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Heat Pump Water Heaters in Small Spaces Lab Testing: "The Amazing Shrinking Room"

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Summary Brief

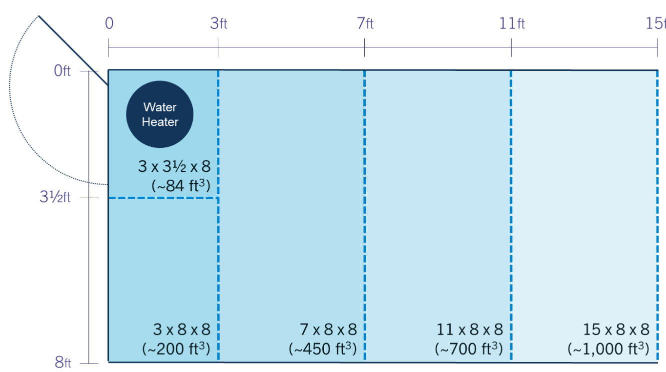
Heat pump water heaters (HPWHs) draw thermal energy from the surrounding air to heat water. When a water heater draws heat more quickly than it can be restored, the thermal resource is depleted and the efficiency of the appliance drops. To prevent or limit this effect, current practice recommends that HPWHs not be installed in closed rooms of less than 700 ft^3 or, when they are, to make accommodations for air exchange to restore the thermal resource. Thermal resource depletion and amelioration techniques are well known and conceptually understood; however, little research exists on the degree of their effects. If current practices are insufficient to address the issue, installed HPWHs are not achieving their expected efficiencies. If current standards are too conservative, a significant opportunity for HPWH retrofit installations may not be sufficiently addressed.

This project was undertaken to provide quantitative detail that is missing from current understanding of HPWH efficiency in small spaces. The project team of Larson Energy Research and Cascade Engineering Services, funded by the Northwest Energy Efficiency Alliance (NEEA), performed laboratory testing to better answer two fundamental questions:

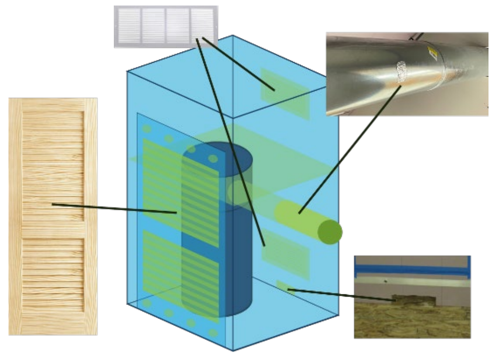
- How does the volume of an enclosed installation room affect HPWH efficiency?
- How effective are different interventions at restoring efficiency compromised by a small enclosure?

The research is designed to explore what happens in the scenarios described not only by the manufacturers but also scenarios inspired by real field installations. A desired outcome is to share solutions that work (and identify those that do not) with manufacturers and HPWH installers to provide useful, actionable guidance.

Research Method



The project team constructed a room that could be adjusted to various volumes, from 1,000 ft^3 (8 x 15 x 8 ft) to as little as 84 ft^3 (3 x 3½ x 8 ft): The Amazing Shrinking Room. The project team also built the room in a way that could be modified to apply various interventions intended to improve air exchange with the surrounding space —for example, by opening ventilation grilles or ducting exhaust out of the room. Simulated-use testing, over an 18-hour period was performed on a HPWH installed inside that room and its efficiency was compared among different room configurations.



Variable Enclosed Room Volume Findings

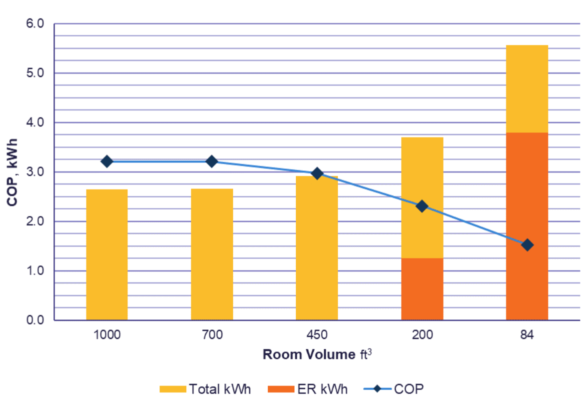
One set of tests investigated how the volume of a closed room affects HPWH efficiency. These were compared to baseline tests during which the HPWH had an unlimited supply of makeup air.

Shrinking the Shrinking Room

84 ft^3 Room Size

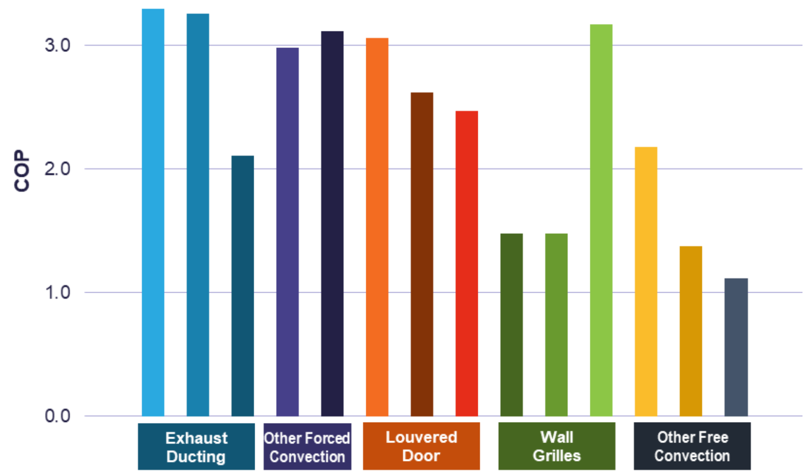
Data Logging and Flow Control

The results show that even at the largest tested volume, 1,000 ft^3, efficiency is lower than the baseline. As volume decreases, so does the efficiency, but very gradually at first. It is not until somewhere between 450 and 200 ft^3 that the decrease accelerates. That more significant drop is due to the use of electric resistance heating triggered by a lowering of the air temperature below the minimum operating temperature of the heat pump compressor.



Despite the depressed efficiency in the enclosed room, **the 450 ft^3 test produced a coefficient of performance around 3**. While this is measurably lower than the equipment's potential in more favorable conditions, it is only 7% lower than efficiency at the commonly specified 700 ft^3 minimum and still factors higher than any non-heat-pump-based water heater.

Interventions Findings



Another set of tests investigated the effectiveness of various interventions intended to improve efficiency in small installation rooms by encouraging air exchange to replenish the HPWH's thermal resource. These interventions included both common methods and novel approaches, and both free- and forced-convection designs.

Tests identified several practical ways to achieve efficiencies in a closet-size room on par with an installation meeting specified minimum requirements. Those interventions include both free-convection methods, such as the addition of wall grilles, and forced-convection methods, such as exhaust ducting.

Tests also revealed important characteristics that distinguish the successful interventions from the less successful:

- Successful free convection necessitates a minimum total open area available for air to pass through. Some of this open area must be located high in the room and some low.
- Successful forced convection requires sufficient airflow across the heat pump's evaporator. This means resistance to flow—such as longer ducts, elbows, and terminations—needs to be minimized.

Implications and Recommendations

Overall, the project shows HPWHs can be effective solutions in smaller spaces than what is generally understood at present. This indicates greater opportunity for HPWH installations.

When installing a HPWH, the project team always recommends first consulting and following manufacturer instructions. Next, the project team makes the following recommendations based on its investigation:

- **An enclosed room should be considered too small for a HPWH only when it causes electric resistance heating under typical load.** Research indicates this volume is less than 450 ft^3, and manufacturers should consider reducing minimum recommended installation room volumes to this level.
- If the volume of a room does not cause electric resistance heating, interventions to improve efficiency are not needed. It is unlikely that their benefit could justify their cost.

- **If applying a forced-convection intervention, ensure an adequate airflow rate.** In particular, this means that one of the most commonly recommended approaches, ducting, deserves careful scrutiny and reconsideration. Given the comparable effectiveness and lower cost of other interventions, ducting might be the best choice in only a small share of cases.
- **If applying a free-convection intervention,** include at least 300 in^2 of net free area, divided between upper and lower positions.

Acronyms and Terminology

- ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers
- CFM: cubic feet per minute
- COP: coefficient of performance, or equipment efficiency
- DOE: Department of Energy
- ER: electric resistance. Backup heating elements in the water heater.
- ERWH: electric resistance water heater
- FHR: First Hour Rating
- Forced convection: the movement of air resulting from a fan
- Free convection: the movement of air resulting from buoyancy forces due to density changes arising from a heating process
- GPM: gallons per minute
- HPWH: heat pump water heater (in this report, specifically integrated hybrid heat pump water heaters with back-up ER heating elements)
- IECC: International Energy Conservation Code
- kWh: kilowatt-hour
- NFA: net free area, open area
- Pa: Pascal, One Newton per metered squared
- UEF: Uniform Energy Factor

1 Introduction

A significant barrier to mass adoption of integrated heat pump water heaters (HPWHs) is that the electric resistance water heaters (ERWHs) they could replace are sometimes installed in locations that are less suitable to HPWHs. While the most common installation cases—garage, basement, large mechanical/laundry rooms, and new construction—do not present this barrier, a considerable opportunity remains for retrofitting HPWHs in smaller rooms. In detached new residential construction, HPWHs in small spaces can be planned not to exist at the design phase. In new multifamily residential construction, however, many of the techniques explored in this report can be used.

Fundamentally, this research seeks to understand what happens when HPWHs are installed in these small spaces, and which installation methods can ensure adequate performance. Important questions to answer include:

- Do they operate at all?
- With what efficiency?
- Is hot water supply compromised?
- How cold does the small space get?
- Can performance be improved by modifying the installation space?

All three of the major manufacturers of HPWHs in the North American market currently recommend a minimum installation room volume of 700 ft^3 before some intervention is needed (AO Smith 2019, Bradford White 2021, Rheem 2022). Below that size, manufacturers provide methods to increase airflow to the install space (AO Smith 2019, Bradford White 2021, Rheem 2022). This lab testing is designed to explore what happens in the scenarios described not only by the manufacturers but also scenarios inspired by real field installations, with a desired outcome of sharing solutions that work (and identifying those that do not) with manufacturers and HPWH installers to provide useful, actionable guidance.

1.1 Background

HPWHs extract heat from the air surrounding them to heat water. When installed in a small enough space, the heat pump can deplete the thermal resource of the ambient air more quickly than it is replenished. This cools the surrounding air and reduces the heat pump efficiency. In the worst case, if temperatures fall below the compressor operating range, the heat pump will turn off completely. In the favored installation locations for water heaters, such as garages, basements, and other spaces with large air volumes, the thermal resource is almost always sufficient for efficient HPWH performance.[1] A thermal resource adequacy concern does arise with installations inside the insulated and conditioned zone of a house if the water heater is located in a smaller room, such as a mechanical room, laundry room, or closet.

While the mechanics of this problem are well understood and the recommendations for addressing it are conceptually sound, little research into the degree of effects has been published. A literature search by the project team yielded scant public material on the topic. Further, manufacturers have reduced the recommended minimum installation room volume over time: Ten years ago 1,000 ft^3 was common, but current specifications are typically 700 ft^3 (Rheem 2013, Rheem 2022). An obvious question to ask is: "Can the volume go lower still?" In the matter of methods used to increase ventilation (including ducting and adding grilles), the project team found no reports of quantitative effectiveness. These interventions are typically applied in the field, case-by-case, and as needed. Because of that, their effectiveness is rarely measured in detail and it prevents the results from informing other interventions for other or different cases.

To date, HPWH manufacturers have addressed the small space problem in two ways: first, by requiring a minimum room volume for installation, and second, by suggesting methods for increasing airflow through a smaller room.

The Rheem Use & Care Manual states that in rooms larger than 700 ft^3, no interventions are needed and that "Installation in a confined space will lead to higher power consumption if adequate ventilation is not provided" (Rheem 2022). Rheem further states, "If air temperature in installed location drops more than 15° F during heating, air circulation is insufficient for efficient operation." Rheem provides several clear options for installing in "locations that provide optimal efficiency."

1. Install a fully louvered door or a door with upper and lower louver panels. No dimensions for louvered area or net free area (NFA)[2] are given.
2. Undercut the door to provide an 18 in^2 opening, install a louver panel in the upper portion of the door at the same height as HPWH exhaust, place HPWH within one foot of louver panel, and direct the exhaust (at a 45° angle or less) at the panel.
3. Undercut the door to have a minimum 18 in^2 air gap, and duct the intake or exhaust from or to another space.
4. Duct both the intake and exhaust from and to another space.

[1] During the winter in moderately cold climates, such as International Energy Conservation Code (IECC) Zone 5, garage air temperature may drop below the compressor operating temperature. In colder climates, such as IECC Zone 6 and colder, water heaters are rarely installed in garages because the winter air temperatures are unsuitable to any water heater due to risks of frozen pipes.

[2] Net free area (NFA) is the total opening area that air is able to pass through. Louvered doors, ventilation grilles, duct terminuses, and other ventilation components have blades, mesh, or other impediments to airflow. NFA measures only the open, or free, area of a component. For example, the wall grilles used in the testing described in this report had louvered sections measuring 8 by 24 inches, or 192 in^2. However, because the individual louver blades themselves have area, only 130 in^2 is open for the passage of air. The NFA, therefore, is 130 in^2, or 68% of total area.

The Bradford White Installation & Operating Instruction Manual states the “unit is designed for any common indoor installation in a space with at least 700 ft^3” (Bradford White 2021). The manual continues, “It can be installed in rooms smaller than 700 ft^3 with the installation of a louvered door, or two louvered sections.” The manual specifies the louvers should provide at least 240 in^2 NFA. Like Rheem, the Bradford White manual also notes that if the air temperature in the installed location drops more than 15° F during heating, air circulation is insufficient for optimum performance. The manual then directs the installer to use a ducting kit to convey exhaust air to a different location. Similarly, the manual cautions that failing to provide adequate air exchange will result in increased energy use. Finally, the manual states to avoid discharging the exhaust against a wall.

As with the others, the AO Smith Use & Care Guide states “For optimal water heater efficiency, the unit must have unrestricted airflow and requires a minimum of 700 ft^3” (AO Smith 2019). The guide also states that unless adequate provisions are made for air exchange (vented or louvered doors, etc.), the unit should not be placed in a small closet or enclosure (AO Smith 2019). The guide does not, however, provide specific room volumes or NFA requirements.

NEEA has an objective to save energy and cost in domestic water heating. HPWHs represent a significant opportunity for such savings, but they must be installed in locations that allow them to achieve high efficiency. Understanding the “small space install problem” can inform the market and NEEA’s actions in this area. If current recommendations for minimum room volume or ventilation are too conservative, they may be unnecessarily deterring HPWH installations or increasing their cost. Improving these recommendations would increase the opportunities for retrofit installations. On the other hand, if those recommendations are insufficient, then some installed HPWHs are not realizing their full savings potential.

1.2 Research Questions

To address this potential barrier to HPWH installation, the project team poses two basic research questions, with additional subparts to each:

- How does room volume affect efficiency?
    - At what volume does room size lower efficiency?
    - How much does limited volume lower efficiency?
    - How much does hot water usage affect those results?
    - At what room size, or position within a room, does the exhaust air recirculate to the air intake?
- How effective are different interventions at improving efficiency?
    - How well do common interventions work?
    - Are there novel interventions that work better?
    - How do passive and active venting interventions compare?

1.3 Research Method

To evaluate the research questions, the project team, consisting of Larson Energy Research and Cascade Engineering Services, constructed a test room configurable to different sizes and airflow regimes. This “shrinking room” was built inside a large lab space conditioned by a customary commercial HVAC system. A HPWH was installed inside the room and subjected to 18-hour hot water draw profiles. The temperature inside the test room was not conditioned, allowing it to respond directly to HPWH operation. Total hot water energy out and total energy input was measured. The quotient of the two is the equipment efficiency, or COP. Draw profiles were run at each configuration and efficiency was compared to understand how each configuration affected performance.

2 Test Method

To answer the two primary research questions, the test team performed two groups of tests. The first varied the room size but kept all ventilation openings sealed, and the second varied the ventilation techniques. The fundamental test procedure for both groups was the same, except as described in Section 2.6 .

2.1 Water Heating Equipment

The heat pump water heater used in the project was the AO Smith HPTU 50 (AO Smith 2022), a 50-gallon HPWH that has been in production by AO Smith for over five years. When it debuted, the product was previously evaluated under a separate NEEA project (Kvaltine 2015). The HPWH has the following specifications:

- UEF (Uniform Energy Factor): 3.45
- FHR (First Hour Rating): 66 gal.
- Upper resistance element power: 4500 W
- Lower resistance element power: 4500 W
- Water connection location: Side
- Height 63”
- Diameter 22”
- Airflow path: Intake on top. Exhaust to right side (when facing control panel)

The HPTU 50 has several user-selectable operating modes that govern when the heat pump and resistance elements turn on. In the test, the HPTU 50 was operated in its “Hybrid” mode. This is the default, as-shipped mode and is described in the manual thus: “This mode uses the heat pump as the primary heating source. One of the heating elements (upper or lower) will provide supplementary heating if demand exceeds a predetermined level so that the set point temperature can be recovered more quickly” (AO Smith 2022). Previous lab investigations have shown that, in Hybrid mode, when the ambient air conditions are outside the compressor operating range the heat pump will turn off and the resistance elements will turn on to heat the water. In this case, the resistance elements provide replacement heating, rather than supplementary heating. With the compressor off, the evaporator fan continues to run to pass warmer air over the evaporator. After the ambient temperature is again within the operating range, the compressor will turn on again.

Other HPWH products on the market have somewhat different operating mode strategies and compressor operating ranges. Those specific differences will lead to somewhat differing responses in the testing. However, the controls of different models are more similar than not, which leads the project team to conjecture that the actionable findings from studying a different water heater would be similar to those of the one studied here.

