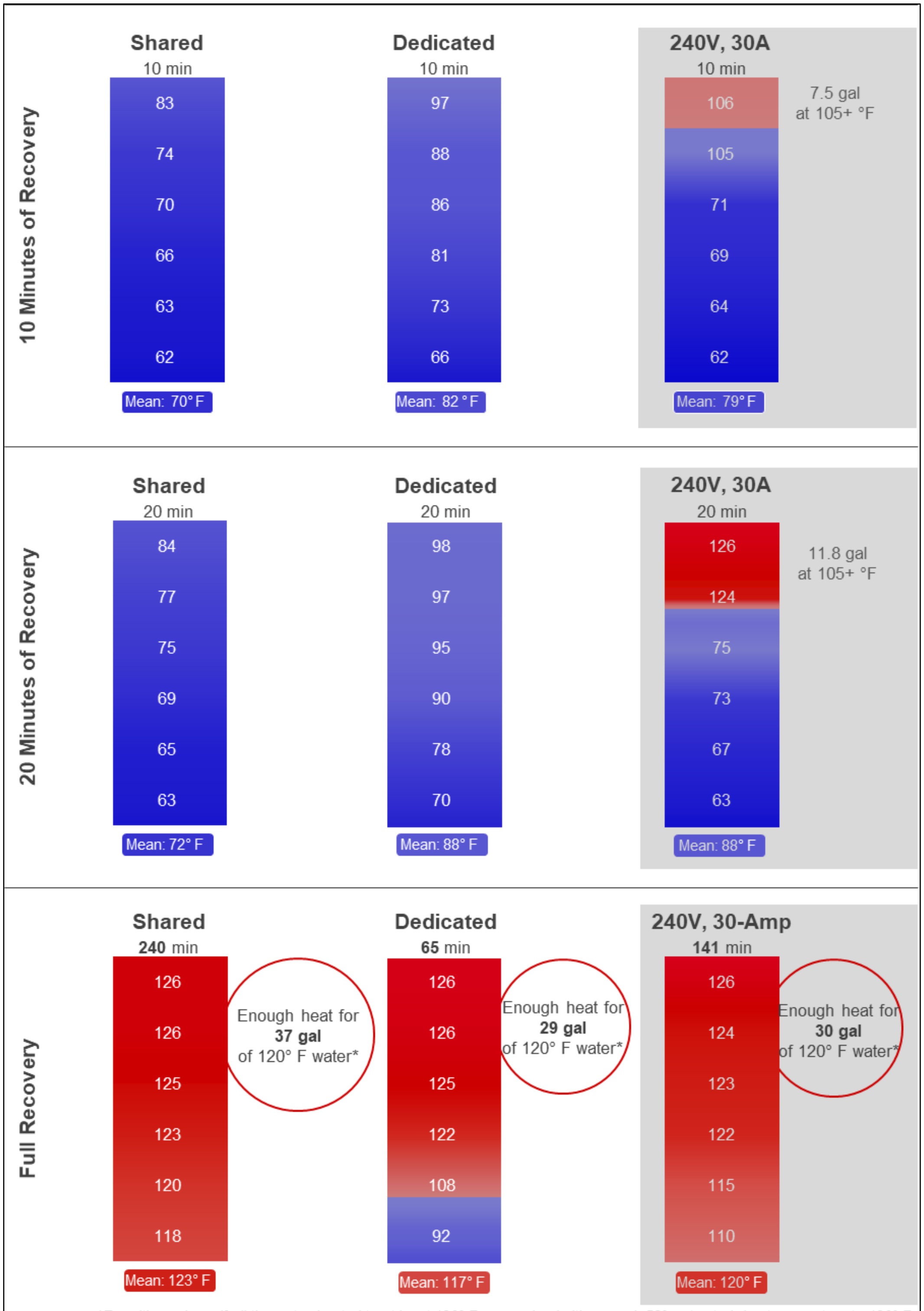
[6] Example taken from a First Hour Rating test of a 50-gallon Rheem HB Duct Ready Series HPWH conducted for NEEA, 2017.

[7] Measurements for all equipment conducted under 67.5° F air and 58° F inlet water conditions.

Figure 8. Tank Temperature Evolution During Recovery Cycle



*Resulting volume if all the water heated to at least 120° F were mixed with enough 58° water to bring temperature to 120° F

The preceding figures illustrate the advantage of being able to concentrate a large output of heating energy in just the upper portion of the tank. The design constraints of the plug-in HPWH make this strategy difficult to implement. Namely, the plug-in electrical constraints limit the current and voltage available for the resistance element to a maximum power of 900 Watts (shared circuit) or 1,440 Watts (dedicated circuit) versus 4,500 Watts for a 240-Volt heater. Figure 8 also demonstrates an advantage of the dedicated-circuit plug-in product's larger heat pump heating capacity. While it doesn't heat the top as quickly as the 240-Volt model, it achieves full recovery in less than half the time.

Table 8 explores scenarios in which a plug-in water heater would use a resistance element in the upper part of the tank (both shared- and dedicated-circuit power), comparing recovery times to heat pump-only heating. Bear in mind that because the heat pump delivers heat throughout the tank, significantly more energy is stored in the tank compared to the same recovery milestone achieved with an upper resistance element. The table shows how quickly usefully hot water can be made available; however, it does not represent the total heating output.

Table 8. Theoretical Upper Tank Reheat Times with and without Resistance Element

		Minutes to Reheat 15 Gal to…	
		105° F	125° F
Theoretical Upper Resistance Element	900 W	61	109
	1440 W	38	68
	4500 W	12	22
Lab-Measured Heat Pump-Only	Shared-Circuit Heat Pump	142	237
	Dedicated-Circuit Heat Pump	35	62

Calculations in the table use the observation that for a tank at 125° F and incoming water at 58° F, after the first draw in the FHR test, the upper tank temperatures are typically 80° F. For a 50-gallon tank, previous lab testing (Kintner 2021) shows the element is roughly 10–15 gallons below the tank top. The lab-measured plug-in heat pump reheat times are those at 68F ambient conditions.

The calculations show that, in practice, an upper element in the plug-in water heater would provide little advantage. Therefore, it is advisable that equipment selection and tank sizing should be undertaken to avoid tank depletion events unless hot water is not likely needed for some time afterward.

4.1.2 Setpoint and Efficiency Tradeoff

The parametric testing demonstrates that increasing the setpoint can effectively increase supply regardless of ambient temperature. The results show that increasing from 125° F to 140° F for a 50-gallon tank helps the water heater cross at least one UPC bedroom/bathroom sizing threshold. Although not tested here, elevating the setpoint further to 145° F or 150° F would clearly further increase the supply and could be an effective strategy for meeting hot water supply needs.

An additional significant test finding is that the efficiency decrease is quite small at 3%–8%. This is a tiny tradeoff to make when netting such a large increase in delivery ability. Consequently, designers, installers, and users should not hesitate to increase the setpoint to meet more demanding peak load situations. This is a convenient option to have in reserve if the water heater is installed at a lower setpoint but turns out to be too small for the occupant's needs. In all cases, the assumption about increasing setpoint is that a tempering/mixing valve will be installed at the water heater outlet (or is already integral to the equipment).

4.1.3 Ambient Conditions and Supply / Sizing

The recovery times measured in the One-Plus tests demonstrate the effect of ambient conditions on the water heaters' ability to meet demand. Compared to 68F ambient, recovery to R_{105} takes 1.5 to two times longer at 50F and half as long at 95F. Air temperatures at the installation location need to be considered in equipment sizing. If temperatures will be below 68° F, a larger tank or higher setpoint may be needed than what product specifications would indicate based on standard condition testing.

It is crucial to avoid installing the HPWH where ambient conditions can drop below the minimum operating temperature, or lower compressor cutoff. Below this temperature, a HPWH without electric resistance elements will not be able to heat water at all. This cutoff limit varies across models.

4.1.4 Heating Output Capacity and Recovery Times

Increasing the setpoint or tank volume to gain more stored energy is only useful if the heat pump has enough output capacity to reheat the tank between usage periods. The test results demonstrate that both the shared-circuit and dedicated-circuit units have enough output capacity over the course of a day to reheat the tank. Using the Hi (140° F) setpoint as an example, the shared-circuit product can heat the equivalent of 56 gallons of water in five hours; the dedicated-circuit product can do so in 80 minutes. Both products are able to heat a full tank of hot water overnight and during the middle of the day—the periods between typical usage peaks. Therefore, from a practical standpoint, the important item in tank selection is to size the tank large enough to cover the day's peak event(s).