2.1.1 Cooling Capacity

A fundamental physical phenomenon underlying the study is the air-cooling effect of the HPWH. While the total amount of cooling during the test depends mainly on the usage (the hot water draw profile),[3] the rate of cooling depends mainly on the heating capacity of the water heater (the heat pump system size). The integrated HPWHs currently on the market may be roughly categorized as having “one-third ton” compressors (Kvaltine 2015, Larson 2015, Kintner 2021). That is, they provide 4,000 Btu/hr of water heating. The air-cooling capacity, while correlated to water-heating capacity, is lower due to the share of energy used to turn the compressor motor. Over a typical tank heating cycle with ambient air of 67° F and 50% relative humidity, air-cooling capacity averages 3,000 BTU/hr.[4]

The HPWH products available from the largest manufacturers (AO Smith, Bradford White, and Rheem) have similar heating capacities (Kvaltine 2015, Larson 2015, Kintner 2021). Therefore, although this study examined one specific HPWH from AO Smith, the findings about the impacts of the air-cooling effect are generalizable to the other makes and models currently on the market.

2.2 Shrinking Room Characteristics

2.2.1 Construction

In constructing the shrinking room, the project team intended to create a space similar to one that would exist in many house interiors. Such a room is likely to be uninsulated and may have little air exchange with the rest of the house. The test room was built to resemble typical light-frame, residential construction. The front and side walls are wood-framed with 2x4s and sheathed with ½-in drywall on both sides. The ceiling was built with 2x6s and similarly sheathed with drywall. The back wall of the room is made from rigid foamboard (two inches thick with R-10 total insulating value) so it can be easily repositioned. This bulkhead wall contains openings that can be sealed depending on test requirements. Additionally, a 3' removable foamboard wall can be fitted perpendicularly to both the front wall and bulkhead to form the smallest space configuration. In one test, the bulkhead and removable wall were switched, creating a room that was deep instead of wide. The floor is covered with ¾” oriented strand board (OSB) to resemble a built-up residential floor construction and create a barrier for radiant heat transfer from the lab floor.

[3] A somewhat analogous test would consist of placing a small air conditioner in the enclosed space and operating it on a predetermined schedule to simulate a fixed amount of cooling and then observing the air temperature profile in the space over time.

[4] Over the duration of the cycle, capacity can exceed 4,000 Btu/hr at the beginning when the water being heated is cooler. Capacity decreases as the compressor successfully heats the stored water and can be under 2,000 Btu/hr at the end of the cycle. In an enclosed space where the HPWH cools the air surrounding it, this means that the rate of cooling decreases even as the temperature continues to drop.

While the drywall was not fully finished with mud, the seams in the ceiling and interior walls, including the bulkhead, were sealed with tape. The seam between walls and floor was not taped. Figure 1 displays several photos of the room during construction, moving the wall, testing for air leakage, and at completion.

The project team conducted an air leakage test with a blower door to measure leakage and with a smoke stick to identify leakage locations. All vents, grilles, and door louvers were sealed for this test. The blower door results at three different pressures and two room sizes are given in Table 1. Smoke stick observations revealed obvious leakage around the doors and plumbing/electrical pass-throughs but no other concentrated locations. The results between the two room sizes bear this out: as the bulkhead is moved back to increase room size, the increase in leakage is small. Overall, the leakage test results, construction techniques, and smoke stick observations confirmed that the room is reasonably sealed, and representative of a light-frame constructed room in a house.

Table 1. Test Room Air Leakage Test Results

Delta Pressure (depressurization test)	**Airflow, 450 ft^3 Room**	**Airflow, 700 ft^3 Room**
25 Pa	175 CFM	205 CFM
12.5 Pa	115 CFM	125 CFM
4 Pa	57 CFM	61 CFM

Figure 1. Shrinking Room Construction

2.2.2 Room Dimensions

Figure 2 shows the shrinking room floor plan with nominal dimensions. The room is approximately 15 ft long, 8 ft wide, and 8 ft tall. The as-built dimensions, measured after construction, are provided in Table 2. Throughout the report, for ease of reference, tests are described using nominal volumes. All analyses were conducted with the actual volumes.[5]

Figure 2. Shrinking Room Floor Plan with Nominal Dimensions

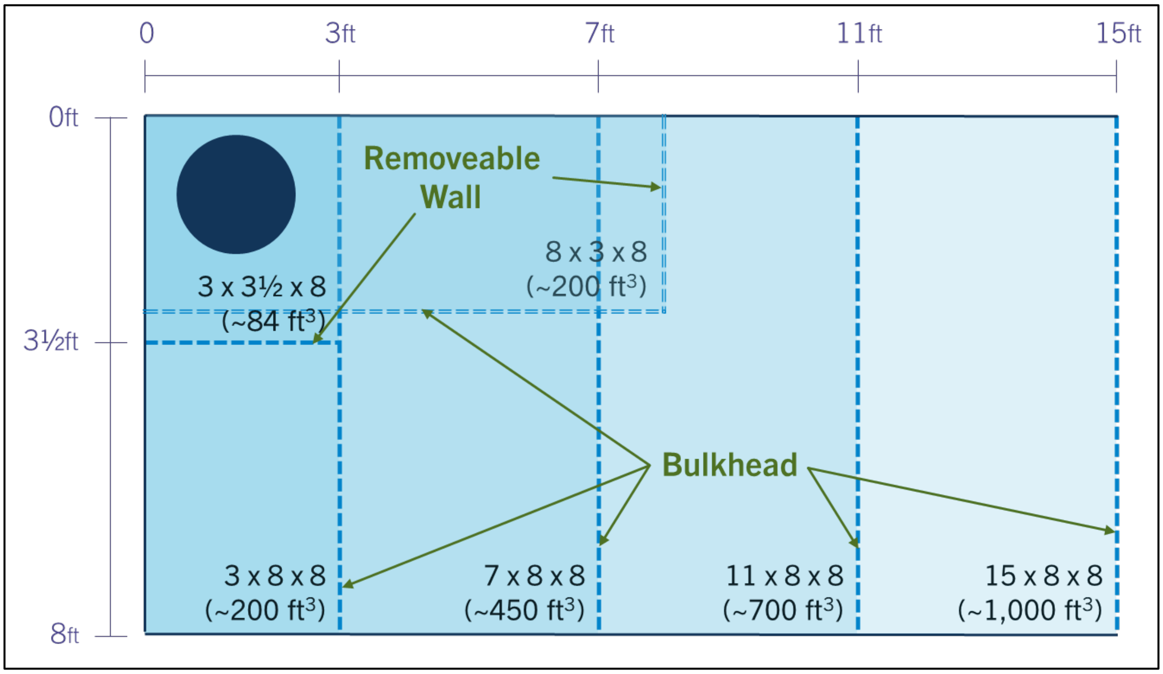


Table 2. Shrinking Room Nominal and Actual Volumes

Nominal Volume (ft^3)	Actual Volume (ft^3)
1,000	960
700	707
450	453
200	200
84	83.5

[5] The original test plan called for a 72 ft^3 closet at the small size, 3 ft x 3 ft x 8 ft. The final door width, with jambs and framing, was larger than anticipated, making the actual width 3.5 ft while the 3 ft depth was maintained. Consequently, the nominal volume for the small closet is 84 ft^3.

2.3 Test Description and Draw Profiles

The fundamental test procedure is a modification of the Department of Energy (DOE) 24-hour simulated use test (DOE 2014) for medium and high draw profiles. The medium profile totals 55 gallons and the high profile 84 gallons. For context, the medium profile is a bit higher than the average daily hot water use from DOE's most recent technical support document for water heater rulemaking (DOE 2022). Therefore, the medium draw profile can be considered somewhat above average daily use and the high profile significantly above.

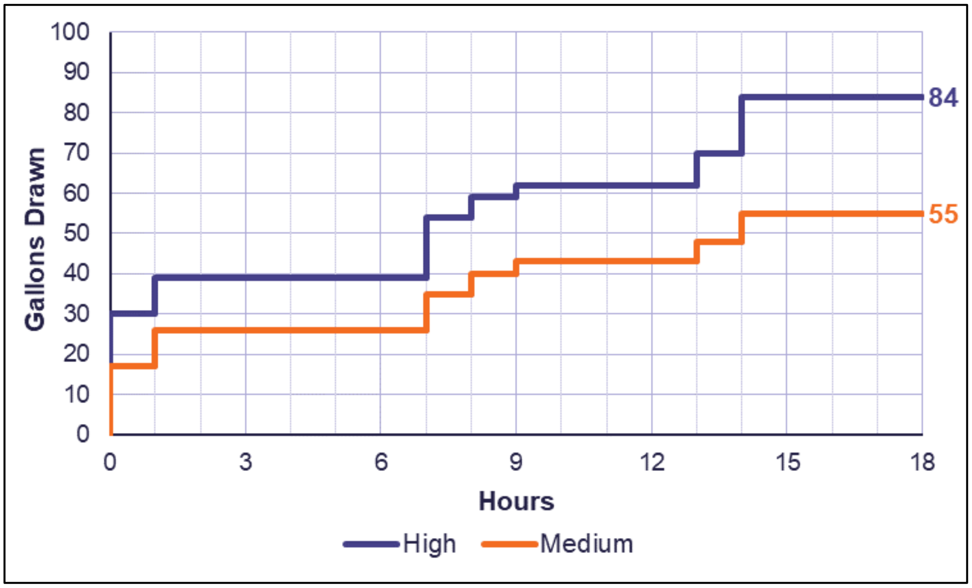
The test team shortened the DOE draw patterns from 24 to 18 hours. Three hours were removed between the first and second draw clusters and three more hours were removed at the end of the test. In all test runs, the water heater was able to fully recover the tank within the shortened idle periods; therefore, only periods of standby operation were removed. This allowed the lab to conduct a complete test, reconfigure the equipment, and start the next test all within a single 24-hour period, while still providing meaningful and comparable test data. Table 3 and Figure 3 show both draw patterns used in the tests.

Table 3. Hot Water Draw Patterns

	Medium		High	
Test Time hr:min	**Volume** gallons	**Flow Rate** GPM	**Volume** gallons	**Flow Rate** GPM
00:00	15	1.7	27	3.0
00:30	2	1.0	2	1.0
00:40	--	--	1	1.0
01:40	9	1.7	9	1.7
07:30	9	1.7	15	3.0
08:30[6]	5 (3)	1.7 (1.0)	5	1.7
09:00	1	1.0	1	1.0
09:45	1	1.0	1	1.0
09:50	1	1.0	1	1.0
13:00	1	1.0	2	1.0
13:15	2	1.0	2	1.0
13:30	--	--	2	1.7
13:45	2	1.7	2	1.7
14:00	7	1.7	14	3.0

[6] The intended volume for the draw at 08:30 was 5 gallons at 1.7 GPM. Due to a programming error, the actual volume and flow rate for the medium profile were 3 gallons and 1.0 GPM. This went undiscovered until partway through the project because several other draws lasted slightly longer than planned and compensated for the water missed in the 08:30 draw. The total hot water flow was still near 55 gallons ±1 gallon for all the medium draws. Instead of rerunning all the previous tests, the team opted to continue the project with the lower flow rate. Repeating the precise UEF draw profile was less important than maintaining consistency and repeatability across all tests in the project. The high profile was not affected by this error.

Figure 3. Hot Water Draw Patterns



2.3.1 Preconditioning Procedure

To ensure comparability of tests, both the water heater and the test room were preconditioned between individual tests to ensure each started with the same conditions. In between all tests, the team opened both test room doors and forced air through the test room to allow the temperature to equilibrate with the lab exterior space. Next, the room was closed in the configuration under test. With the room configuration established, the water heater itself was preconditioned following the DOE method. That is, hot water was drawn until the heat pump turned on and then the water heater was allowed to reheat the tank completely. The actual test draw pattern commenced one hour after recovery. In sum, the room preconditioning brought the room components to an equilibrium temperature with the lab, and the water heater preconditioning subsequently changed those room conditions to more closely resemble a water heater in continuous operation in a real-world installation. (Water heaters run in a continuous loop of reheating and standing by. Except for the installation day, it never starts operating in a room unaffected by previous water heater operation.)

2.4 Data Collected

The following data were measured throughout testing. Except where noted, all measurements were recorded at one-second intervals.

2.4.1 Air Temperatures

Test Room Interior

- 3 in. from surface of wall, 1 ft. below ceiling
- 3 in. from surface of wall, equidistant to floor and ceiling
- 3 in. from surface of wall, 1 ft. above floor

Lab Space

- At four different points proximate to test room (readings averaged in result reports)

Water Heater

- At air intake
- At exhaust

2.4.2 Airflow Rates

- Inside exhaust duct (measured once during setup of each ducting configuration)

2.4.3 Water Temperatures

- Water heater water inlet
- Water heater water outlet
- Six internal tank measurements, placed at the center of six sections of water of equal volume, vertically divided

2.4.4 Water Flow Rates

- HPWH outlet

2.4.5 Electrical Power

- HPWH current, voltage, and power factor

2.4.6 Smoke Stick Observations

The project team used a fog puffer kit, or "smoke stick," to qualitatively understand air movement into and out of the enclosure in different test configurations. Figure 4 shows evidence of air exiting the closet enclosure through a lower grille. Smoke sticks easily demonstrated the direction of airflow. They also qualitatively indicated the velocity of the flow with some testing configurations clearly exhibiting more or less vigorous airflow in and out of the enclosure.

Figure 4. Visualization of Airflow Using Smoke Stick

2.5 Variable Room Volume Testing Configurations

To answer the first research question, how room volume effects efficiency, the project team performed a series of tests (according to the procedure described in Section 2.3   above), varying the room volume and draw profile.

To establish baselines, the test was first performed with both doors open and without either the bulkhead or removable wall. This is referred to as the "open" condition. The HPWH effectively had an unlimited supply of room-temperature air, as the surrounding lab space was of sufficient volume to disperse the cooled exhaust air. Measurements of air temperature at the HPWH air intake recorded throughout the baseline tests confirm this.

For the remaining tests, the room was closed with no intentional airflow openings present. Tests were performed at each of the room volume configurations described in Section 2.2.2
.

Tests were performed with both the high and medium draw profiles.

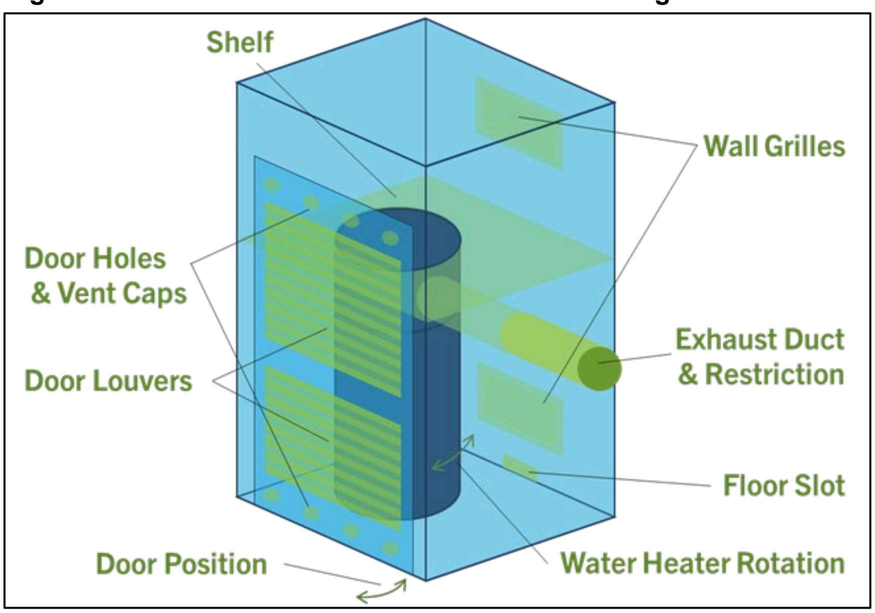
Table 4. Variable Room Volume Tests

Test	Room Volume, W / H / D ft, approximate	Draw Profile
Open-High	n/a	High, 84 gal
Open-Med	n/a	Medium, 55 gal
Closed-High-1000	960 ft^3, 8 / 8 / 15	High, 84 gal
Closed-Med-1000	960 ft^3, 8 / 8 / 15	Medium, 55 gal
Closed-High-700	707 ft^3, 8 / 8 / 11	High, 84 gal
Closed-Med-700	707 ft^3, 8 / 8 / 11	Medium, 55 gal
Closed-High-450	453 ft^3, 8 / 8 / 7	High, 84 gal
Closed-Med-450	453 ft^3, 8 / 8 / 7	Medium, 55 gal
Closed-High-200	200 ft^3, 8 / 8 / 3	High, 84 gal
Closed-Med-200	200 ft^3, 8 / 8 / 3	Medium, 55 gal
Closed-Med-200b	200 ft^3, 3 / 8 / 8	Medium, 55 gal
Closed-High-84	84 ft^3, 3.5 / 8 / 3	High, 84 gal
Closed-Med-84	84 ft^3, 3.5 / 8 / 3	Medium, 55 gal

2.6 Intervention Testing Configurations

To answer the second research question about the effectiveness of various methods of improving efficiency in small spaces, the project team tested a variety of methods, or interventions, intended to increase the available thermal resource to the water heater. To allow this, the test room includes features, seen in Figure 5 and further described in Section 2.6.1 , that can be used to alter airflow in and out of the test room.

Figure 5. Features to Alter Test Room Airflow Configurations



These features allowed the project team to create both forced convection and free (passive) convection airflow regimes. Forced convection uses the HPWH's fan to induce isolated flows of warmer makeup air to the unit's intake and of cooler exhaust air out of the enclosure. Free convection interventions simply add openings to the enclosure through which the air may flow.

All the intervention tests used the 55-gallon medium draw profile. All but one used the 84 ft^3 room volume. The draw pattern and room size were chosen based on the variable room volume test results as being the most useful for the comparison of interventions.

While the high profile was useful for evaluating the air-cooling effect of the HPWH, it exceeds the design case for the model tested: Many instances of resistance heating in the high-profile tests were the result of the draw volumes being high relative to the storage volume rather than just the ambient air temperature. Testing with the medium profile isolates the air temperature effect, the aspect being investigated in this group of tests.

The 84 ft^3 room volume was chosen because the Closed-Med-84 test produced results that make a good starting point for improvement. The efficiency was low (less than half of UEF) and resistance heating was triggered by the drop in air temperature. Such operation would be considered a problem in a real-world installation, calling for intervention.

2.6.1 Intervention Test Room Ventilation Features

Door Louvers

A 36-in x 80-in, wooden, two-panel louver door was installed. The louvers were left open or covered, partially or fully, with insulating sheets from the inside depending on the test requirements.