4.1.5 First-Hour Supply

To understand the first-hour supply results and their implications for product sizing, it is useful to consider them in the context of other storage tank water heaters. Table 9 compares tested results for the shared-circuit and dedicated-circuit products at two setpoints to product specification values for a 240-Volt heat pump, 240-Volt electric resistance tank, and a common-size gas storage water heater with a 38,000 BTU/hr input rate. The table shows that the shared-circuit plug-in product has a limited supply compared to the others, due especially to the distribution of heating throughout the tank. A more comparable supply could be achieved with a setpoint of 150–155° F.[8] Meanwhile, the dedicated-circuit product shows a supply comparable to conventional products at the 125° F setpoint, and higher at 140° F.

Table 9. First-Hour Supply Comparison

Equipment		First-Hour Supply (gal)
50-gal Shared-Circuit Plug-in	125° F Setpoint	42
	140° F Setpoint	56
50-gal Dedicated-Circuit Plug-in	125° F Setpoint	61
	140° F Setpoint	74
50-gal 240V Heat Pump[9]		67
50-gal 240V Electric Resistance[10]		62
40-gal Gas Storage[11]		71

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[8] Consumer water heaters typically do not allow users to select a setpoint higher than 140° F; the use of higher temperatures would require changes to control systems.

[9] Integrated HPWH https://s3.amazonaws.com/WebPartners/ProductDocuments/E0F7330F-87AE-448A-8EE0-E2F0BAC2383D.pdf

[10] Electric resistance https://s3.amazonaws.com/WebPartners/ProductDocuments/A87B2024-2AA9-4626-8DFE-C580A6BA0993.pdf

[11] Common gas storage size and efficiency https://s3.amazonaws.com/WebPartners/ProductDocuments/E08589D2-0E3A-4E5E-94AB-5D497001995B.pdf

Increasing the tank setpoint is not the only way to increase the first hour supply; increasing the tank volume will likewise do so. Increasing the tank from 50 to 65 gallons for the shared-circuit product would lead to an expected 13.5 more gallons of stored hot water.[12] This additional hot water would add to the first draw in the test (there is no second draw in the first hour for this unit). At a 125° F setpoint, the shared-circuit 65-gallon tank could be expected to yield 55.5 gallons. A 140° F storage setpoint and 120° F delivery temperature would yield an estimated 73 gallons.[13]

The tank upsizing strategy, however, runs the risk of exacerbating the problem in cases where it cannot prevent it. Because the plug-in heat pumps do not reheat the top of the tank first, it is important to avoid depleting the hot stratum. If that happens, the user will be without usable hot water until the tank has fully recovered, and that recovery time increases in proportion to the tank volume.

When the first hour rating is dominated by the first draw volume, as is the case with the plug-in products, hot water supply can be considered in terms of equivalent energy storage. A smaller tank at a higher temperature can provide the same amount of useful hot water as a larger tank at a lower temperature. Figure 9 shows the tank volume and temperature equivalence provided in terms of the amount of stored energy required to produce 105° F water with mixing from 58° F inlet water. Figure 9 illustrates that making a 40-gallon tank into a performatively 50-gallon tank (at 125° F) necessitates a setpoint of 142° F.

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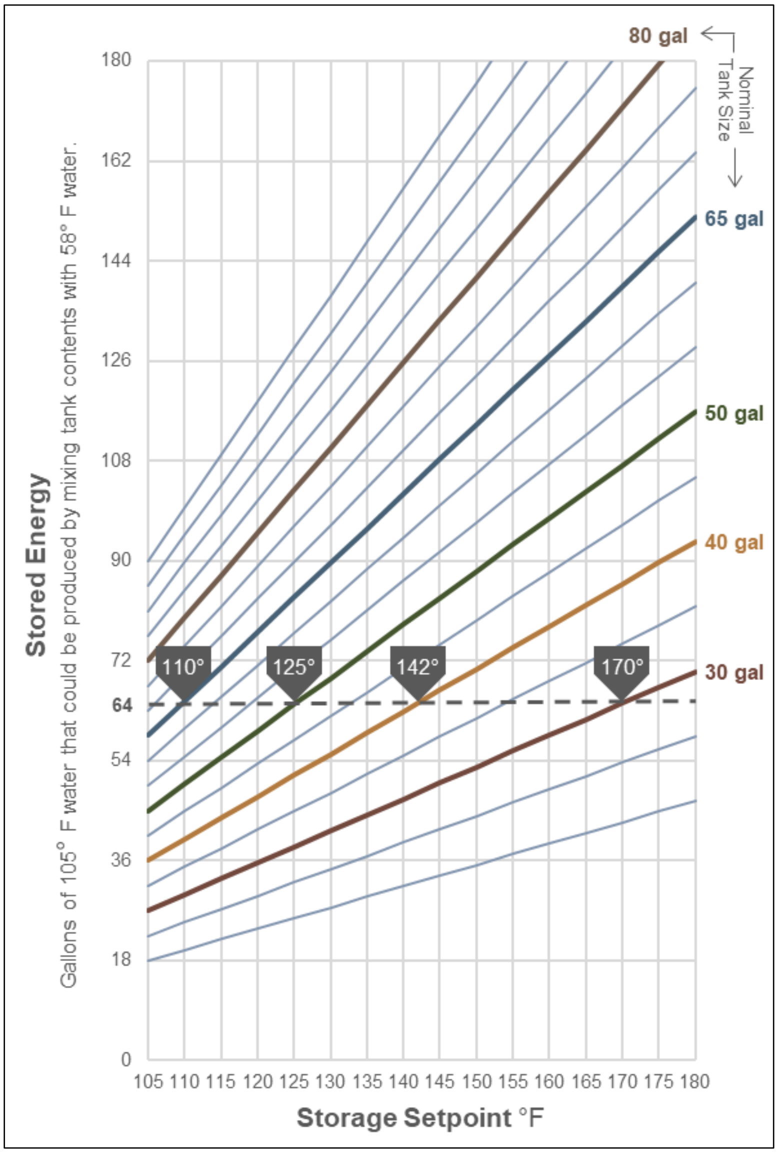
[12] Tanks typically have 10% less actual volume than the nominal volume.

[13] Delivered water setpoint at 120° F to match settings used in lab testing. Note that the 120° F delivery increases the FHR compared to 125° F.

Figure 9. Equivalent Hot Water Storage[14]



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[14] This analysis explores the amount of heat energy stored in the water, which is somewhat higher than what could be practically extracted. As cold water refills the tank during a hot water draw, some of the heated water will mix with the fresh water and cool below a useful temperature. Nevertheless, the chart provides an approximate equivalence of tank size and storage volume that is useful in considering water heater sizes.

4.1.6 Testing Method and Metrics

The results presentation and interpretation indicate the advantages and disadvantages of both the FHR and the One-Plus testing approaches. For water heaters that do not reach 105° F water at the tank top within the FHR test, there is a significant piece of information missing. It could take the water heater 65 minutes or 650 minutes to reach a useful temperature (or fully recover). That information is not reflected in the FHR, nor can it be reliably gleaned from the FHR testing data. Additional metrics that are useful to the consumer, such as R_{105} or R_{125}, provide critical information about low-output-capacity water heater performance. Specifically, an R_{105} of 65 minutes may be entirely acceptable for a use case, but an R_{105} of 650 minutes (over 10 hours) is likely not to be. This clearly demonstrates the usefulness of the additional metrics.

Additional useful tests and metrics could be thought of as a “Two Hour Rating” or “Three Hour Rating,” under which the test is run for that many hours rather than for just one. These data would prove informative for tanks that recover meaningfully within that time. However, slower tank recoveries may still be missed, and it would then be necessary to have a metric defined in terms of time to reach certain tank conditions and not in terms of the tank conditions at an arbitrary time.