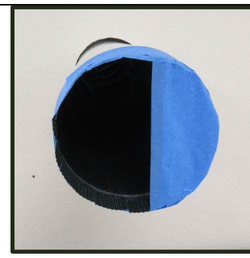
Door Position

The door was kept closed in all but one test, in which it was propped open to produce a 1.5-in gap along the jamb.

Exhaust Duct

A straight length of smooth, 8-in, round ducting approximately eight feet long could be attached to the water heater's exhaust using the manufacturer's adapter kit. When attached, the duct passes through the test room wall to terminate in the adjacent lab space. When the duct was not attached, the holes in both the interior and exterior drywall sheets were covered. This design emulates exhaust ducting to an adjacent space within the conditioned envelope (does not cross air barrier to outside).

Exhaust Restriction



In one test, tape was used to partially cover the duct terminus and reduce airflow rate by one half, compared to the uncovered terminus.

Exhaust Elbow

Using the manufacturer's adapter kit, a 90-degree duct elbow was attached directly at the exhaust to direct it downward, within the test room.

Wall Grilles

24-in x 8-in wall grilles were installed, approximately 8 in from the ceiling and approximately 8 in from the floor in the moveable bulkhead wall. When not needed for testing, the openings were filled with rigid foam and the edges sealed with tape.

Floor Slot

An 18-in^2 slot was cut into the moveable bulkhead wall next to the floor. This is intended to simulate the gap below a door when it does not fully fill the doorframe. When not needed for testing, the opening was filled with rigid foam and the edges sealed with tape.

Door Holes

Eight, 3-in diameter holes were cut into the door, four spread across the top rail and four across the bottom rail. Depending on the test requirements, these holes were fitted with soffit vent caps or plugged with the wood cut from the door and sealed with tape.

Vent Caps

Two types of soffit vent caps were used with the door holes: **Wire Mesh**, with a higher total free area, and **Plastic**, which were more restrictive.

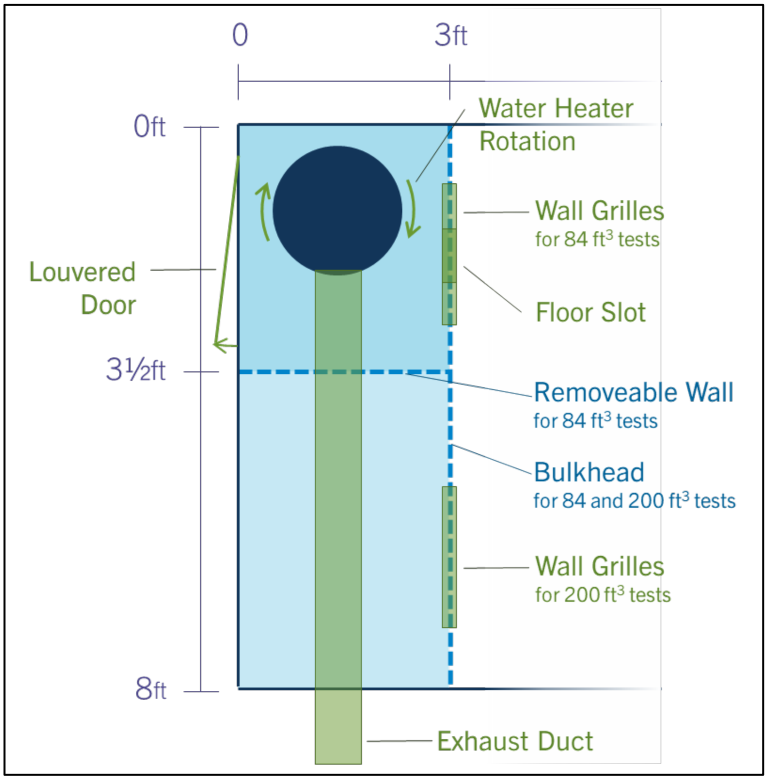
Shelf

For one test, a “shelf” of rigid foam was fitted horizontally across the full area of the test room at the height of the top of the water heater, with an opening cut for the evaporator air intake. This effectively divided the room into two compartments, with the intake and exhaust open to different compartments.

HPWH Rotation

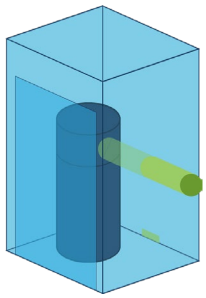
For most tests, the water heater was positioned such that the exhaust was directed parallel to the plane of the door—to the viewer’s right when facing the door from outside the room. In one test, it was rotated 45 degrees toward the door.

Figure 6. Test Configuration Schematic Overview



2.6.2 Intervention Test Descriptions

Duct-SmMakeup-Full



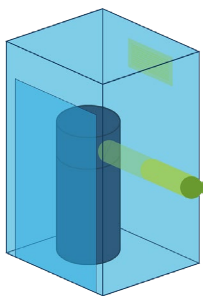
Forced Convection

Makeup Intake: Floor slot (18 in^2 NFA)

Exhaust Path: Unrestricted duct

Simulates a favorable exhaust ducting scenario: duct run is short, straight, and smooth, though opening for makeup air is small

Duct-LgMakeup-Full



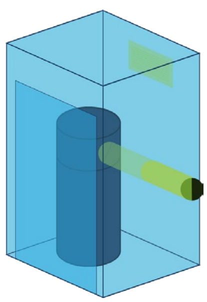
Forced Convection

Makeup Intake: Upper wall grille (130 in^2 NFA)

Exhaust Path: Unrestricted duct

Simulates a best-case exhaust ducting scenario: duct run is short, straight, and smooth; large opening for makeup air

Duct-LgMakeup-Half



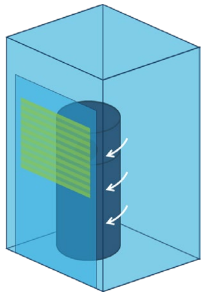
Forced Convection

Makeup Intake: Upper wall grille (130 in^2 NFA)

Exhaust Path: Duct restricted to half the flow rate of the unrestricted duct

Simulates a less-favorable ducting scenario. Common installation details such as flex ducting, turns, longer runs, and louvers or other restrictions at duct terminus reduce airflow.

DirectedExhaust



Forced Convection*

Openings:

Upper louver panel of door (129 in^2 NFA)

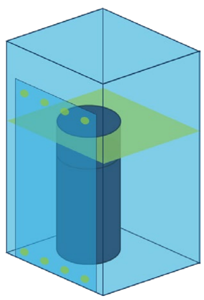
Floor slot (18 in^2 NFA)

Other: HPWH rotated to blow exhaust more toward door

A method recommended by some HPWH manufacturers. Uses the fan to more intentionally direct the exhaust airflow.

*While the airflow paths in this configuration are intentionally directed, exhaust and intake were not fully isolated. Even though some part of the makeup air was drawn in through the door louvers, the approach is better understood as a forced convection intervention.

Shelf



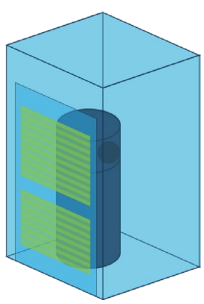
Forced Convection

Makeup Intake: Upper door holes, fitted with wire-mesh vent caps (25 in^2 NFA)

Exhaust Path: Lower door holes, fitted with wire-mesh vent caps (25 in^2 NFA)

"Shelf" of rigid foam divides room into two compartments, with the HPWH intake drawing from the upper compartment and the exhaust discharging into the lower. Forces convection without ducting.

Louvers-Full

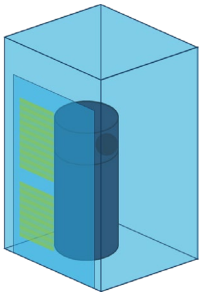


Free Convection

Opening: All door louvers (218 in^2 NFA)

A simple approach to increasing air exchange, one that is often recommended for small-space installs.

Louvers-Half

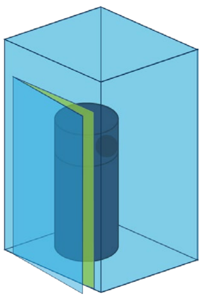


Free Convection

Opening: Half the width of all door louvers, side opposite exhaust (109 in^2 NFA)

Designed to test the importance of total free area on intervention effectiveness—to provide information useful when considering different door designs/dimensions which may have less free area.

Doorstop

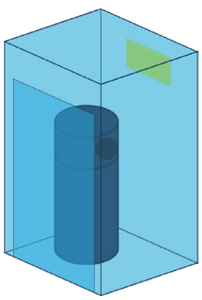


Free Convection

Opening: 1-1/2 in gap between door and jamb, louvers are sealed (114 in^2 NFA)

Extremely low-cost intervention. Could be applied immediately upon water heater installation until homeowner is able to implement a more permanent, sophisticated solution.

Grille-Upper

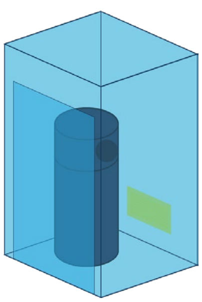


Free Convection

Openings: Upper wall grille only (130 in^2 NFA)

Fairly low-effort, low-cost intervention. Compared to both wall grilles, this test was designed to reveal the degree to which the stack effect (thermal stratification of air within room) drives air exchange.

Grille–Lower

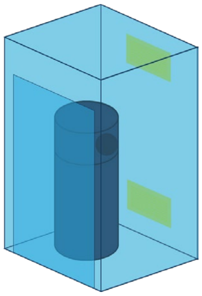


Free Convection

Openings: Lower wall grille only (130 in^2 NFA)

Fairly low-effort, low-cost intervention. Compared to upper grille, this test was designed to reveal whether height of opening has a significant effect.

Grilles-Both

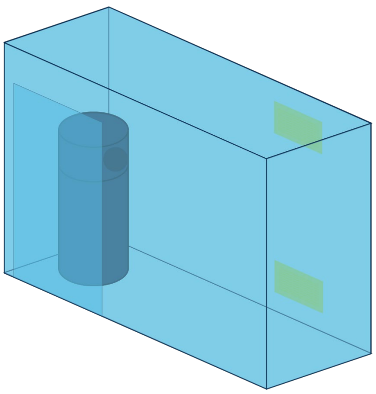


Free Convection

Openings: Two wall grilles, one high and one low (260 in^2 NFA)

Fairly low-effort, low-cost intervention that adds significant area for air exchange,

Grilles-Both(200)



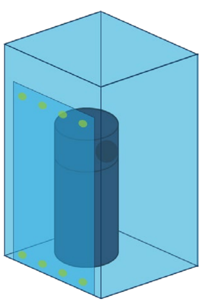
Free Convection

Openings: Two wall grilles, one high and one low (260 in^2 NFA). Grilles placed several feet from HPWH.

Note: Uses 200 ft^3 room configuration

Fairly low-effort, low-cost intervention that adds significant area for air exchange

VentCaps-HighNFA

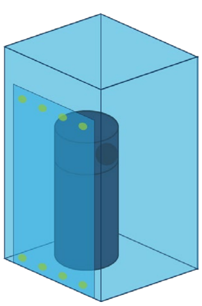


Free Convection

Openings: Door holes, fitted with wire-mesh vent caps (51 in^2 NFA)

Intended to be an intervention that plumbers could apply with tools and parts on hand.

VentCaps-LowNFA

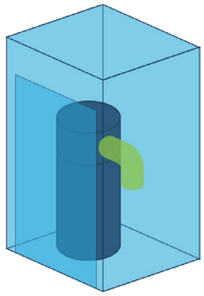


Free Convection

Openings: Door holes, fitted with plastic vent caps (22 in^2 NFA)

Compared to the metal caps, designed to test minimum free area needed for approach to be effective.

DownElbow



<u>Closed Room</u>

Opening: *None*

Other: Exhaust directed immediately downward with duct adapter and 90 degree elbow

Designed to test possibility of forcing thermal stratification of air within test room—concentrating cool air at bottom to allow heat to build up in upper portion of room near HPWH intake.

2.7 Analysis Approach

The fundamental quantity determined from the testing is the equipment efficiency, referred to herein as the coefficient of performance (COP). The COP is the total useful hot water output divided by total energy input over the test duration. The COP calculation follows that outlined in American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 118.2 and the DOE test procedure, except that it does not make corrections to the efficiency to standard conditions of inlet water, outlet water, or air temperature (ASHRAE 2022, DOE 2014). The energy content of the useful hot water output is calculated from the measured mass of water flowing and the temperature rise from the measured inlet to the measured outlet temperature.

2.7.1 Surrounding Space Temperature Stability

The space surrounding the shrinking room was a large room with its temperature controlled by the building HVAC system. The HVAC system thermostat does not control temperatures as tightly as those inside a thermal/environmental chamber; as such, the surrounding space experienced temperature variability. The project team monitored the temperature throughout each test, which showed the median for all tests was 67.2° F. Most tests averaged between 66.6° F and 67.8° F while the most extreme tests average 65° F and 68.7° F. Some temperature excursions beyond the average occurred and, while they add noise to the test data, previous experience by the project team suggests the noise does not meaningfully impact the results. Specifically, the resulting COP differences between tests are substantially greater than any difference in surrounding space air temperature could cause. Further, no obvious way exists to calculate adjustments for the difference in exterior space temperature. Accordingly, the project team opted for less data manipulation and made no corrections, except in one case where noted.

3 Results & Analysis

3.1 Test Results Overview

Table 5 shows the summary results for all the tests conducted. The terms in the table are defined as follows:

- **Test Name:** Name of test used in references throughout report
- **COP:** Coefficient of Performance, calculated as described in Section 2.7
- **Draw Pattern:** *Medium* or *High*, as described in Section 2.3
- **Room Volume:** Actual amazing shrinking room volume (see Section 2.2.2)
- **Ventilation Regime:** *Open*, for the baseline tests; *Closed*, for the variable room volume tests; *Forced* or *Free*, for intervention tests using convection (see Section 2.6)
- **NFA:** Total net free area of openings between interior and exterior as configured for test
- Runtime:
  - **Total:** Number of minutes during test that water heater used ER, heat pump, or fan. ER and heat pump can run simultaneously, and fan can run without heat pump; therefore, total may not equal sum of ER and HP runtimes
  - **ER:** Number of minutes during test that ER element operated
  - **HP:** Number of minutes during test that heat pump operated
- **Average Air Temperature:** See Section 2.4.1 for measurement locations. Mean average over the duration of the test of:
  - **Intake:** …air at HPWH air intake
  - **Exhaust:** …air at HPWH exhaust port
  - **Room:** …air inside the test room
  - **Exterior:** …air in the lab space surrounding test room

Table 5. Results Summary Master Table

	Test Name	COP	Draw Pattern	Room Volume	Ventilation Regime	NFA	Runtime Total	Runtime ER	Runtime HP	Average Air Temperature Intake	Average Air Temperature Exhaust	Average Air Temperature Room	Average Air Temperature Exterior
				ft^3		in^2	min	min	min	°F	°F	°F	°F
Open	Open-Med	3.54	Medium	n/a	Open	n/a	409	0	397	66.5	51.8	65.5	66.6
	Open-High	3.69	High	n/a	Open	n/a	613	0	602	65.9	51.2	64.7	66.3
Variable Room Volume	Closed-Med-1000	3.21	Medium	960	Closed	0	462	0	451	54.9	42.4	58.7	65.1
	Closed-Med-700	3.21	Medium	707	Closed	0	465	0	453	54.0	42.1	59.1	66.9
	Closed-Med-450	2.97	Medium	453	Closed	0	522	0	510	48.3	37.4	54.5	65.0
	Closed-Med-200	2.32	Medium	200	Closed	0	484	22	447	47.2	37.2	55.5	67.6
	Closed-Med-200b	2.17	Medium	200	Closed	0	516	23	501	42.1	33.1	52.1	66.6
	Closed-Med-84	1.53	Medium	83.5	Closed	0	547	67	372	43.0	37.4	52.5	67.1
	Closed-High-1000	2.58	High	960	Closed	0	669	28	657	54.0	41.6	55.8	65.3
	Closed-High-700	2.63	High	707	Closed	0	649	27	634	53.4	41.5	56.4	67.1
	Closed-High-450	2.26	High	453	Closed	0	636	47	600	51.4	39.9	55.8	68.0
	Closed-High-200	1.88	High	200	Closed	0	621	76	539	46.3	36.3	51.9	67.2
	Closed-High-84	1.24	High	83.5	Closed	0	530	172	348	43.8	37.6	53.3	66.7
Interventions	Duct-LgMakeup-Full	3.30	Medium	83.5	Forced	180	454	0	442	68.0	38.2	69.1	68.1
	Duct-SmMakeup-Full	3.26	Medium	83.5	Forced	68	462	0	442	67.4	37.7	69.4	68.2
	Duct-LgMakeup-Half	2.11	Medium	83.5	Forced	180	434	37	376	67.5	37.6	68.8	67.7
	DirectedExhaust	2.98	Medium	83.5	Forced	188	497	0	484	49.5	37.0	54.9	67.7
	Shelf	3.12	Medium	83.5	Forced	33	480	0	468	56.6	37.9	57.6	68.7
	Louvers-Full	3.06	Medium	83.5	Free	286	487	0	473	53.7	39.3	55.2	65.5
	Louvers-Half	2.62	Medium	83.5	Free	143	488	13	453	51.9	38.3	56.8	67.7
	Doorstop	2.47	Medium	83.5	Free	115	497	15	476	49.0	37.0	55.4	67.0
	Grille-Upper	1.48	Medium	83.5	Free	130	415	80	309	45.1	36.3	56.9	67.8
	Grille-Lower	1.48	Medium	83.5	Free	130	411	77	306	44.6	37.5	58.1	68.4
	Grilles-Both	3.17	Medium	83.5	Free	259	472	0	460	57.2	41.1	57.8	66.5
	Grilles-Both(200)	3.30	Medium	200	Free	259	446	0	435	57.8	44.6	60.7	67.4
	VentCaps-HighNFA	2.18	Medium	83.5	Free	33	507	23	476	46.3	33.7	52.9	67.9
	VentCaps-LowNFA	1.38	Medium	83.5	Free	22	410	89	357	43.1	36.0	56.6	67.8
	DownElbow	1.12	Medium	83.5	Closed	0	336	128	250	56.7	44.5	64.0	67.8