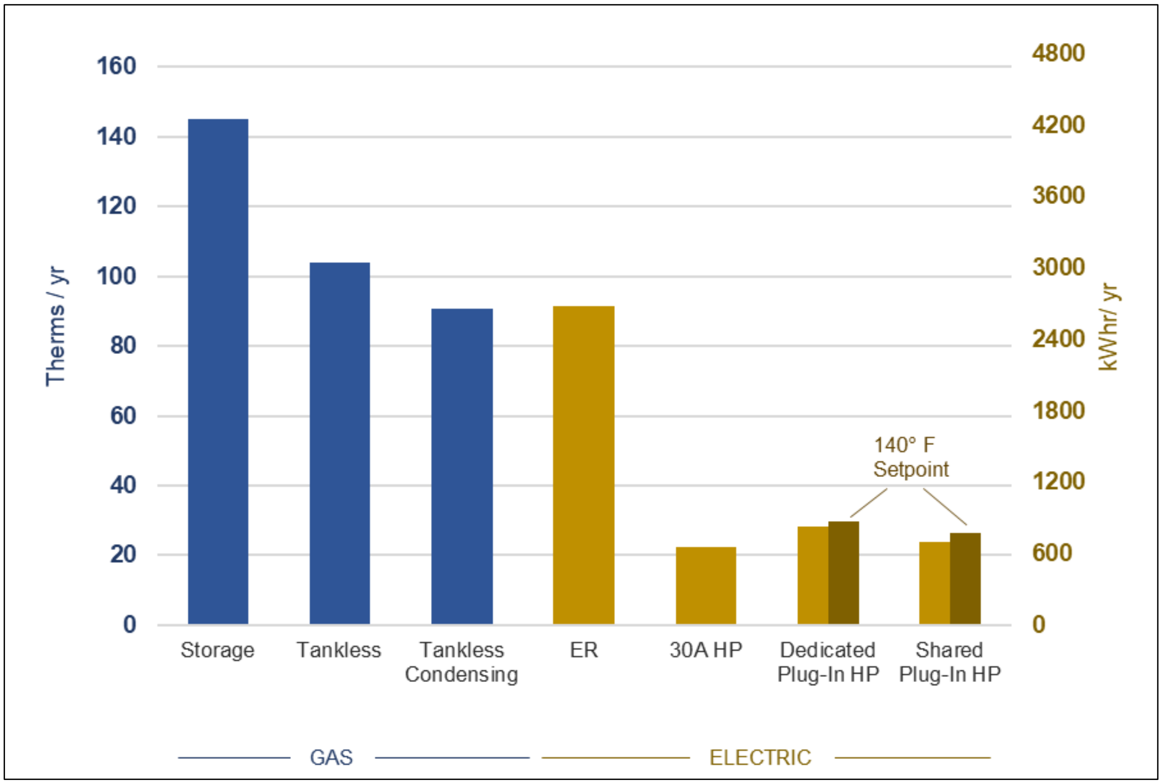
The One-Plus testing method also demonstrates a helpful way to measure output capacity and corresponding efficiency for a given set of operating conditions. This method is similar to measuring the recovery efficiency in the 24-hour simulated use (UEF) test, with the advantage that the One-Plus test is much shorter to run. This allows researchers to quickly compare tank performance across changing conditions. While not comparable to the UEF, One-Plus tests are comparable to one another, so they highlight the advantages and disadvantages of different situations. A drawback of the One-Plus test is that it does not include the lengthy standby periods and varied draw patterns of the UEF test. The result is that the COP from a One-Plus test will be higher than a UEF for comparable conditions (One-Plus has deeper draws which benefit efficiency, and no standby period to lose substantive heat).

The One-Plus test at non-standard ambient conditions provides critical information to those sizing water heater installations in unconditioned locations. If temperatures drop in the winter in a garage install, the recovery time increases. It is also exacerbated by colder inlet water temperatures. Thus, understanding the changes in delivery and output capacity is essential.

4.2 Comparative Energy Use and CO_2 Emissions

Just as it is useful to set the plug-in product first-hour supply in context across water heaters, so too is it useful to compare energy use and, ultimately, CO_2 emissions across products. Both factors prove informative in selecting a water heater, as described in Section 4.3 . Energy-use calculations are conducted in a straightforward manner using the UEF (or similar measured value) to represent energy efficiency. Hot water use is set at 41.5 gallons per day per the DOE Technical Support Document (DOE 2009), and temperature rise is from 58° F to 125° F, which calculates to energy content of 2,500 kWh/yr or 84 therms/yr. Figure 10 shows annual site energy use and includes electric resistance and gas water heating products for reference. The plug-in product energy use is based on preliminary 24-hour testing. The 140° F versions are estimates of slightly reduced efficiency using the observed reduction in recovery efficiency from the One-Plus tests when operating at the higher setpoint.

Figure 10. Comparison of Annual Site Energy Use



CO_2 emissions associated with the water heating energy use are calculated and displayed in Table 10. Energy use for the water heater is determined as calculated previously. The CO_2 emissions factors used for natural gas are 11.7 lb/therm and for electricity correspond to a given regional electric grid. The emissions factors are sourced from Environmental Protection Agency (EPA) eGRID data (EPA 2020). Factors used are the total output emissions from eGRID, which represent the current state of the electric grid, neither marginal emissions nor a future grid. The calculations show HPWHs offer a significant advantage over electric resistance and that once the move to a HPWH has been made, the differences between each type are small.

Table 10. CO_2 Emissions lb/year

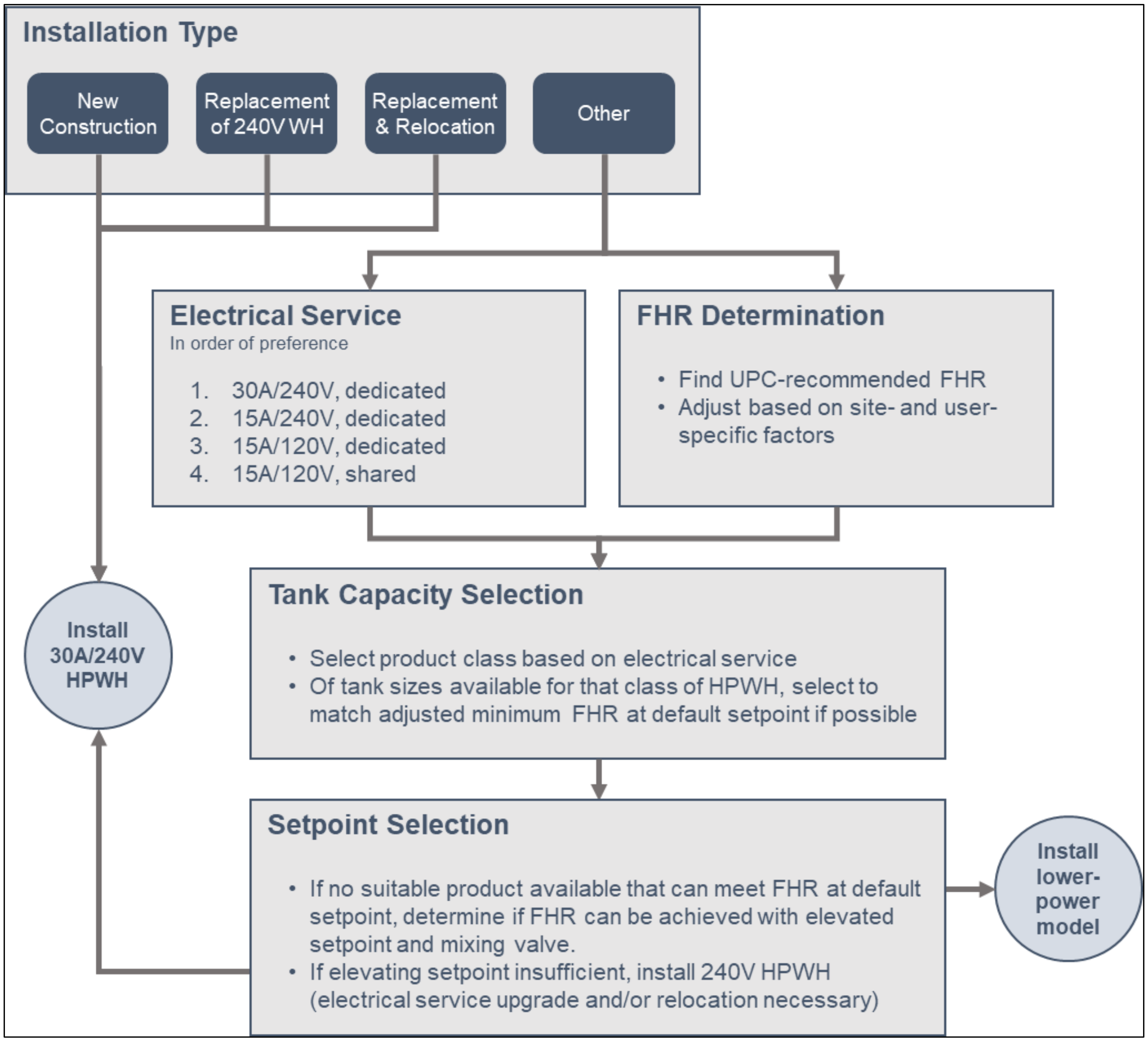
	Gas			Electric					
						Dedicated-Circuit Plug-In HP		Shared-Circuit Plug-In HP	
	Storage	Tankless	Tankless Condensing	ER	30A HP	Default	140° F	Default	140°F
UEF:	0.58	0.81	0.93	0.92	3.75				
NWPP	1698	1217	1060	1713	421	526	444	554	494
CAMX	1698	1217	1060	1331	327	409	345	430	384
MROW	1698	1217	1060	3324	816	1020	862	1074	958
US Average	1698	1217	1060	2540	624	779	659	821	732

Note: NWPP = Northwest; CAMX = California; MROW = Dakotas, Iowa, Nebraska, Minnesota, Western Wisconsin; US Average = the country as a whole.