3.1.1 "Baseline" Test Results

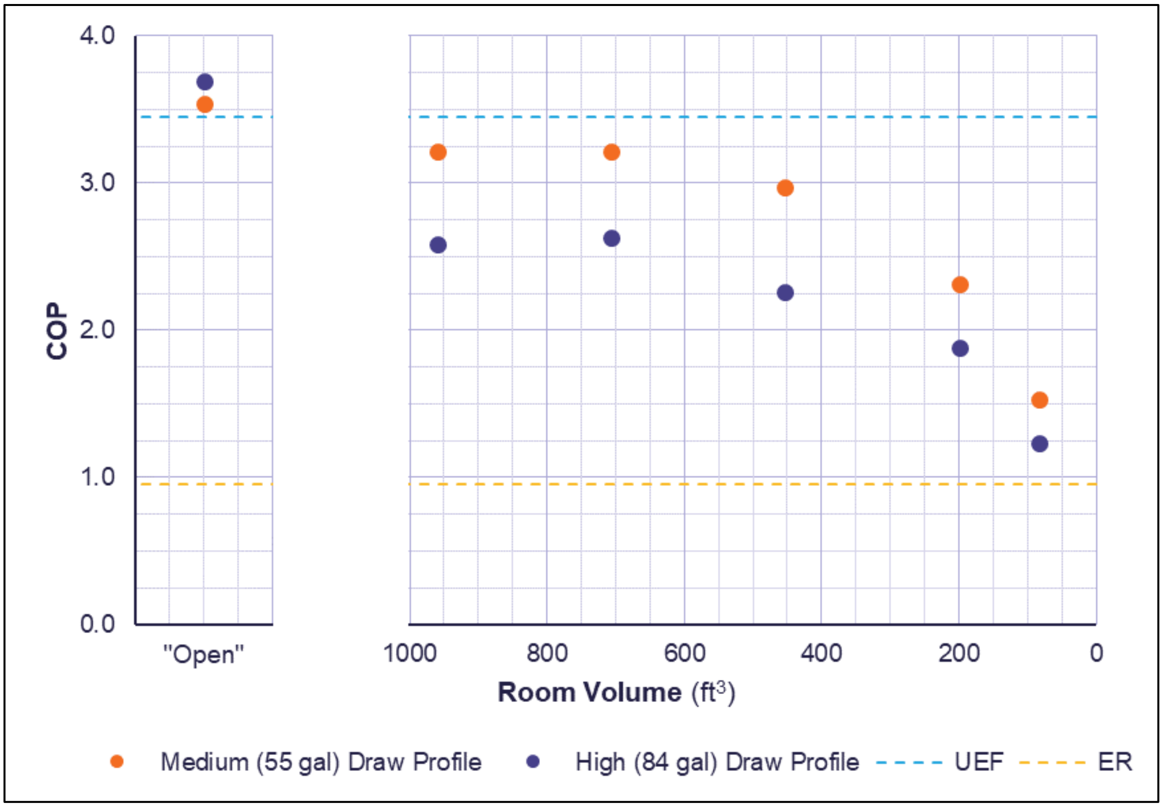
The test results for the "baseline" condition, in which the unit effectively had an unlimited supply of room-temperature air, compare favorably to the product's UEF value. Compared to the DOE 24-hr simulated use test that produces the UEF, the baseline tests have six fewer hours of standby time, and the high draw profile uses 29 more gallons of water. Both of these differences would be expected to increase the COP, because they increase the ratio of heating time to standby loss. The baseline tests had higher COPs than the 3.45 UEF: 3.54 for the medium draw and 3.69 for the high draw. This establishes the test method reliability. The baseline tests also establish a reference point to which other test results can be compared.

3.2 Effect of Room Volume on Efficiency

Figure 7 shows the relationship between enclosed room volume and efficiency. The upper limit for efficiency is the "open" unlimited airflow case. In the enclosed room, efficiency declines with volume. The graph helps to show:

- The high draw pattern produces a lower efficiency than the medium draw pattern at each room volume tested. This is due primarily to the HPWH's use of its ER elements to meet the higher demand.
- For a given draw pattern, the efficiencies in the 1,000 ft^3 and 700 ft^3 volumes are nearly identical, but they are also lower than the baseline tests. This suggests that at these higher volumes, while the enclosure does reduce efficiency, the incremental benefit of increasing volume is low.
- Efficiency starts to drop for both draw patterns with volumes less than 700 ft^3 and more steeply below 200 ft^3. Even at the 450 ft^3 volume, the medium draw profile yields a COP near 3—only 7% less than at 700ft^3, the manufacturer-recommended minimum.

Figure 7. HPWH Efficiency in Enclosed Spaces



**UEF test procedure includes an additional 6 hours of standby time, which produces slightly lower COP.*
***Typical UEF for a high-performing electric-resistance storage water heater is 0.95.*

The test results revealed three factors that determine the COP in enclosed rooms:

- **The ambient air temperature during compressor operation:** Heat pumps work more efficiently when the air is warmer. Further, cooler temperatures slow the heating rate, which can trigger ER operation (to avoid hot water runout).[7]
- **Hot water use:** High hot water use within a short time period triggers ER heating to avoid hot water runout.
- **Compressor operating temperature range:** The HPWH switches to ER heating when the air temperature falls below the compressor's operating range.

The operational efficiency of the water heater's heat pump depends on the temperature of the air it takes in. For this reason, the research team recorded air temperature data during the tests to shed light on factors that affect the intake temperature in a closed space.

[7] Close analysis of the results shows that this secondary effect, ER use due to slow recovery rate caused by low ambient temperatures, did not occur in these tests. Regardless, the effect is a known performance factor related to ambient air temperature and is mentioned here as an important point to consider for small-space installations.

Figure 8 and Figure 9 show air temperatures recorded over the first six hours of two different tests, one with sufficient thermal resource for continued, efficient heat pump operation and one without. At the beginning of both tests, air temperatures inside and outside the room are about equal, near 65° F. The first hot water draw triggers a heat pump heating cycle about 10 minutes into each test and temperatures inside the room drop quickly. At this point the test outcomes diverge.

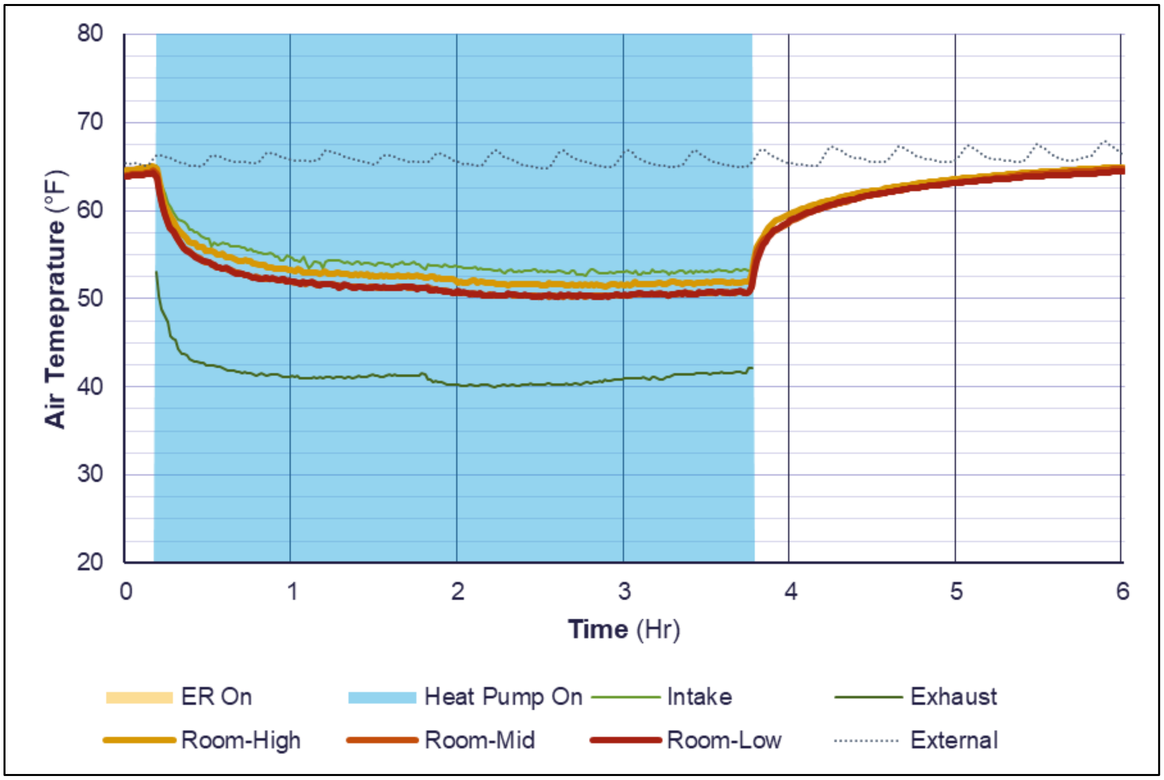
3.2.1 1,000 ft^3 Room

In the 1,000 ft^3 medium draw test, the temperature drop slows after the first, steep drop and eventually levels off around 51° F. The heat pump continues to run at this temperature until the water tank is fully reheated, around hour four. The minimum temperature is limited by both the heat pump and the enclosure. As the air cools, the capacity of the heat pump—both to heat water and further cool the air—is reduced.[8] Simultaneously, the temperature gradients between the room and both the outside and the water tank increase. This increases the rate at which heat conducts into the room air through the walls,[9] and from the heated water (standby loss). When the heat pump turns off, the air temperature rises. Again, the temperature change starts quickly and then slows.

[8] Instantaneous COPs may approach 2 at the end of the reheat cycle, meaning half the heating energy comes from the compressor motor and half from the air, compared to a COP of 4–5 at the beginning.

[9] In theory, the decreased efficiency and increased heat flow would eventually reach a steady state and temperatures would be stable. This was not observed in the testing as the heat pump did not run long enough. The project team expects heat pump runs in the field to also end before a steady state is reached.

Figure 8. Room Air Temperature During Closed-Med-1000 Test

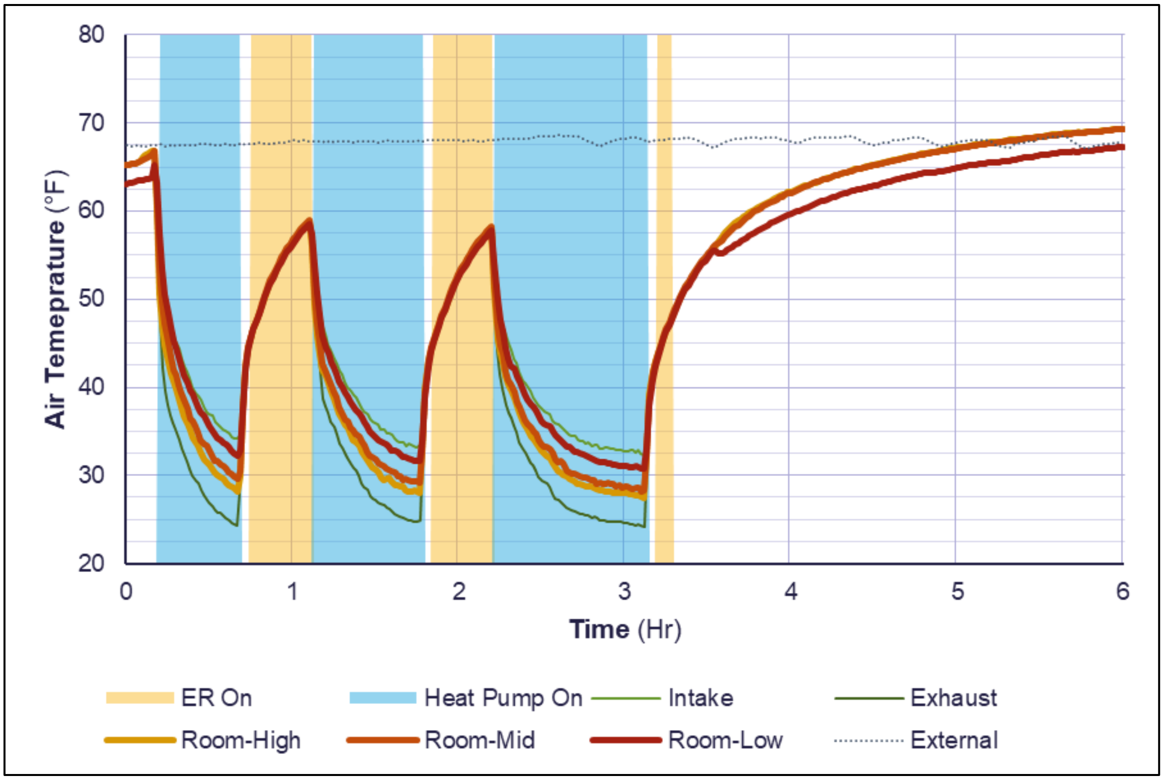


3.2.2 84 ft^3 Room

In the 84^3 ft medium draw test, the heat pump quickly "crashed" the room temperature. About 35 minutes into the cycle, the room temperature drops below the operating limit for the compressor and causes a defrost cycle. In defrost, this model switches from heat pump to ER heating while the evaporator fan runs. After about 20 minutes of defrosting, the air temperature recovered from around 30° F to 60° F and the water heater switched back to heat pump mode. Again, this quickly crashed the temperature, instigating another defrost cycle. The pattern repeats one more time before the water tank is fully reheated.

After that third heat pump cycle, no water heating demand occurs for several hours and the room temperature recovers to its initial level.

Figure 9. Room Air Temperature During Closed-Med-84 Test



3.2.3 Room Temperature

Ambient air temperature is a major determinant of HPWH efficiency, and a critical factor in small spaces. The tests revealed several useful patterns related to air temperatures.

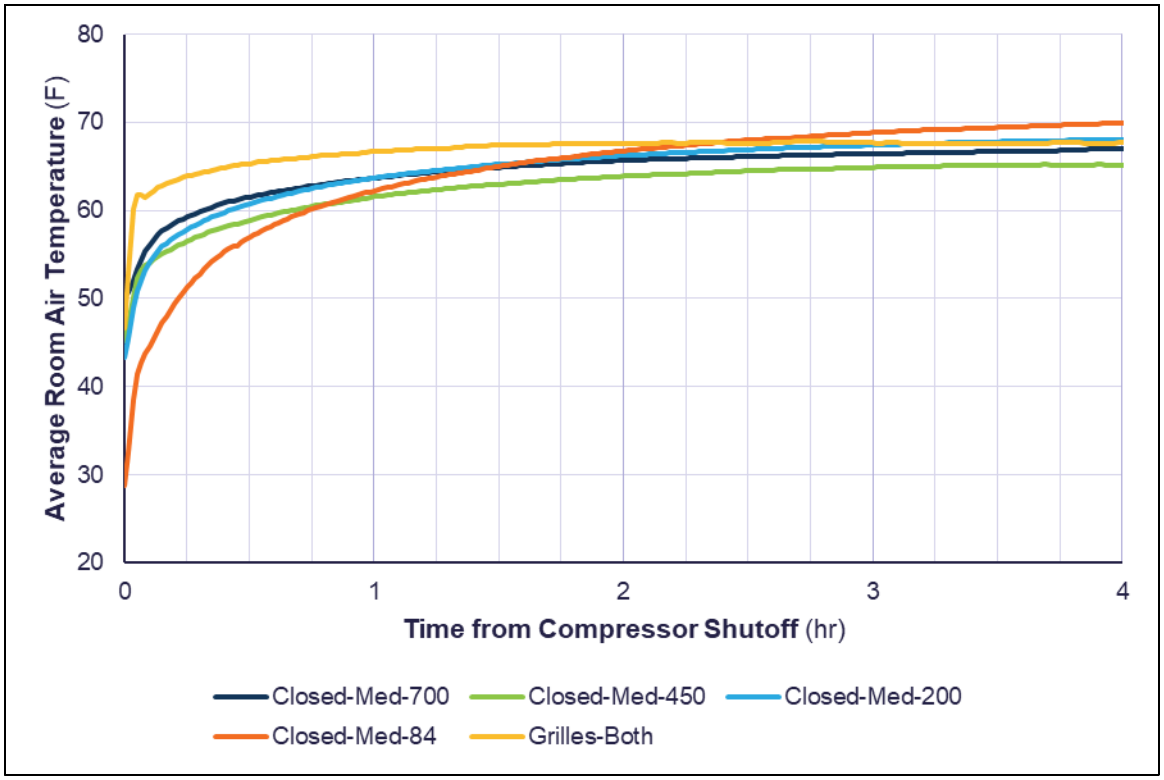
3.2.3.1 Temperature Rebound

How quickly the room temperature recovers after being cooled by the HPWH is useful in understanding how soon after a heat pump heating cycle the thermal resource is restored.

While the heat pump does cool down the room, the heat extracted by the HPWH is restored when the compressor is idle/off. The sources of the heat include infiltration through any openings to the outside (intentional or other), conduction across the enclosure walls, and heat transfer from the tank itself (standby loss).

Across all tests, temperature was restored to the initial level in two–three hours, with half of the rise occurring within the first 15 minutes. Exact times varied with the duration of the heat pump cycle. Figure 10 plots the air temperature rebound in the space during the standby period. For each test graphed, the plot starts the minute the heat pump shuts off after the reheating the tank from the first draw cluster.

Figure 10. Enclosed Space Air Temperature Rebound

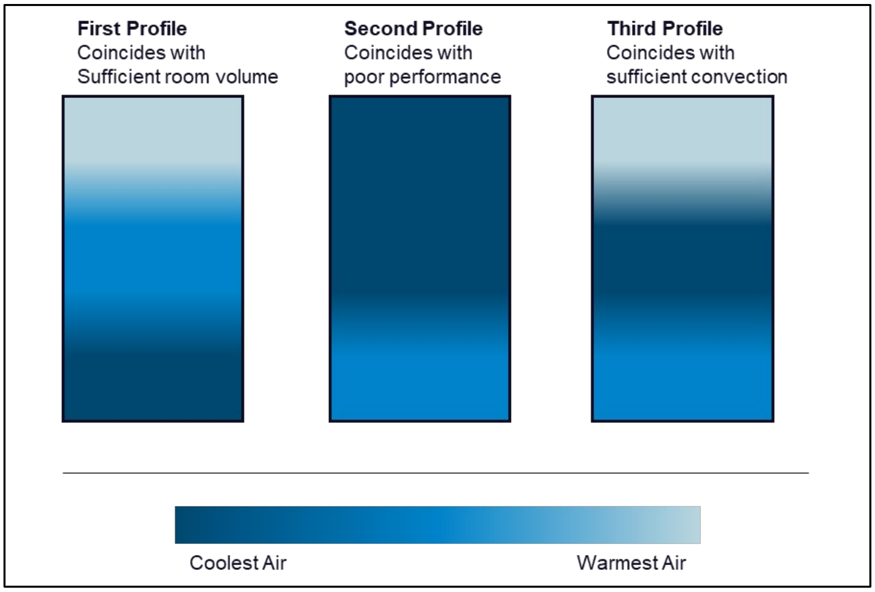


Given a long enough idle period, temperatures inside the room actually exceeded the outside temperature, a result of standby loss from the tank. Because most of that lost heat is trapped in the room, it is available for the heat pump to recover during the next water heating cycle. This effect is more prominent in the smaller room volumes, because the heat is more concentrated and has less surface through which to transfer outside.

3.2.3.2 Room Vertical Air Temperature Profiles

Understanding the vertical distribution of heat within the room is useful, both because most HPWHs draw in air from above, and because that distribution is indicative of how air is moving. Each of the free convection tests exhibited one of three distinct vertical air temperature profiles during heat pump operation. Two of those profiles are related to higher COPs, with the other appearing in tests with low COPs.

Figure 11. Air Temperature Profiles



In the larger closed-room tests (450–1,000 ft^3), those that achieved higher COPs, air was warmer at the top and colder at the bottom.

In the smaller closed-room tests (84 and 200 ft^3) and in intervention tests that yielded low COPs, the lower portion of the room was warmest while both the middle and upper temperature measurements were cool. This suggests that the exhaust air was being drawn from the middle height of the room and back into the air intake while the warmest air was largely stagnant, stuck in the lower portion of the room.

The third profile occurred in successful intervention tests, the configurations that yielded higher COPs despite the small room size. In those cases, the middle temperature sensor was coldest as it was directly affected by the exhaust air. The top sensor recorded the warmest temperature, and the lower sensor was slightly cooler than that, but still warmer than the middle. This indicates that a successful convection loop with outside air was established, unlike in the small closed-room tests that were recirculating the exhaust into the intake. The free convection intervention is discussed further in Section 3.3.3 .

The project team notes that the air temperature sensors were located on the bulkhead, so their distance from the HPWH varied depending on the room configuration. Therefore, in the larger rooms, the sensors were less directly influenced by air movements and stratifications at the HPWH. It is possible the air next to the water heater mixed similarly for all room sizes but was not observed. Nevertheless, specific vertical air temperature profiles in the larger room configurations appear to have minimal explanatory power for performance.

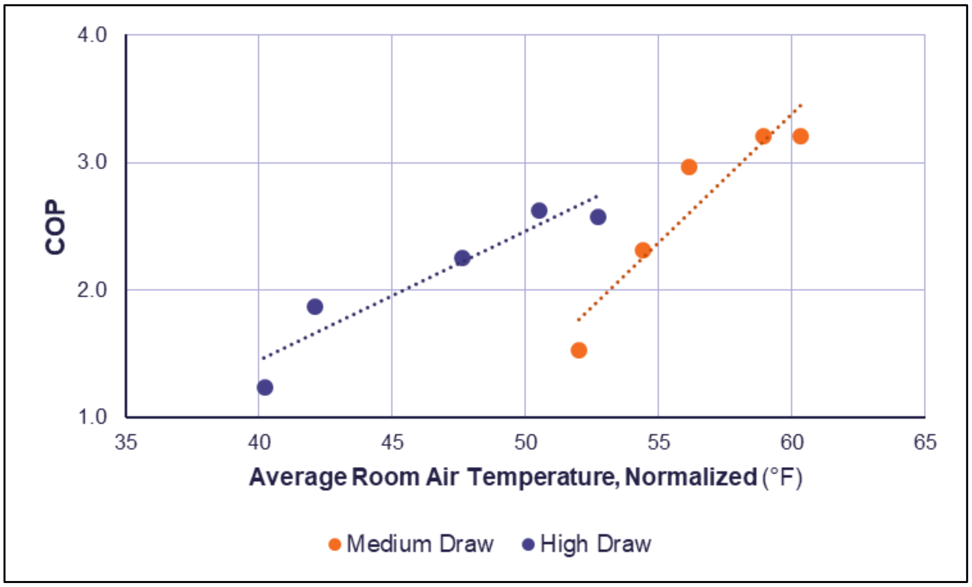
3.2.3.3 Average Room Temperatures During Tests

Analyzing the average room temperature during closed-room tests provides an approach to predicting efficiency at room volumes that were not tested. Of particular interest, extrapolation of the findings produces an estimate of the enclosed volume that would produce efficiencies equal to an open space.

Average room air temperature is correlated to efficiency. An exterior-temperature-normalized[10] average room temperature was produced for the full duration of each closed-room test. Using the average over the full period, rather than including only periods when the heat pump was running, incorporates the dampening effect of thermal mass and allows for an averaging effect needed due to the longer time constant of conduction from the exterior and heat exchange with the drywall rather than of the heat pump operation itself.

Figure 12 demonstrates the relationship between average temperature and efficiency. The correlation is clear when medium and high draw tests are considered separately.

Figure 12. COP as Function of Average Room Temperature



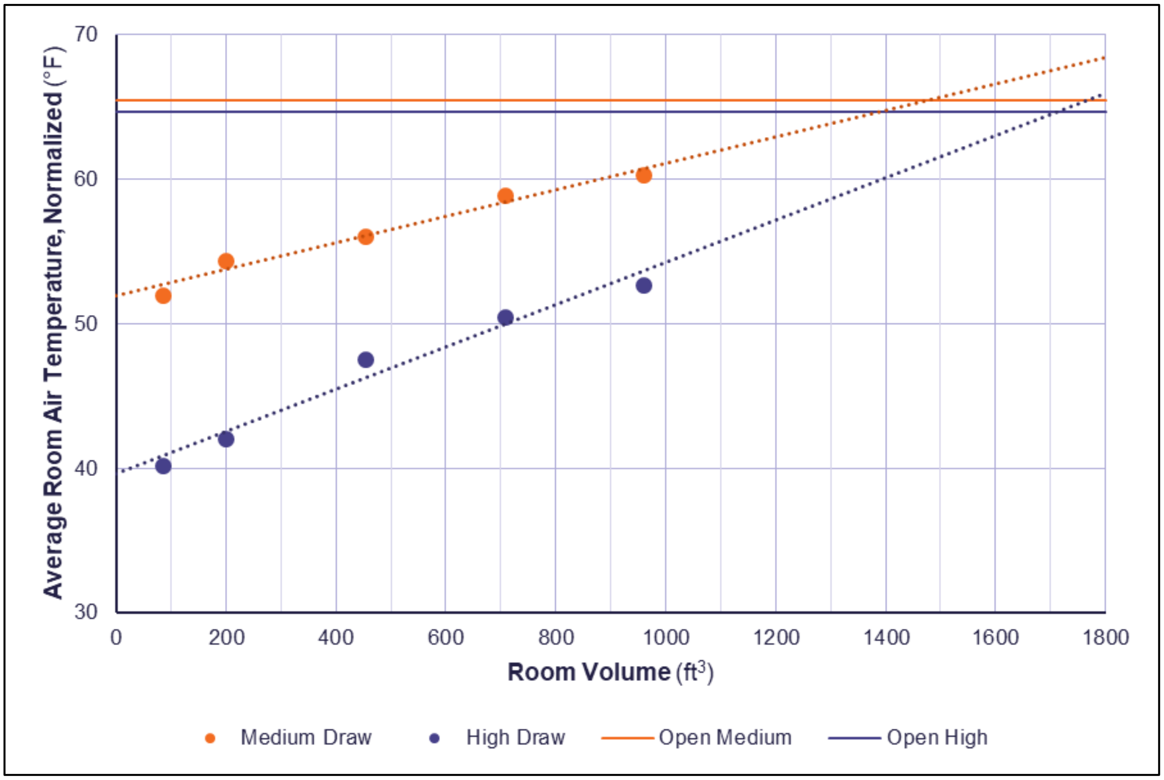
Comparing the average temperatures to room volume reveals a relationship between those two factors as well. Figure 13 plots the space volume against the average room temperature during the test. Again, the medium and high draw tests are considered separately.

Assuming the relationship between volume and temperature holds as volume increases, the closed-room temperatures would be the same as those for the open baseline tests, around 1,500 ft^3 for the medium draw and 1,700 ft^3 for the high draw. Similar efficiencies would be expected between closed rooms of those volumes and the respective open test. This is one

[10] The average room temperature was adjusted to account for the fact that the exterior was warmer or cooler during the reference wide-open space test. This is a simple, constant-value adjustment for each test, which ranges from -1.6° F to +1.7° F.

approach to predict the minimum enclosed room volume needed to achieve the UEF rated-level efficiency, though this was not tested because the test enclosure maximum size is 1,000 ft^3.

Figure 13. Enclosed Space Volume vs Average Room Temperature



Plotted points indicate normalized average temperature observed at each volume and for each draw profile. Trend lines extrapolate linear relationships for each profile. Horizontal lines indicate average temperature observed in those baseline tests.

3.2.3.4 Minimum Temperature

The 84 ft^3 tests demonstrate that a limit exists as to how cold the HPWH can make a room, around 30° F for that configuration. Because the heat pump enters defrost mode at that point and will not restart until the temperature has risen, the heat pump will not push the temperature below that minimum. Also, because room temperature begins to recover quickly, these minimums occur only briefly. Table 6 lists the coldest temperatures observed in the tests.

Table 6. Room Air Temperature Minima

Room Volume	Minimum Room Air Temperature	
	Medium Draw	High Draw
1,000 ft^3	51 °F	50 °F
700 ft^3	50 °F	50 °F
450 ft^3	44 °F	47 °F
200 ft^3	40 °F	39 °F
84 ft^3	29 °F	30 °F

3.2.3.5 Exhaust Air Orientation

In most of the enclosed room configurations, the 84 ft^3 test being the exception, the HPWH exhaust was discharged into relatively free space, directed toward a wall nearly 5.5 ft away. To examine the importance of the proximity of the HPWH to a wall, the project team performed a variation of the 200 ft^3 test, denoted Closed-Med-200b, in which the bulkhead and removable wall were swapped, creating a room of equal volume but with a vertical surface within 1 ft of the exhaust port.

The reduced distance appears to have caused some of the cold exhaust to be deflected upward and back toward the intake. Compared to the Closed-Med-200 test, this variation produced HPWH air intake temperatures 5° F lower and a COP 0.15 lower. The project team expects that in larger volume rooms with the same impediment to exhaust flow, a similar reduction in COP would occur. In the 84 ft^3 room, the effect is reflected in all tests as the problem, exhaust directed toward a near wall, is unavoidable at those dimensions.

3.2.4 Electric Resistance Operation

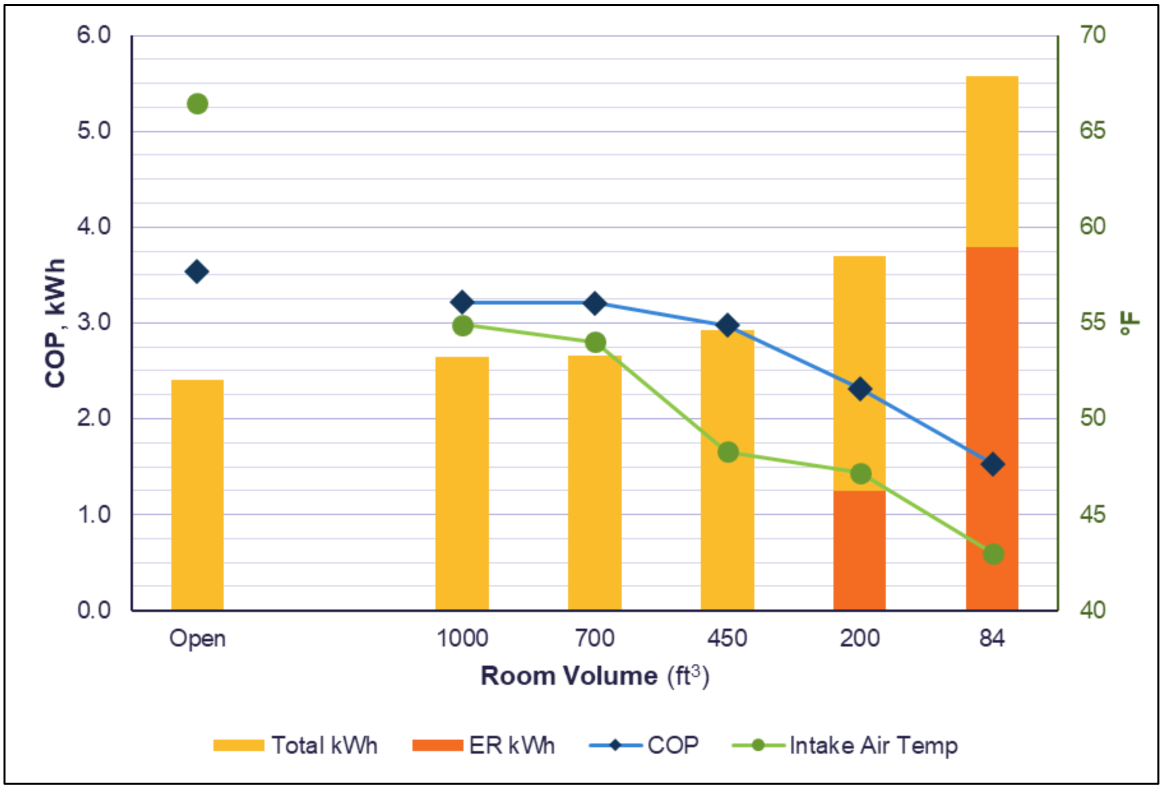
The overall efficiency of a hybrid electric water heater, one that uses both heat pump and electric resistance (ER) heating, is highly dependent on the share of heating delivered by each method. While heat pump efficiency varies based on a number of conditions, its average efficiency is factors higher than ER. Understanding when and why the ER elements run is key to understanding the overall efficiency of such water heaters.

This HPWH model, as with most, will use its ER elements either when hot water use exceeds the capacity of the heat pump or when the ambient air is too cool for the compressor to run. Both causes were seen in the closed-room tests. With the high draw profile, high water use triggered ER operation in all of the closed-room tests. This is not surprising as this draw pattern is especially demanding for the water heater’s storage. With the medium draw profile, ER operation occurred only in the two smallest room sizes and was not triggered solely by high demand. In these cases, the ER elements engaged because the room temperature was below the compressor’s operational limit.

Figure 14 shows efficiency and the average air temperature measured at the intake during heat pump operation in the medium draw tests. While the intake air temperature varies during the course of a heat pump run cycle (starting warm and then decreasing), the average over that cycle is an indicator of the conditions within the room.

- The 1,000 ft^3 and 700 ft^3 volumes have similar intake air temperatures, which is expected given they have similar COPs. Their intake temperatures are already 10° F below the wide-open reference, showing exactly why the efficiency is less in the enclosed space.
- At 450 ft^3, there is a drop in temperature and an associated drop in COP.
- At 200 ft^3, there is almost no further drop in temperature but a large drop in COP compared to 450 ft^3. This is indicative of cold air temperatures pushing the heat pump beyond its operating envelope.
- At 84 ft^3, the effects of persistently cool air are apparent. The temperature is more often below the compressor's operating limit, driving ER use, and heat pump efficiency is depressed when it does run.

Figure 14. Intake Air Temperature and ER Use—Medium Draw Pattern



3.3 Intervention Effectiveness

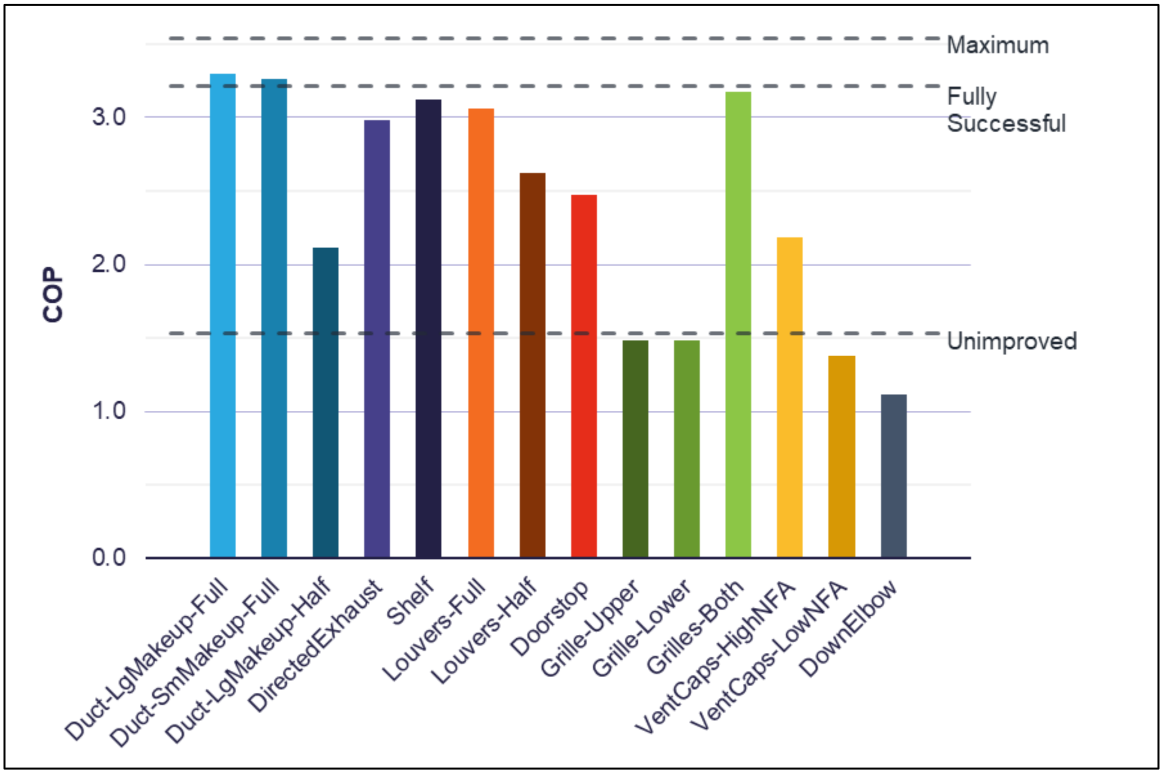
3.3.1 Intervention Efficiency Results

Figure 15 shows the efficiency of each of the intervention tests performed with the 84 ft^3 space. Three reference levels are marked for comparison:

- **1.53:** The COP observed in the 84 ft^3 closed configuration. This is the result achieved without any intervention, so any efficiency above this level is an improvement.
- **3.21:** The COP observed in the 700 ft^3 closed configuration. This test represents a typical manufacturer minimum requirement, implying that the resulting efficiency and hot water delivery performance is acceptable.
- **3.54:** The COP observed in the baseline "open" test. This represents the maximum efficiency possible with the given draw profile and makeup air temperature.