4.3 HPWH Selection Guide

The differences between conventional 30-Amp, 240-Volt HPWHs and the new plug-in styles dictate a need for guidance in selecting the best option for individual installations. The lack of backup electric resistance (ER) elements and lower heating capacity of the plug-ins add new implications for using FHR as the sole metric of supply sufficiency. In addition, the use of elevated setpoints opens up the possibility to meaningfully change the effective supply without changing the storage tank volume. Figure 11 lays out a recommended decision-making process for the selection of the appropriate style of HPWH.

Figure 11. Selection Guide Overview



Electrical Service (in order of preference):

1. 30A/240V, dedicated
2. 15A/240V, dedicated
3. 15A/120V, dedicated
4. 15A/120V, shared

FHR Determination:

- Find UPC-recommended FHR
- Adjust based on site- and user-specific factors

Tank Capacity Selection:

- Select product class based on electrical service
- Of tank sizes available for that class of HPWH, select to match adjusted minimum FHR at default setpoint if possible

Setpoint Selection:

- If no suitable product available that can meet FHR at default setpoint, determine if FHR can be achieved with elevated setpoint and mixing valve.
- If elevating setpoint insufficient, install 240V HPWH (electrical service upgrade and/or relocation necessary)

The guide considers four styles of HPWH. Where specific performance numbers are considered, they are based on the Rheem product line, as this is the only line with plug-in models available for comparison for this report. The research team believes the guide applies to comparable integrated HPWHs currently available from any manufacturer in the U.S./Canadian market.

- **30A/240V**—A “conventional” HPWH, assumed to have 4.5 kW ER backup
- **15A/240V**—Assumed to have 2.2 kW ER backup
- **15A/120V**—Such as the dedicated-circuit plug-in model discussed in this report
- **7A/120V**—Such as the shared-circuit plug-in model discussed in this report

This guide only provides recommendations for integrated HPWHs; it does not consider split-system, gas-fired or electric-resistance options. Also, while a conventional 30A HPWH will nearly always yield the highest delivery capacity and energy efficiency, the reductions in total energy use and equivalent CO_2 emissions from gas/ER to any HPWH is a more significant improvement than from one HPWH to another. Therefore, the guide prioritizes finding a HPWH that can most easily replace the existing water heater.

4.3.1 Installation Type

Choose a conventional 30A/240V HPWH for any of these situations:

- **New construction**—Follow best practices for install location conditions (Widder and Larson, 2018)
- **Replacement of 30A/240V WH**—Either electric resistance or heat pump
- **Relocation and replacement**—Select and prepare a new install location to accommodate 30A HPWH.

For other situations (for example, if a consumer expresses a preference to replace a gas water heater), achieve the highest delivery capacity and energy efficiency by upgrading electrical service at the existing location or relocating and providing the necessary service to accommodate 30A HPWH. For reduced installation cost, continue with this guide to determine whether a lower-power HPWH (15A/240V, or plug-in) is appropriate.

4.3.2 Electrical Service

Determine HPWH style based on existing electrical service, giving preference to higher power:

- **15A/240V:** Use an existing dedicated 15A/240V circuit, or upgrade an existing dedicated 15A/120V circuit to 240V*
- **15A/120V:** Use an existing dedicated 15A/120V circuit, or dedicate an existing shared circuit to the HPWH (remove all receptacles and loads from the circuit)*
- **7A/120V:** Use an existing 15A/120V circuit

*In accordance with applicable code. Consult with a qualified, licensed electrician.

4.3.3 FHR Determination

Compared to the process for conventional models, sizing a lower-power HPWH should be done with informed caution, especially for models without ER backup. Begin with the UPC recommendation and then adjust the minimum FHR – up or down – based on other factors.

Room Count and FHR							
Number of Bathrooms	1 - 1½		2 - 2½			3 - 3½	
Number of Bedrooms	1	2 - 3	2	3 - 4	5	3	4 - 6
Minimum FHR (Gallons)	38	49	49	62	74	62	74

Other factors:

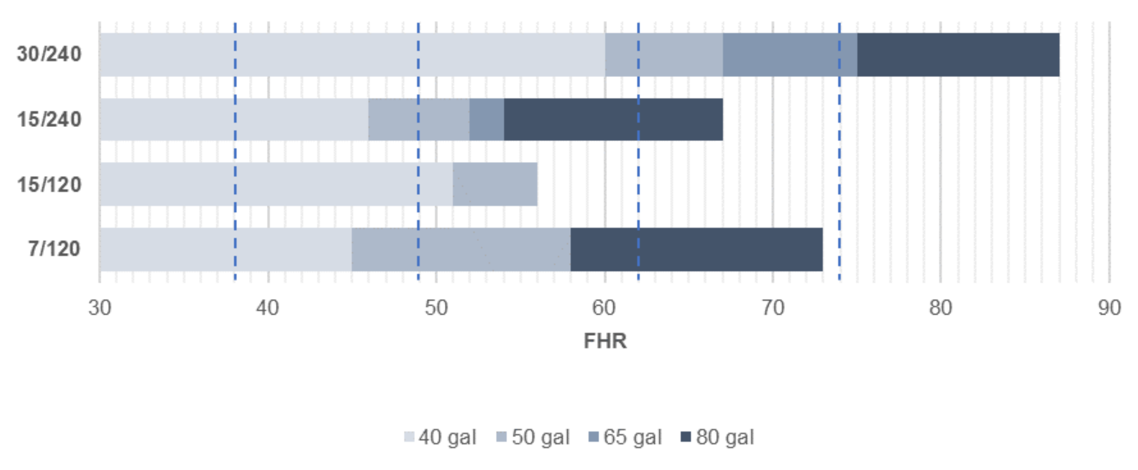
- **Low make-up air supply**: If the install location is an enclosure of less than 700 ft^3 with limited air exchange, expect lower heating capacity. This can be improved by adding additional ventilation paths (wall grilles, door louvers, ducted intake/exhaust) or co-locating with other appliances producing waste heat.
- **Cool ambient conditions**: If the install location will be cooler than 68° F, expect reduced heating capacity. Even if the site is cool only seasonally, the water heater must meet demand at all times of the year. This can be improved by ducting intake air from a warmer location. Lower water inlet temperatures, which often accompany lower air temperatures, will add to heating load.
- **Warm ambient conditions:** If the install location will be warmer than 68° F, expect increased heating capacity. Higher water inlet temperatures will also reduce the heating load. As with cooler conditions, the tank must still be sized to meet demand at all times of the year. Lower temperatures overnight might not be of concern since there is typically plenty of time to fully recover tank temperature.

- **User Factors:** Though the UPC estimates hot water need based solely on number of bedrooms and bathrooms, other factors can be taken into account. Caution should be applied when discounting FHR requirements since these factors often change within the life cycle of a water heater.
  - Users: How many people use hot water in the dwelling?
  - Draw profile: Is hot water use highly time-concentrated or more distributed across the day?
  - Habits: Do users take frequent baths? Longer, hotter showers than average?
  - Fixtures: Are low-flow fixtures installed at sinks and showers? If not, consider upgrading.
  - Appliances: Dishwasher vs. hand-washing? Front-loading or cold-water clothes washer?