In all, a COP of 1.53 can be considered the floor, 3.54 a theoretical ceiling, and 3.21 a fully successful intervention.

Figure 15. Intervention COPs



3.3.2 Forced Convection Intervention Results Interpretation

Five tests, summarized in Table 7, explored interventions with forced convection. Interpretation of the results reveals three important conclusions about makeup area, exhaust airflow rate, and ductless forced convection.

Table 7. Forced Convection Intervention Test Results

Test	Intake	Exhaust	COP	Improvement over 84 ft^3 closed
Duct-SmMakeup-Full	Floor slot (18 in^2 NFA)	Ducted to adjacent space Unrestricted duct terminus	3.26	113%
Duct-LgMakeup-Full	Upper wall grille (130 in^2 NFA)	Ducted to adjacent space Unrestricted duct terminus	3.30	116%
Duct-LgMakeup-Half	Upper wall grille (130 in^2 NFA)	Ducted to adjacent space Restricted duct terminus	2.11	38%
DirectedExhaust	Floor slot (18 in^2 NFA) Note: Some portion of makeup air was also drawn through the upper door louvers	Exhaust pointed toward door's upper louver panel (129 in^2 NFA)	2.98	95%
Shelf	Four 3-in door holes fitted with wire mesh vent caps (25 in^2 NFA)	Four 3-in door holes fitted with wire mesh vent caps (25 in^2 NFA)	3.12	104%

3.3.2.1 Makeup Area

Comparison of the *Duct-LgMakeup-Full* and *Duct-SmMakeup-Full* tests, in which the only difference was the size of the makeup air opening, shows that makeup area has a small effect on improvement. There is presumably a minimum threshold area needed (and 18 in^2 certainly met it), but the more than seven-fold increase in opening area between these two tests produced no significant improvement. The result of the *Shelf* test further supports this finding: With a total of just 51 in^2 NFA for both intake and exhaust, the *Shelf* intervention still achieved a COP greater than 3.

3.3.2.2 Ducted Airflow Rate

Comparison of the *Duct-LgMakeup-Full* and *Duct-LgMakeup-Half* tests, which differed only in the exhaust flow rate, shows that the flow rate has a significant effect on efficiency. This is to be expected, as the flow rate directly relates to the amount of thermal energy available to the heat pump.

3.3.2.3 Ductless Forced Convection

Both the *DirectedExhaust* and *Shelf* tests produced COPs near 3. They show it is possible to move enough of the cool exhaust air outside of the room to retain efficiency without the use of ducting.

3.3.3 Free Convection Intervention Results Interpretation

Ten tests explored interventions with free convection. For the cases in which those interventions were successful, a stack effect[11]-driven convection loop was observed. In these cases, warmer air near the top of the room is drawn into the HPWH. Once cooled and exhausted from the HPWH, the air's higher density causes it to settle toward the bottom of the room. Where openings to less-dense air on the exterior are present, the cooled air will exit the room. This draws in warmer air through openings higher in the room, completing the loop.

These convection loops were confirmed both through the comparison of air temperatures at different heights in the room (see Section 3.3.3.2) and through the use of smoke sticks. In tests with higher COPs, the smoke was clearly drawn into the room at higher elevations and flowed out from the room at lower elevations. This held true in configurations with continuous open area from low to high (the doorstop test, for example), with the middle section of the opening showing little or no air movement. A qualitative relationship between COP and airflow vigor was also observed.

Further interpretation of the results reveals important conclusions about how total grille/vent/louver area and its distribution contribute to the formation of convection patterns.

Table 8. Free Convection Intervention Test Results

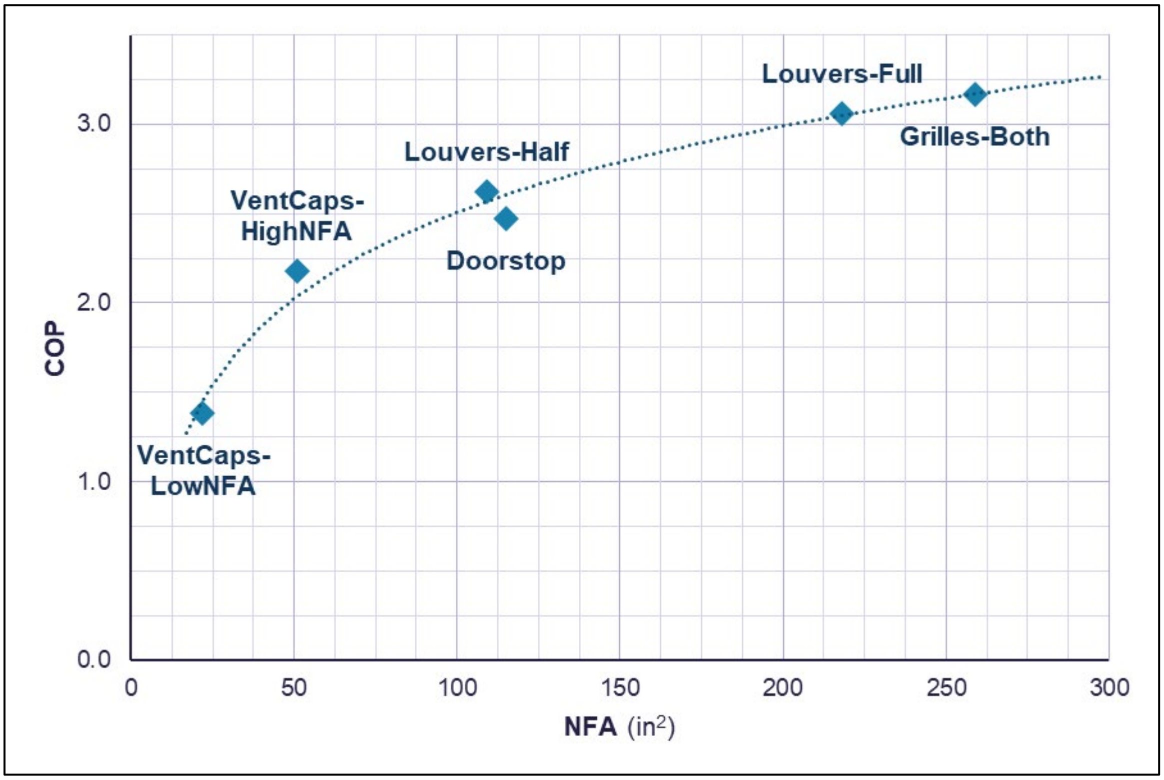
Test	Configuration	Total NFA	Room Volume	COP	Improvement over closed configuration
Louvers-Full	All louvers uncovered	218	84	3.06	100%
Louvers-Half	Half the width of all louvers uncovered	109	84	2.62	71%
Doorstop	Door propped open 1½ in	114	84	2.47	61%
Grille-Upper	Upper wall grille uncovered	130	84	1.48	-3%
Grille-Lower	Lower wall grille uncovered	130	84	1.48	-3%
Grilles-Both	Upper and lower wall grilles uncovered	260	84	3.17	107%
Grilles-Both(200)	Upper and lower wall grilles uncovered	260	200	3.30	116%
VentCaps-HighNFA	8 holes fitted with 3-in wire mesh vent caps	51	84	2.18	42%
VentCaps-LowNFA	8 holes fitted with 3-in plastic vent caps	22	84	1.38	-10%
DownElbow	Exhaust directed immediately and directly downward using ducting adapter and 90° elbow	0	84	1.12	-27%

[11] For a description of the stack effect as it applies to entire buildings, see Chapter 16 Section 3 in the 2021 ASHRAE Handbook – Fundamentals (ASHRAE 2021).

3.3.3.1 Correlation of Total NFA and COP

Increasing NFA relates to an increase in COP. This is to be expected, as larger openings allow more air to move in and out of the room and more freely. Excepting the single-grille tests as outliers (addressed in the following section) and *DownElbow* (because it has no NFA), Figure 16 shows a clear trend. A logarithmic curve provides a useful fit to the data with the equation COP = 0.697ln(NFA) – 0.701 where NFA is in square inches. The logarithmic function captures well the observed behavior in the regimes tested. It highlights the gradual decline in efficiency as NFA decreases and then the sudden acceleration of degraded performance in the lower NFA ranges, suggesting there is somewhat of a “cliff” to fall off. Further, it suggests that increasing NFA leads to diminishing returns, especially above 300 in^2. The equation is not meant to extrapolate performance much beyond the tested range. However, it does suggest that near 500 in^2, the water heater may operate as well as it does in wide open space. This remains untested. On the low end, the curve already predicts performance worse than a closet with no intervention whereby declaring the curve fit useful only to the smallest NFA tested.

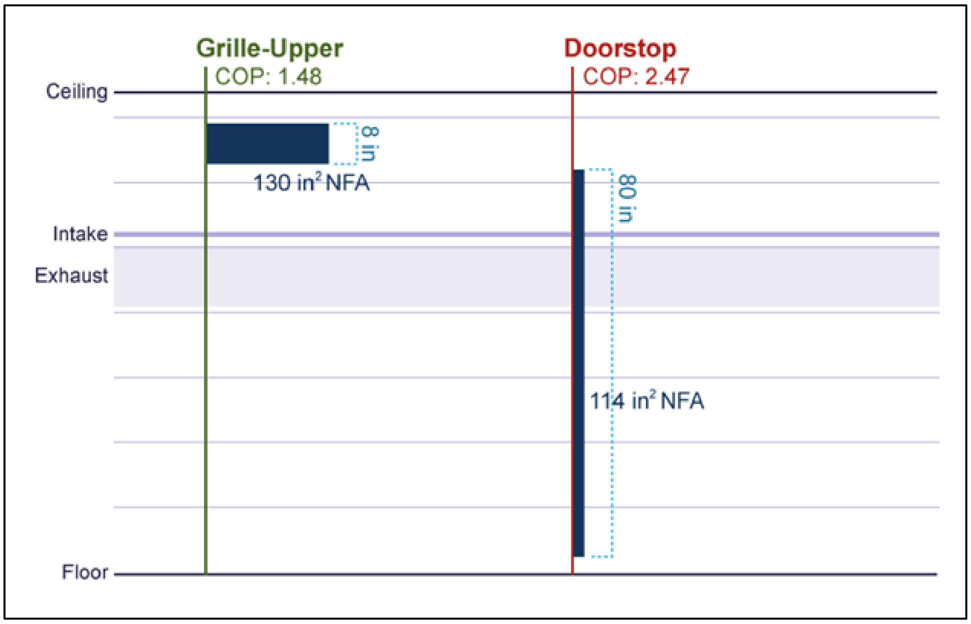
Figure 16. Enclosure Net Free Area (NFA) vs. Coefficient of Performance (COP)



3.3.3.2 Distribution of NFA

With the amount of NFA constituting the first factor, the second determining factor for free convection intervention effectiveness is the vertical distribution of NFA. This is necessary to allow the colder, denser air, which pools at the bottom of the enclosure, to escape and exterior air to enter at the top. The comparison of *Grille-Upper* and *Doorstop* in Figure 17 clearly demonstrates the importance of vertical NFA distribution. While the grille test had slightly higher NFA than the doorstop test, it produced an efficiency one point lower. In fact, neither of the single-grille tests showed any improvement over the closed condition test.

Figure 17. NFA Diagrams (Vertical Distribution) for Two Configurations



The concentration of all NFA across just eight inches of height—whether it be high on the wall or low—prevents a convection current from forming. In contrast, when a similar NFA is spread across 80 inches, it becomes easy for the coolest air to exit near the floor and draw in new, warmer air from above. Refer to Appendix B: NFA Location Visualization to further explore the topic.

The interventions explored in this project cover a variety of NFA vertical distributions, which generally fall into three types: **continuous** (*Louvers-, Doorstop*), **divided** (*Grilles-Both*, *VentCaps-*), and **concentrated** (*Grille-Upper*, *Grille-Lower*). While the total NFA-COP correlation suggests that continuous and divided openings might be equally effective, further research could reveal an ideal distribution. For example, ideally placed divided openings (in relation to room floor and ceiling and to HPWH intake and exhaust) could prove to be meaningfully more effective than continuous openings of equal NFA. Smoke-stick observations of *Louvers-Full*, for example, suggest that most of the air exchange occurs at the top and bottom of the free area and that the middle louvered areas do not contribute to air exchange.

3.3.3.3 Additional Notes

Grilles-Both(200)

The two-grille intervention was tested on both the 84 ft^3 and 200 ft^3 room sizes. In variable room volume testing, the 200 ft^3 size was the largest that resulted in electric resistance heating with the medium draw profile. Opening the two grilles was sufficient to prevent ER heating, showing that this particular intervention can provide a benefit not only to small closet-sized enclosures but to larger volumes as well.

VentCaps

The wire mesh caps, with their greater free area, did produce a substantial efficiency benefit, yet this intervention underperformed many others. The plastic caps actually reduced efficiency compared to a closed room. The project team has not explored the cause for this but attribute it primarily to an insufficient total NFA. For practical applications of the research, detail about interventions with such little NFA are not of interest.

DownExhaust

To confirm that the stack effect indeed contributes to the efficiency improvements of free-convection interventions, this test design attempts to thermally stratify the air within the room (so that the intake in the upper portion of the room can draw from the warmest remaining air) without allowing for air exchange. The design reduced efficiency, for which the project team offers two possible explanations: First, the ducting likely reduced the airflow across the evaporator; and second, directing the exhaust down may have induced a current of cool air first down, but then back up towards the intake—like an ouroboros.

4 Discussion

4.1 Defining a “Small” Space

A complicating characteristic of HPWHs is that while their efficiencies exceed other available options, that efficiency varies significantly depending on several factors. While the standardized UEF rating is informative, it does not guarantee that level of performance in all real-world situations. A main goal of this project is to provide information that better predicts how one factor, the volume of the installation room, will affect efficiency. The results demonstrate that the question of “how small is too small” may be a subjective matter.

- The industry has implicitly endorsed a lower efficiency as satisfactory. The 700 ft^3 minimum that manufacturers currently recommend results in efficiencies lower than the UEF value. Based on the lab testing, that reduction is likely to be about 9%.
- Testing also shows that at just 450 ft^3 HPWHs can achieve impressive COPs, around 3. Even at 200 ft^3 the COP is still around 2.
- The lowest bar might be to exceed the efficiency of the next-best available technology. The lowest COP recorded in testing, 1.24 for the 84 ft^3 closed room with high draw profile, is 30% higher than a high-performing ER water heater.
- For many, the most pragmatic answer to “how small is too small” is the break-even point in cost—the efficiency level at which reduced energy use outweighs higher up-front costs. The room volume required to break even, however, will vary depending on other factors that influence efficiency.
- The high bar would be to match the UEF rating. Direct testing shows that 1,000 ft^3 is insufficient to reach that goal, and estimates extrapolated from the results suggest the volume may be 1,500 to 1,700 ft^3, depending on hot water use.

The project team recommends the definition of a “small” space be based on whether it limits a HPWH’s use of its defining advantage: its heat pump. As discussed above, use of ER heating significantly reduces a hybrid water heater’s efficiency and must be avoided to achieve a HPWH’s potential. Therefore, a room would be “too” small if it has insufficient thermal resource to avoid ER operation under typical demand.

The test results show that point to be below 450 ft^3. Under the medium draw, resistance heat will start to be used somewhere between the 450 ft^3 and 200 ft^3 volumes. At that point, temperatures in the room fall below the compressor’s operating range and the ER elements turn on. Up until then, efficiency drops only due to lower air temperature, and to far less a degree than ER use would cause.

Even under the demands of the high draw profile, the 450 ft^3 room still yields a COP of 2.26. Given that this draw amount is much higher than the average, it should occur on only a few days in a year for a HPWH properly sized for the residence. The COP of 2.97 from the medium draw will dominate on an annual basis. Taken as a whole, the project shows that down to 450 ft^3, a COP of around 3 can be expected from the HPWH. This is with no extra effort to increase the thermal resource.

Concomitantly, the project team defines a “small” space in the context of heat pump water heating to be less than 450 ft^3. Further, the project team recommends manufacturers move their required minimum install volume to this level. Doing so will increase the market of “easy” installs for HPWHs by lowering installation costs in this segment of the building stock.

4.2 Ventilation Improvement Methods

4.2.1 Successful Interventions

The most successful interventions increased the thermal resource within the closet to produce results with COPs near 3 or greater. That COP value is comparable to the performance of a water heater in the 450 ft^3 enclosure and only 6% less than the tested performance in a 700 ft^3 enclosure. The tested methods clearly demonstrate HPWHs can be installed in small spaces and achieve efficiencies equivalent to those in larger rooms. The tests show which methods work well and those that work less well. The best interventions worked through either free or forced convection.

4.2.1.1 Successful Free Convection

The louvered door and wall grille methods both work through free convective air exchange with the adjacent space. To achieve the best efficiencies with free convection, the ventilation NFA should be in excess of 300 in^2 and separated vertically (150 in^2 in upper grille and 150 in^2 in lower grille, for example). Having the grilles as high and low as possible appears to deliver the best results. The full-height louvered door also works in this scenario. Figure 16 shows that NFA as low as 200 in^2 can yield COPs in excess of 3—a threshold for successful intervention. Exceeding the 200 in^2 value is likely not difficult to achieve and will further improve air circulation. Further, in real-world applications, the openings can become fouled or blocked over time. Consequently, the project team recommends 300 in^2 total to achieve best performance. Beginning with slightly more NFA allows the water heater to operate well even if some of the vent area becomes blocked.

4.2.1.2 Successful Forced Convection

The ducting approach, the directed exhaust, and the shelf separating intake from exhaust, all work via forced convection. In the ducting case, the exhaust air is routed to an adjacent space within the building envelope.[12] Exhausting to a location that could benefit from a lower temperature, such as the back of a refrigerator or freezer, could be an energy-optimum way to install a HPWH in a house. Making the duct run as simple as possible when attaching ducting is of utmost importance. The more elbows, the longer the length, and the more complicated the termination cap, the larger the resistance to airflow will be. Also, while testing was only performed with smooth ducting, using flexible ducting is likely to further restrict airflow. The restricted airflow testing, emulating tortuous duct runs, showed substantial drops in efficiency. Considering that most real-world ducting interventions are likely to substantially reduce airflow, in combination with the finding about the effect of such a reduction, the ability to force convection without ducting is significant—which is what the next two options allow.

The direct exhaust approach uses the HPWH fan to move exhaust air out of the closet but does so without ducting. In the case tested, the fan exhaust was aimed at a 45º angle to the louvered door. It was rotated only 45º, not 90º, to maintain access to the water heater control panel. It seems possible that angling the exhaust more directly at the louvers would move more of the cold air out of the space and improve performance. This could be achieved while maintaining access to the controls by using a large transfer grille in the wall directly in front of the exhaust instead of a louvered door.

To be successful, both the ducted and directed approaches require adequate makeup air; 18 in^2 of NFA was demonstrated to suffice. That low amount of area can be achieved with a door undercut, a small grille, or wire mesh vent caps allowing air to enter the enclosure.

Another successful forced convection intervention used a shelf to divide the enclosure into two compartments. In HVAC terminology, the shelf created a “return” plenum and a “supply” plenum. Air entered the return side, at the top of water heater, through ports with a total NFA of 25 in^2, passed across the fan and evaporator, and exited the supply side through ports with a total 25 in^2 NFA. The resulting COP was 3, and it appears that increasing the NFA on both sides will likely increase the COP somewhat. Consequently, for those attempting this approach, the project team recommends a minimum 40 in^2 NFA on each side.

4.2.2 Less Successful Interventions

The interventions that did not provide tested COPs near 3 included exhaust ducting with restricted airflow, a single grille with little vertical extent (either high or low), vent caps/grilles/louvers with NFA less than 200 in^2, and an attached duct elbow to point the exhaust down. These should be avoided in field installations.

[12] Previous work has demonstrated that exhausting to the exterior of the structure is a net energy penalty on the dwelling (Ecotope 2015, Widder and Larson 2018).

4.2.3 Special-Mention Intervention

The doorstop deserves special mention. While it may not be a permanent solution and the tested COP is 2.47—below our desired threshold—it is a free intervention, and its performance is still substantially better than an ERWH. The doorstop could also be used as a temporary solution when retrofitting a HPWH. In cases where the installer is unable to immediately address a small-space challenge with a long-term solution, the HPWH installation could proceed as scheduled and a doorstop left in place until the contractor can return. Such an approach can make the best use of an installer's schedule.

4.2.4 Implications for Exterior Conditions Not Equal to Typical Room Temperatures

All the testing in this project was conducted with air surrounding the install room at room temperature. Other installation configurations exist, including those with an exterior wall or ventilation with the outside. The performance of the HPWH in those installations is expected to differ in the following ways.

4.2.4.1 Air Exchange with Outside

For the small space installations with venting strategies, the temperature of the air being exchanged will matter greatly. If the HPWH is installed in a balcony closet (for example in multifamily) with vents to/from the outside, the air is subject to the outdoor seasonal variation. As long as the air entering the room is within the compressor operation range, the stack effect will drive convection. The HPWH will cool the small space below the outside temperature and create a driving force for ventilation whether the outside air is 50° F or 95° F. If the outdoor air temperature is below the heat pump operating limit, the HPWH will operate in ER mode. Similarly, forced convection strategies will continue to work until the outside temperature drops below the heat pump lower limit. In all cases, the efficiency of the HPWH will be subject to the outside air conditions, which will largely come to dominate the small space temperature. This temperature dependence has been widely studied elsewhere (Kintner 2021, Kvaltine 2015, Larson 2015). Thus, the efficiency of the system can be modeled, although that is not part of this work.

4.2.4.2 Enclosed Volumes with Walls on the Building Exterior

For HPWHs installed in enclosed rooms, it is not unusual for one, or even two, walls of the room to be exterior walls. When outdoor temperatures are below room temperature, the surface area exposed to it will likely slow, and possibly limit, the temperature rebound that follows a heating cycle. The majority of the enclosed conductive surface area, however, will be dominated by conditioned-space temperature. Therefore, the project team conjectures that the presence of an exterior surface will have a minimal impact on efficiency.

4.3 Practicality and Cost Assessment

The benefits of installation interventions constitute an important question raised by the results of this research. In terms of achieving the highest possible energy efficiency in water heating, several of the tested interventions show significant benefits. However, most homeowners are likely to be motivated primarily by cost. Interventions can meaningfully decrease lifetime operating costs by reducing energy consumption through improved efficiency, but they can also add significantly to the up-front installation costs. Moreover, they can potentially require installers with additional skills and/or trades. Given the fairly high efficiency levels found in closed rooms as small as 450 ft^3, consideration should be given to the situations in which intervention, and which interventions, would result in a net benefit to the owner.

The answers to these questions will depend on the priorities of individual homeowners as well as specific conditions of the installation site and usage patterns too numerous to account for here. Instead of attempting to prescribe a method for making such choices, the project team offers a hypothetical example to illustrate a decision that a homeowner may face and some factors they could weigh.

In this example, a homeowner is replacing an ER water heater in an existing structure. The current water heater is installed in a closed room of 84 ft^3. That room is surrounded by spaces conditioned to 67.5° F. The home is in the Pacific Northwest region. Relocating the water heater is prohibited by the cost of rerouting plumbing and electrical service. Table 9 compares the likely efficiencies and estimated costs of various interventions,[13] as well as for both ERWH and HPWH without any intervention (Manclark 2022). Equipment and standard installation costs are not included.

[13] Labor and parts costs estimated by a member of NEEA's HPWH installation implementation team: Bruce Manclark of CLEAResult. CLEAResult works directly with water heater distributors and plumbers to improve HPWH installation quality throughout the Pacific Northwest. The numbers are informed, but rough estimates intended for illustration. Actual costs will vary in real-world installations.

Table 9. Intervention Methods Installation Cost Estimates

Water Heater Type	Ventilation Intervention	Expected COP	Intervention Cost Estimate	
ER	None	0.95	**$0**	
Heat Pump	None	1.53	**$0**	
	Exhaust ducting	2.11–3.30 +38% to +116%	**$360–$890**	
			Labor: $125–$315	Parts: $235–$575
	Two wall grilles	3.17 +107%	**$360**	
			Labor: $310	Parts: $50
	Replace solid door with louvered door	2.62–3.06 +71% to +100%	**$325–$875**	
			Labor: $125–$375	Parts: $200–$500
	3-in. holes with vent caps (8)	2.18 +42%	**$210**	
			Labor: $190	Parts: $20
	Ductless forced convection with shelf	3.12 +104%	**$320**	
			Labor: $250	Parts: $70

While this is just one example and would not apply to many individual installations, it demonstrates some of the decisions an owner or installer may now consider given the new research.

- Installing a HPWH without intervention will still result in higher efficiency than a non-heat pump water heater, though the cost savings in reduced energy consumption may not overcome the higher purchase price of a HPWH.
- Exhaust ducting has significant ranges in both efficiency and cost, due to the range of methods and requirements that may apply. These ranges are likely inversely related—installation costs tend to increase with duct complexity, which itself is likely to reduce the airflow rate and consequently the efficiency.
- Two wall grilles or ductless forced convection are both interventions in the lower range of costs and can more than double efficiency.
- The costs of two of the simplest options (wall grilles, 3-in holes) are dominated by labor costs. Homeowners with even basic tools and carpentry skills could implement those interventions themselves at a much lower cost.
- In rooms between 84 ft^3 and 450 ft^3, the intervention costs are likely to remain the same, but the relative increase in efficiency will be less. In this volume range, one may be hard-pressed to justify the cost of any intervention.

5 Conclusions

The laboratory testing provides detailed information about known but previously unquantified challenges for HPWH efficiency in enclosed rooms. Interpretation and application of the findings can help increase the number of cases in which a HPWH retrofit installation can be recommended and successfully implemented. When installing a HPWH, the project team always recommends first consulting and following manufacturer instructions.

5.1 Research Questions

The project produced many actionable findings under its two primary research questions.

5.1.1 How Does Room Volume Affect Efficiency?

The project team identified three main factors that determine the COP of a HPWH in an enclosed room: **Ambient air temperature** during heat pump operation, **hot water use**, and **compressor operating range**.

Compared to an installation space with an unlimited supply of room-temperature makeup air, the project team estimates that an **enclosed installation room will reduce efficiency if its volume is less than 1,500–1,700 ft^3**.

The incremental reduction in efficiency increases as room volume decreases.

- From an open space to a 1,000 ft^3 room, efficiency may drop as little as 9%
- From 1,000 to 700 ft^3, no loss in efficiency is observed
- From 1,000 to 450 ft^3, the efficiency loss is around 7%, and the COP remains near 3
- Between 450 and 200 ft^3, the incremental efficiency loss accelerates, producing significantly lower COP
- At 84 ft^3, COP is very low for a HPWH, but still above that of electric resistance water heaters

Heavier hot water use patterns produce lower efficiencies in an enclosed room than moderate use patterns, but **the relative effect of room volume is similar on both medium and high water use patterns**.

Room volumes below 450 ft^3 and the presence of a wall within five feet of the water heater exhaust port can increase the likelihood that exhaust air will circulate directly back to the HPWH intake.

5.1.2 How Effective are Different Interventions at Improving Efficiency?

Tests demonstrated that various interventions have a wide range of effectiveness and also identified factors that contribute to effectiveness or that indicate low performance.

The most commonly recommended interventions, **ducting**, **directing exhaust through an opening**, **louvered doors**, and **wall grilles**, can all effectively improve efficiency in small rooms. Some novel approaches, including other forms of ductless forced convection, are also effective.

Both **forced** and **free convection** can successfully restore efficiency. In forced convection, **maintaining sufficient airflow across the evaporator** is critical. In free convection, the key factors are the **total NFA** and its placement **both high and low** in the room.

5.2 Implications and Recommendations

Based on the answers to the research questions and other findings of the research, the project team has identified potential implications and recommendations for the installation of HPWHs in small spaces. Overall, HPWHs can be considered an effective solution in spaces smaller than generally understood at present.

5.2.1 Enclosed Rooms

An enclosed room should be considered too small for a HPWH when it causes ER operation under typical use. With the equipment tested, that volume is between 200 ft^3 and 450 ft^3. Manufacturers of equipment similar to this model should consider reducing minimum volume specifications.

Additional volume beyond that threshold is beneficial. The incremental benefit of adding volume, however, decreases as the rooms get larger and the benefit of volume over 700 ft^3 appears insubstantial. Below the 200 ft^3 to 450 ft^3 threshold, interventions should be considered.

5.2.2 Intervention

Several methods can increase HPWH efficiency in even a closet-sized room to match the performance of HPWHs installed in rooms meeting current manufacturer specifications. For all interventions, efficiency benefit is likely to decrease as room volume increases. Especially given the relatively high efficiencies seen in closed-room tests, interventions in rooms over 200 ft^3 may not justify their costs.

One of the most commonly discussed methods, ducting, merits critical reconsideration. This approach may only be effective when the equivalent duct length is very short. Especially where cost-effectiveness is a concern, other options are likely to compare favorably.

In forced-convection interventions, minimizing restrictions to airflow is critical. Ductless designs—such as the directed exhaust and shelf interventions—can be effective. Allowing a path for makeup airflow is important, but it does not require a large NFA.

In free-convection interventions, a minimum of 300 in^2 should be added to the enclosure, and it should be split between the upper and lower portions of the room. Having one opening at the floor and one above the HPWH air intake is likely beneficial.

5.3 Future Research

The project team has identified several areas in which further research could provide more detailed and actionable information about HPWHs in small spaces:

- Perform similar laboratory testing with additional makes, models, and storage capacities of HPWHs to evaluate generalizability of findings
- Perform testing with larger enclosures to confirm the volume necessary to match efficiency seen in the open condition
- Perform ducted-exhaust tests with a more granular range of flow rates/static pressures to improve ability to estimate performance with various duct configurations
- Identify ideal vertical position of vents for free convection interventions
- Evaluate interventions tests using makeup air cooler than 67.5° F
- Create simulation capability to model HPWHs in small spaces exchanging air with the outside

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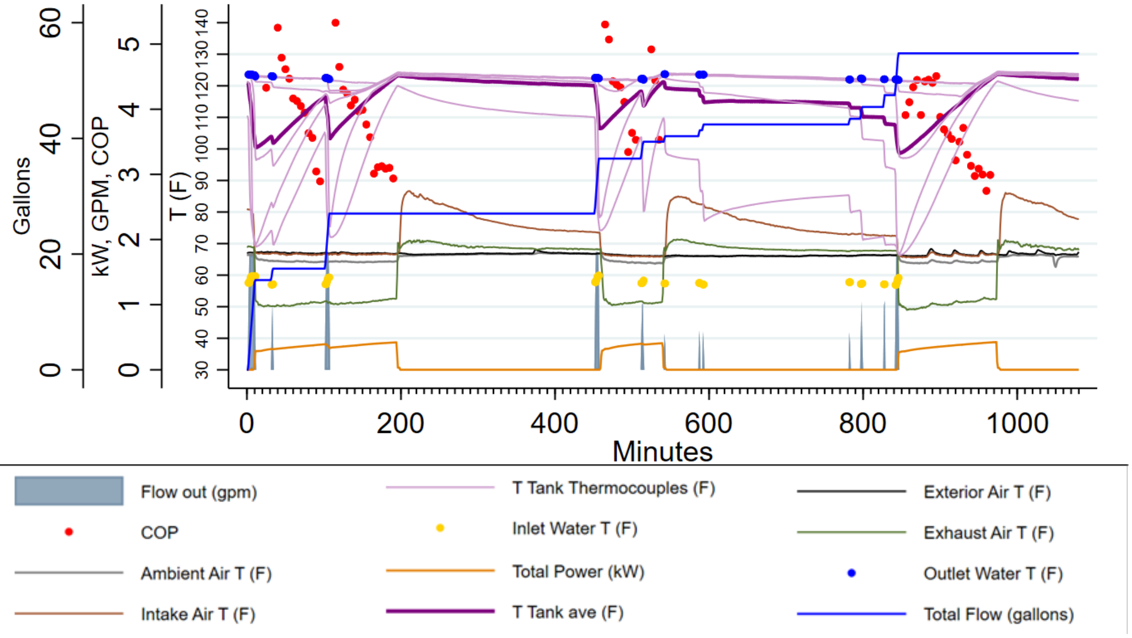
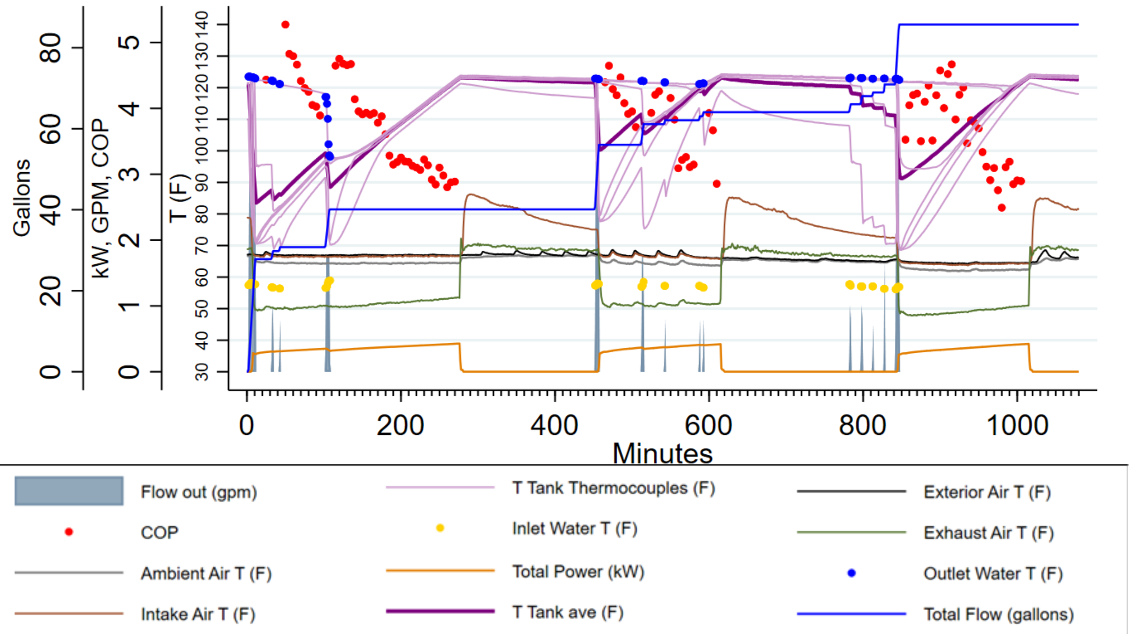
Appendix A: Test Data Graphs