4.3.4 Tank Capacity Selection

Use this chart (Figure 12) to determine minimum tank size based on adjusted FHR minimum and style of HPWH (UPC thresholds highlighted with dashed lines for reference). If the adjusted FHR minimum is near the limit of a tank size's rating, go to the next size up if possible; costs of upsizing are negligible compared to the dissatisfaction of hot water depletion.

Figure 12. Typical HPWH FHR by Power Input and Tank Volume



4.3.5 Setpoint Selection

If the largest available tank size of the selected HPWH style has an insufficient FHR, increasing the water storage setpoint above the factory setting may sufficiently increase supply.

Also, if the smallest sufficient tank model does not fit in the install location, a smaller tank with an increased setpoint may produce a sufficient supply. If not, relocation of the water heater becomes necessary, and the new location should be prepared to accommodate a 30A HPWH.

Notes:

- Raising setpoint requires the use of a mixing valve for user safety.
- Increasing setpoint significantly affects the first-hour supply but will not decrease recovery times.
- Higher storage setpoints can decrease tank life.

5 Conclusions

Testing results and data interpretations provide the following conclusions:

- The first-hour hot water supply of plug-in products can be limited compared to their more conventional counterparts due to the challenge of providing heat just to the top portion of the tank. Under standard test conditions, the first hour supplies are:
  - 50-gallon Plug-In Shared: 42 gallons
  - 50-gallon Plug-In Dedicated: 61 gallons
  - 50-gallon Conventional HPWH 240V: 67 gallons
  - 40-gallon Conventional Gas Storage: 71 gallons
- Elevated setpoints (e.g. 140° F) can effectively increase the stored energy and first-hour supply:
  - 50-gallon Plug-In Shared: 56 gallons
  - 50-gallon Plug-In Dedicated: 74 gallons
- Elevated setpoints decrease efficiency but by only 3%–8%. Because the decrease is small, raising the setpoint is an effective strategy to boost supply. This can be especially useful in space-constrained locations where installing a larger size tank is not possible. Further, if an installed water heater turns out to be insufficient for the occupants' needs, increasing the setpoint somewhat can be a post-installation solution, assuming a mixing valve is in place.
- Ambient air temperature has a significant impact on recovery time and efficiency.
  - The effect is an important consideration when sizing the product for installs.
  - The FHR metric is not particularly useful for understanding the impact of ambient air temperature when the water heater output capacity is limited. Instead, metrics such as R_{105}, R_{125}, and R_{140} can be more informative.
- The first-hour supply/rating may not provide enough information for plug-in products to size the unit due to the extended recovery durations. The peak demand may be met in the first hour, but useful hot water is not available again for up to several hours depending on the product. Therefore, a two- or three-hour rating test or a metric such as R_{105} may be more valuable and worth exploring in future water heater comparisons. Further, a first draw metric may also be valuable in understanding the water heater full delivery profile.

- The importance of not running out of hot water is magnified for plug-in products since the recovery time for useful hot water can be lengthy, underscoring the need for a tank large enough that the top hot water layer is not depleted. If hot water remains, the user will not notice any issues and the water heater can reheat the cold portion of the tank at its leisure. This sizing practice can work for typical usage patterns that have larger peaks and time in between to reheat.
- HPWH selection is influenced by several factors of the installation location, including electric circuit availability, and should be informed by the lab findings described previously.
    - Wherever practical to install, a 240V HPWH will provide the best user experience. Where electric circuit capacity is limited, select a water heater with the highest possible remaining power input allowed.
    - Next, identify the FHR sizing recommendation for the household and select a tank to meet those needs. Consider possible effects that may reduce the FHR in colder conditions or specific installation scenarios.
    - If a tank at a standard setpoint is not able to meet the need, consider increasing the storage setpoint with a mixing valve installed.

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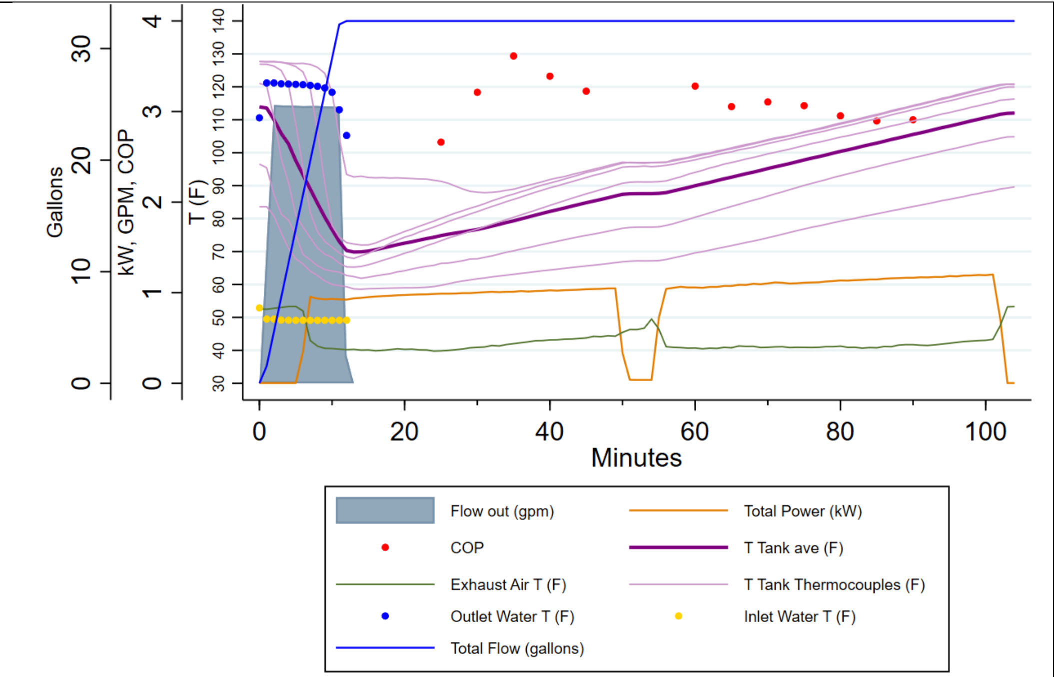
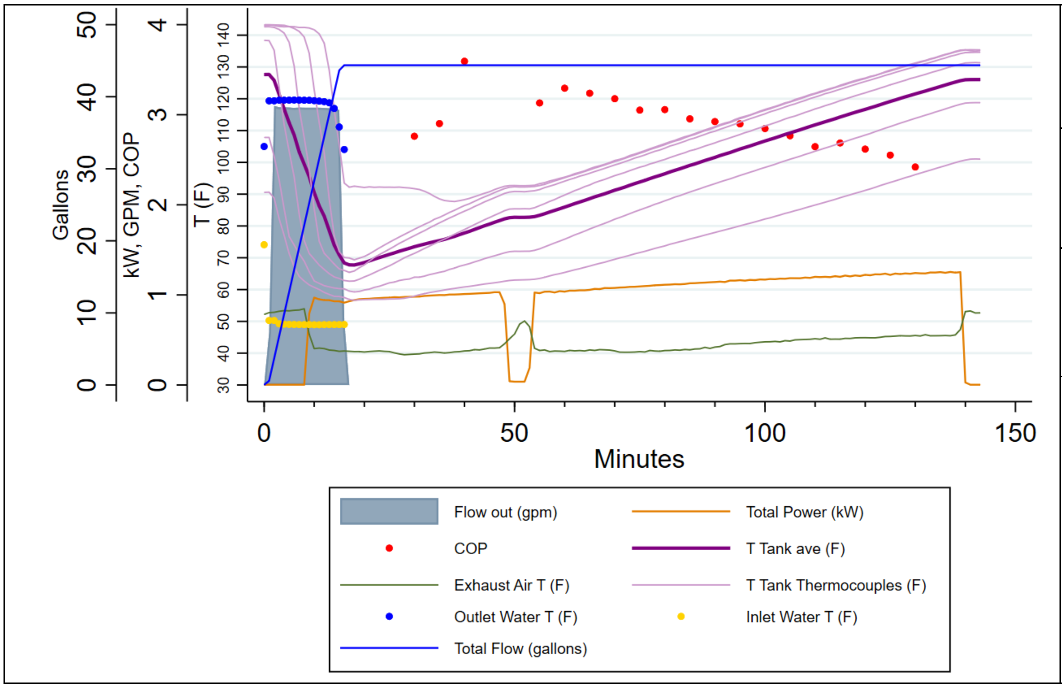
Appendix A: Test Graphs

Figure 13. Dedicated-50F-Lo Test



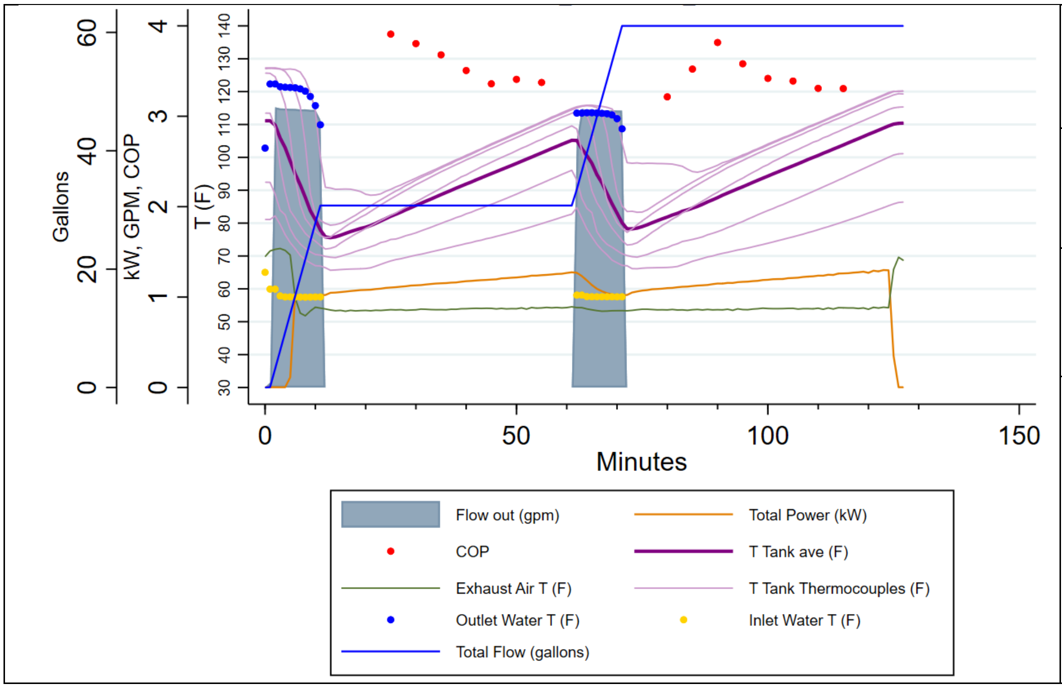
Supply	32.5
Recovery Efficiency	2.9
Recovery Time	
R_{105}	78
Full	100

Figure 14. Dedicated-50F-Hi Test



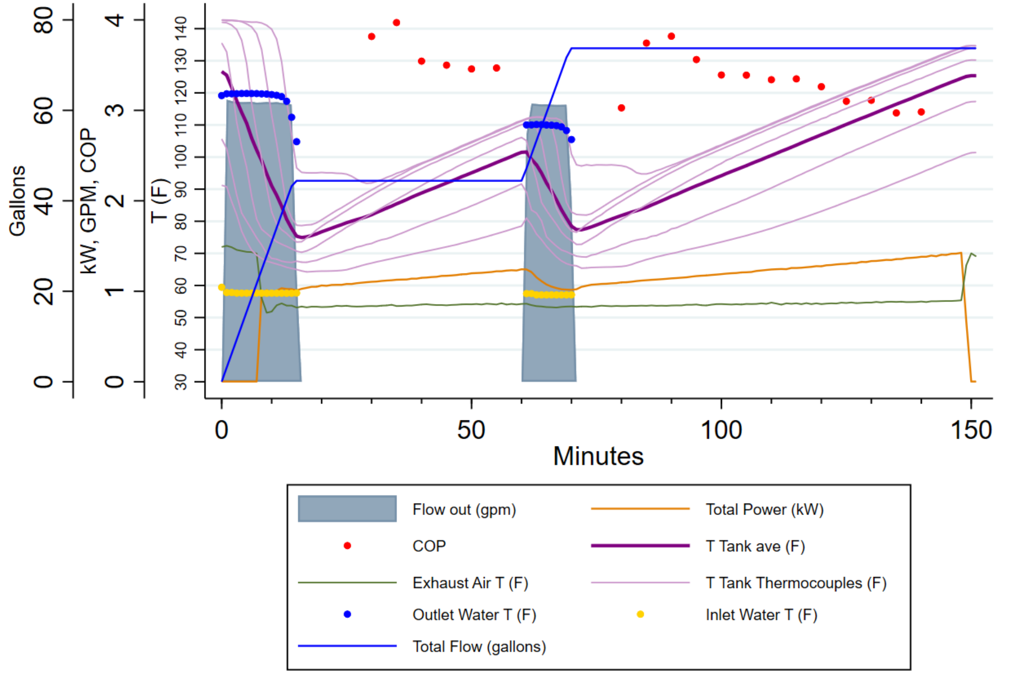
Supply	
44.4	
Recovery Efficiency	
2.8	
Recovery Time	
R_{105}	78
Full	140

Figure 15. Dedicated-68F-Lo Test



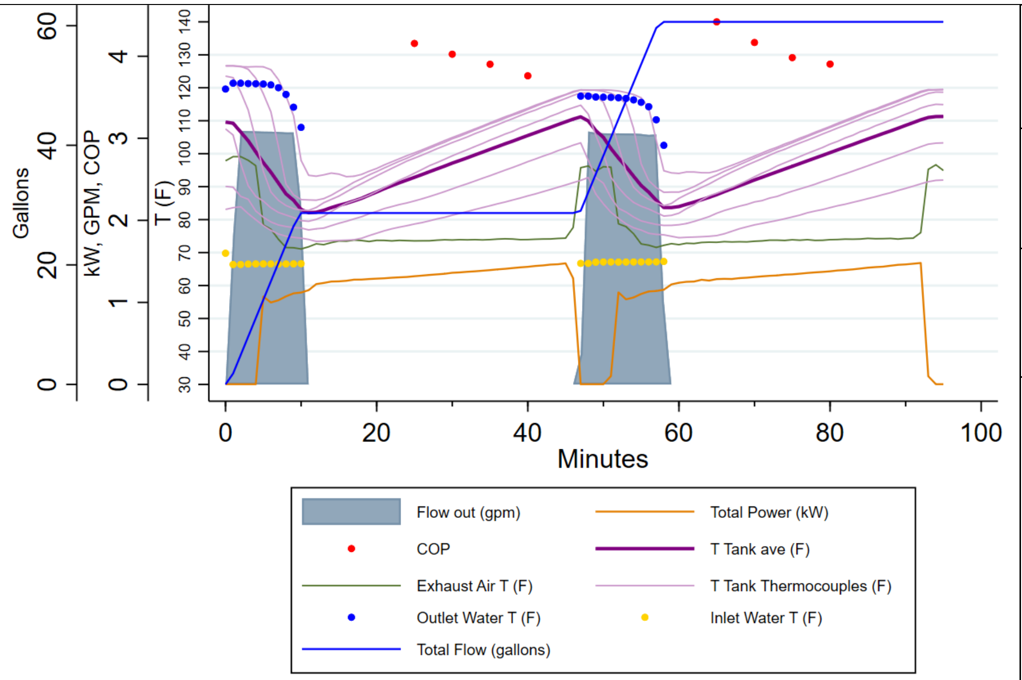
Supply	
61.1	
Recovery Efficiency	
3.4	
Recovery Time	
R_{105}	34
Full	62

Figure 16. Dedicated-68F-Hi Test



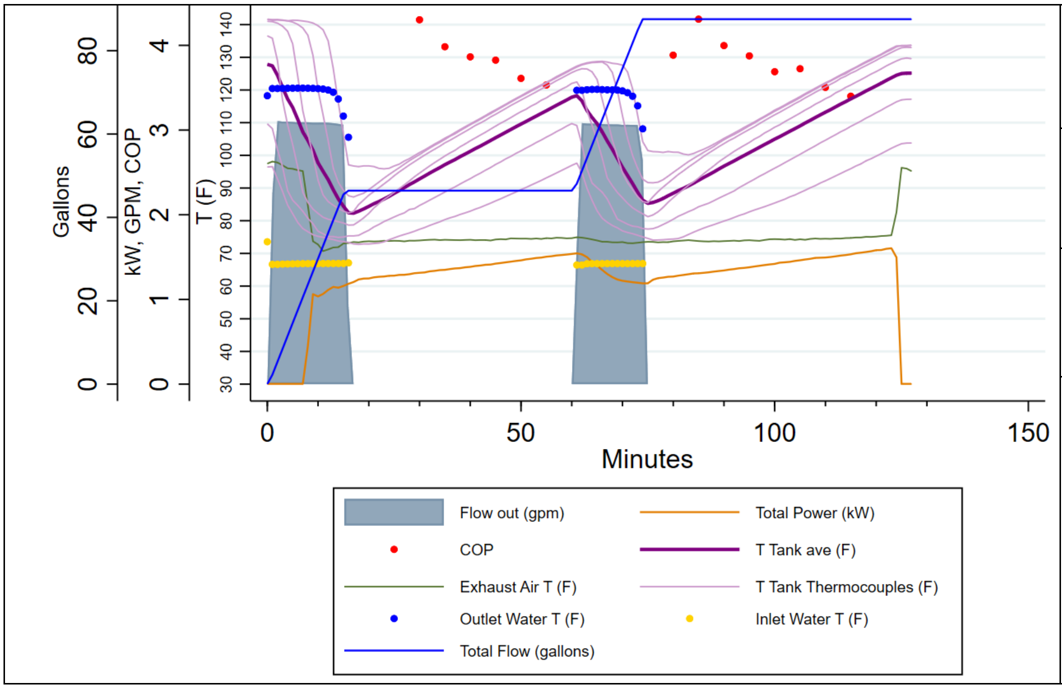
Supply	73.7
Recovery Efficiency	3.3
Recovery Time	
R$_{105}$	34
Full	80

Figure 17. Dedicated-95F-Lo Test



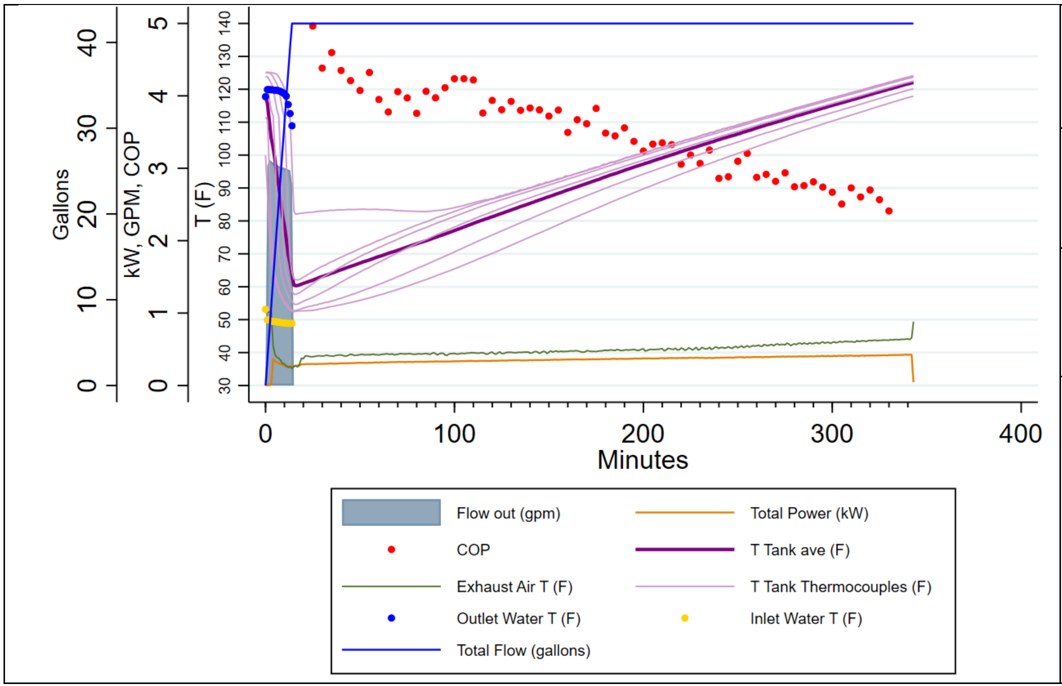
Supply	60.6
Recovery Efficiency	4.0
Recovery Time	
R$_{105}$	18
Full	39

Figure 18. Dedicated-95F-Hi Test



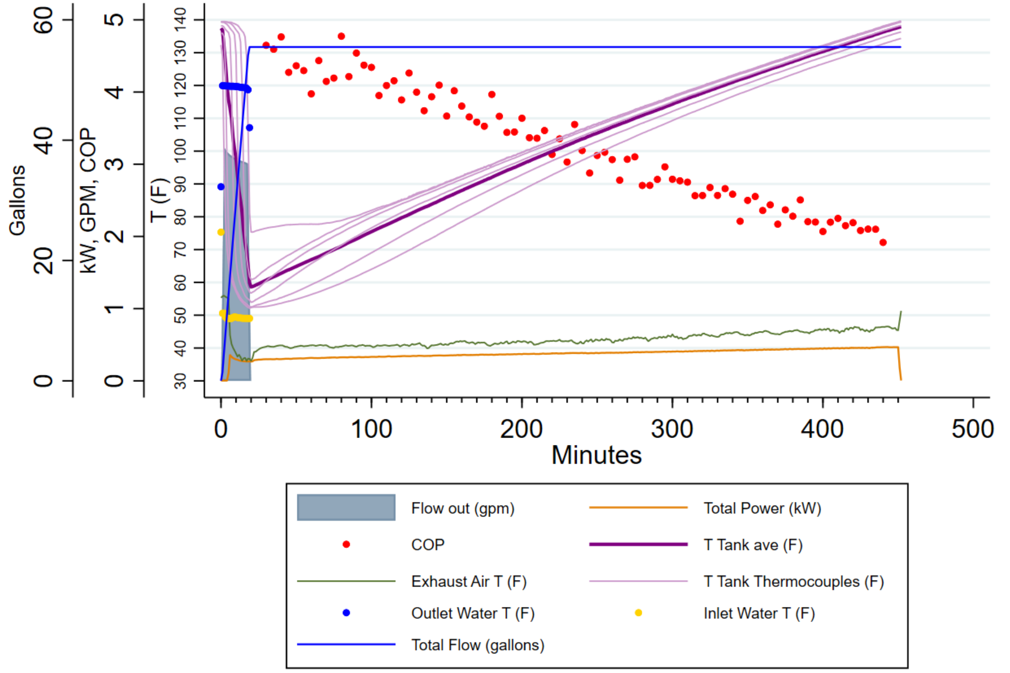
Supply	87.6
Recovery Efficiency	3.7
Recovery Time	
R_{105}	18
Full	52

Figure 19. Shared-50F-Lo Test



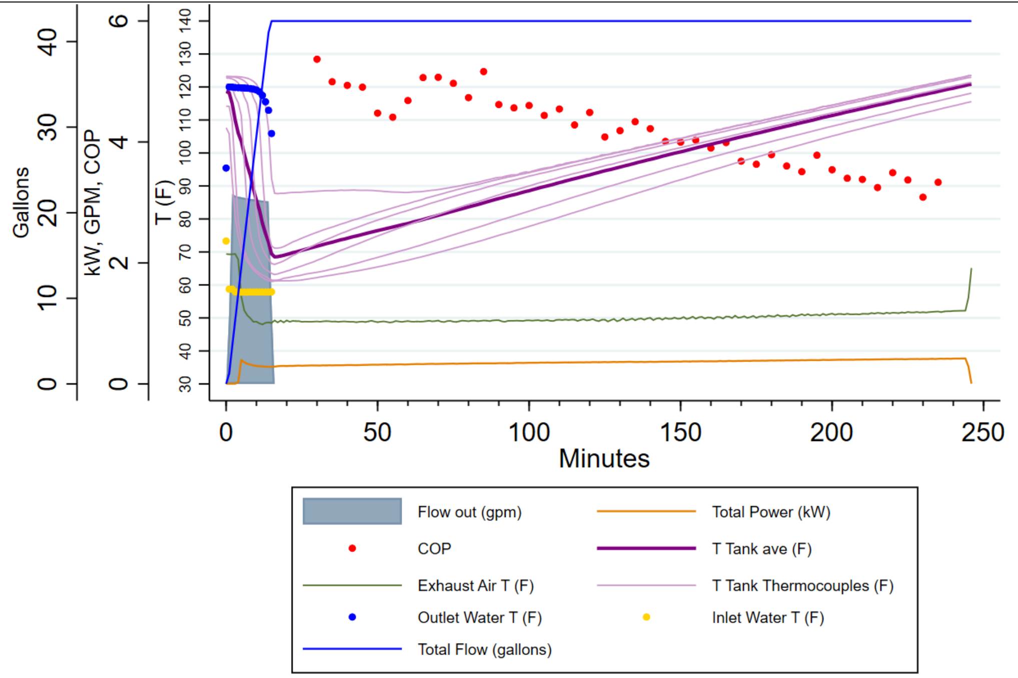
Supply	42.2
Recovery Efficiency	3.3
Recovery Time	
R_{105}	231
Full	334

Figure 20. Shared-50F-Hi Test



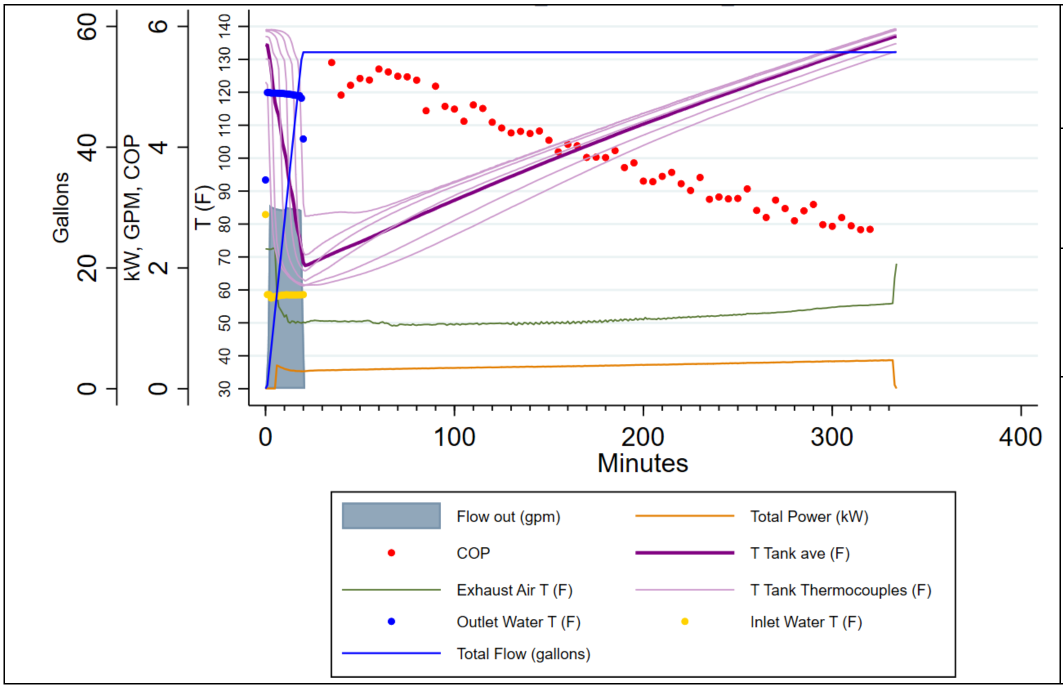
Supply	55.5
Recovery Efficiency	3.1
Recovery Time	
R_{105}	231
Full	449

Figure 21. Shared-68F-Lo Test



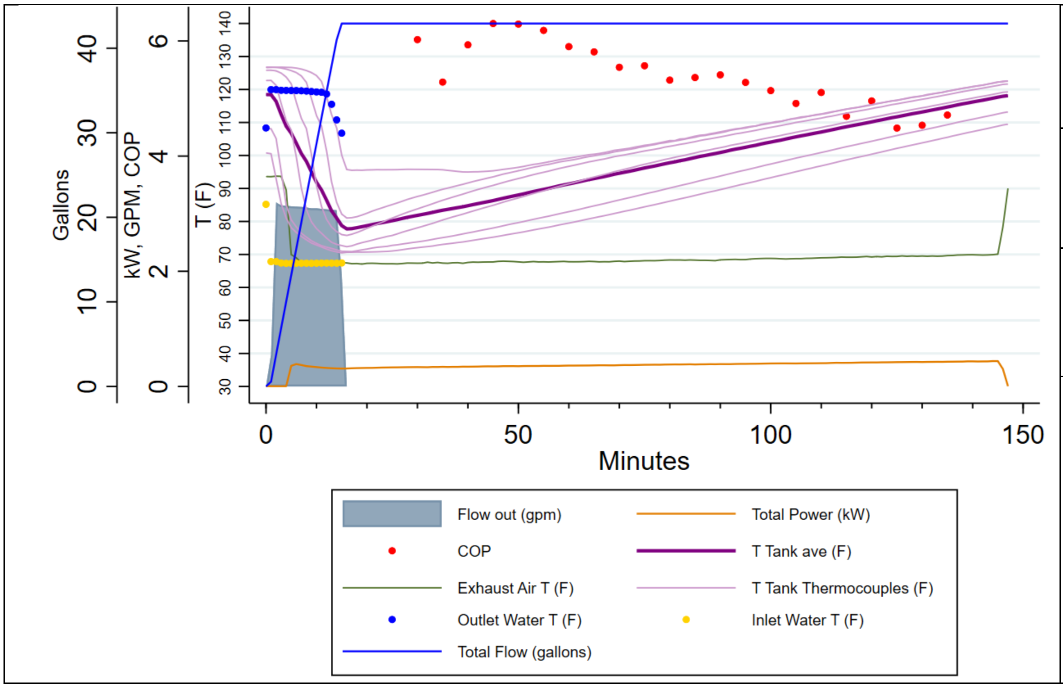
Supply	42.4
Recovery Efficiency	4.0
Recovery Time	
R_{105}	159
Full	237

Figure 22. Shared-68F-Hi Test



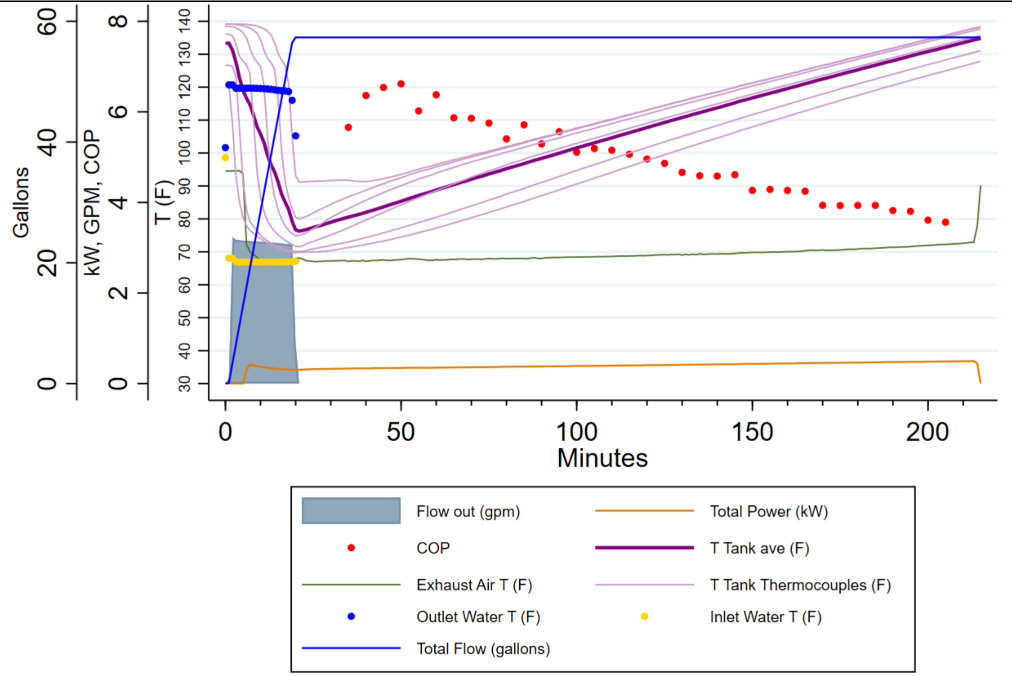
Supply	
55.7	
Recovery Efficiency	
3.7	
Recovery Time	
R_{105}	159
Full	331

Figure 23. Shared-95F-Lo Test



Supply	
42.9	
Recovery Efficiency	
4.9	
Recovery Time	
R_{105}	93
Full	143

Figure 24. Shared-95F-Hi Test



Supply	
57.3	
Recovery Efficiency	
4.6	
Recovery Time	
R$_{105}$	93
Full	212