A.1 Open

A.1.1 Open-Med

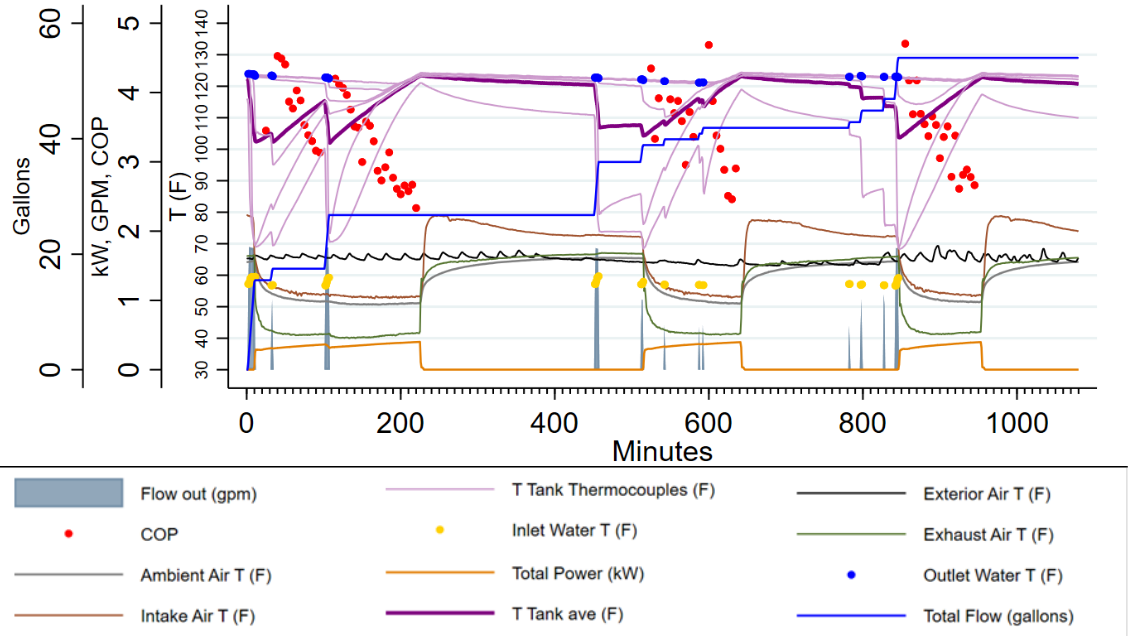


A.1.2 Open-High

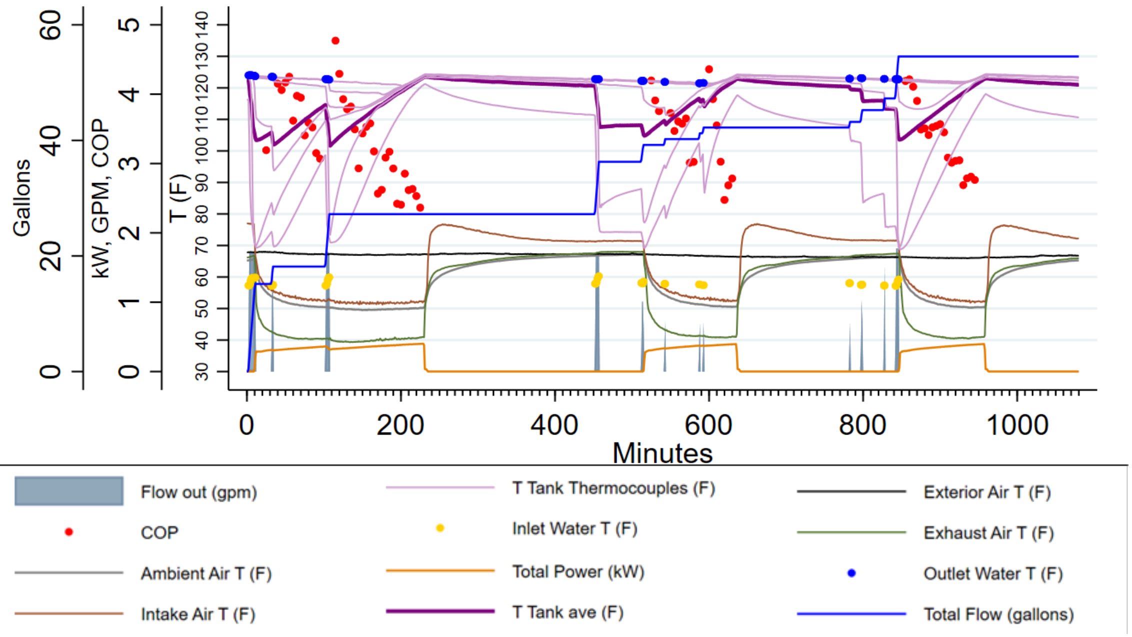


A.2 Variable Room Volume

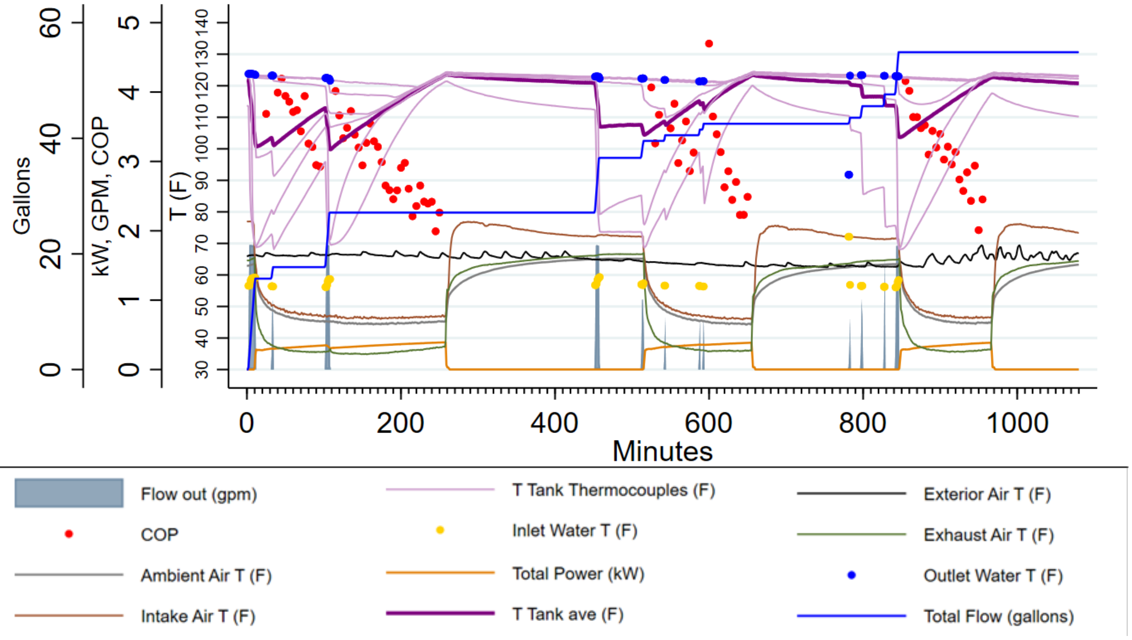
A.2.1 Closed-Med-1000



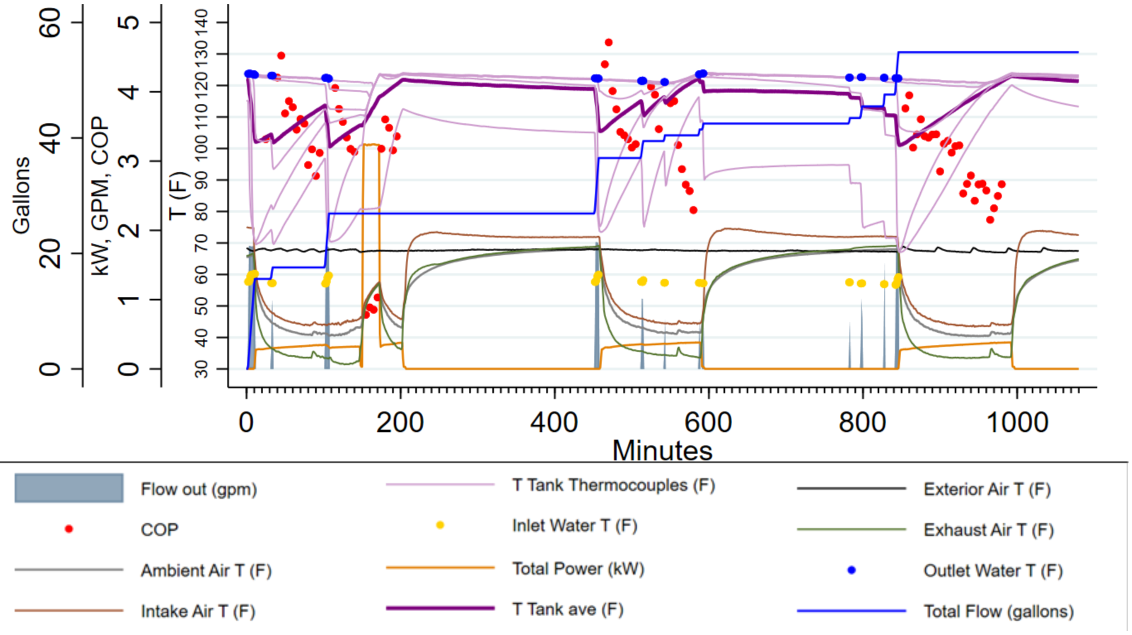
A.2.2 Closed-Med-700



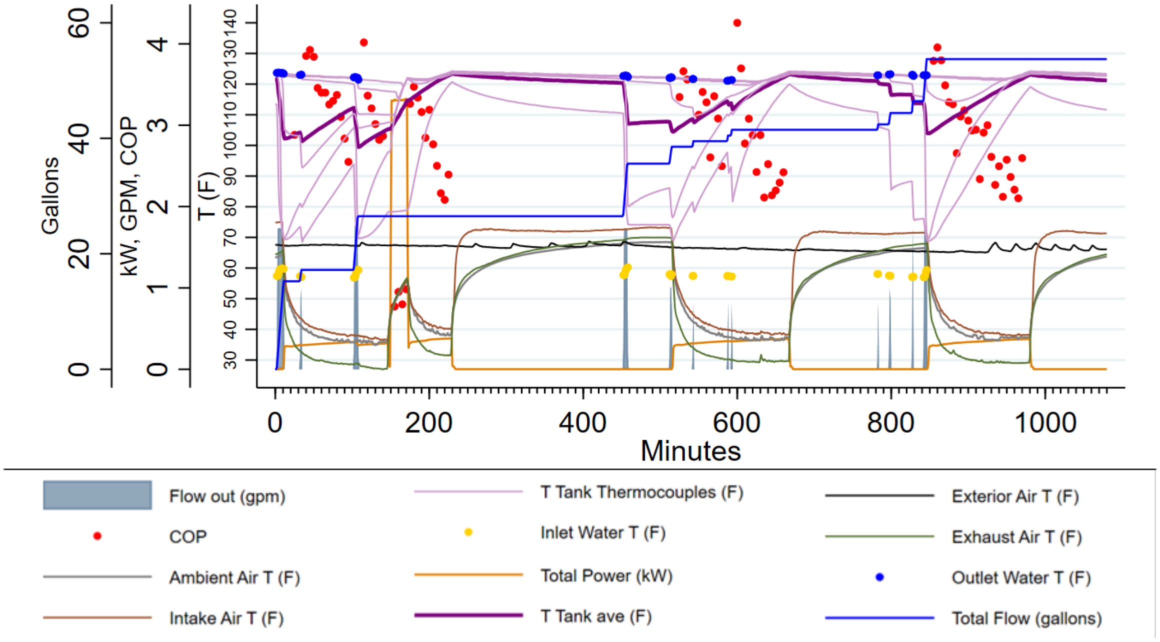
A.2.3 Closed-Med-450



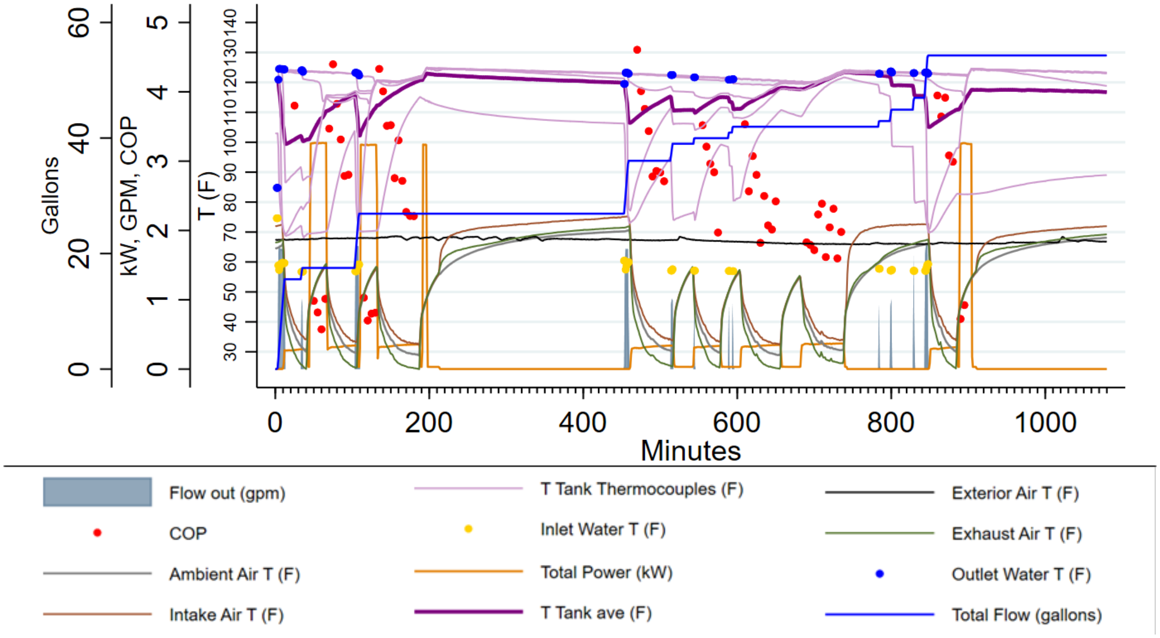
A.2.4 Closed-Med-200



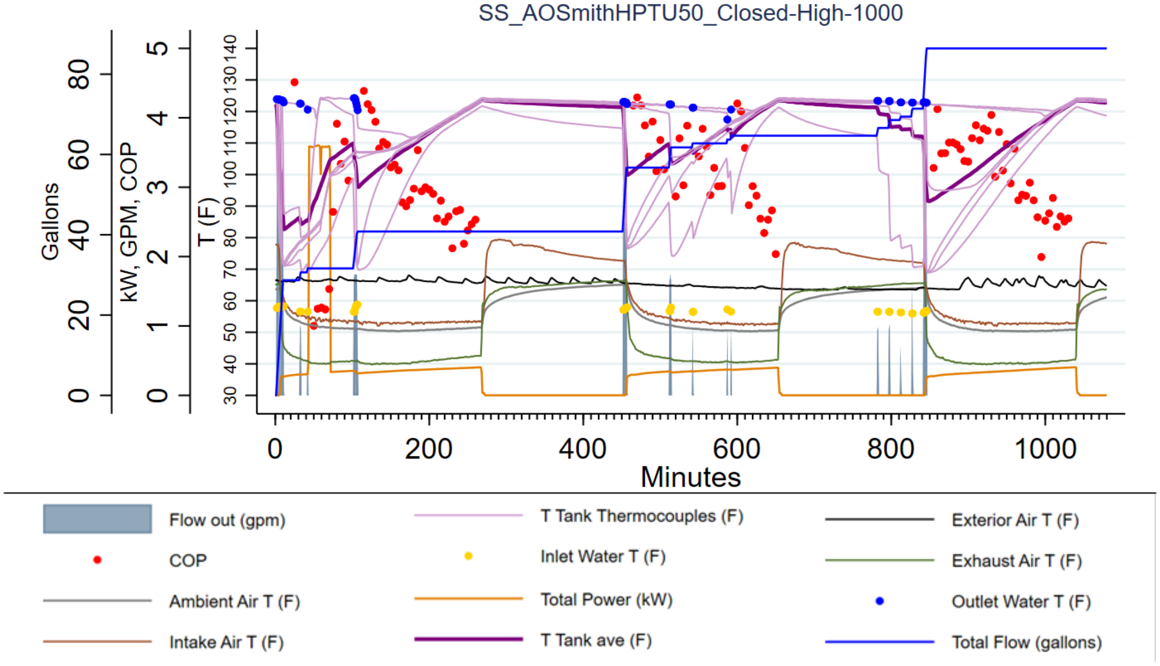
A.2.5 Closed-Med-200b



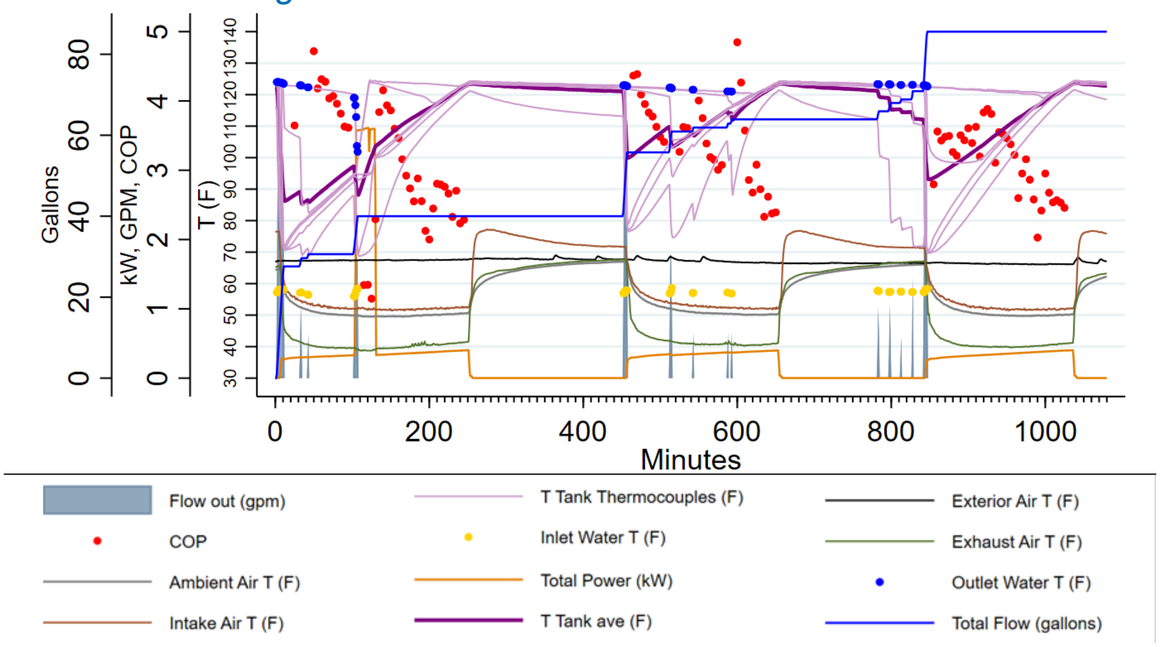
A.2.6 Closed-Med-84



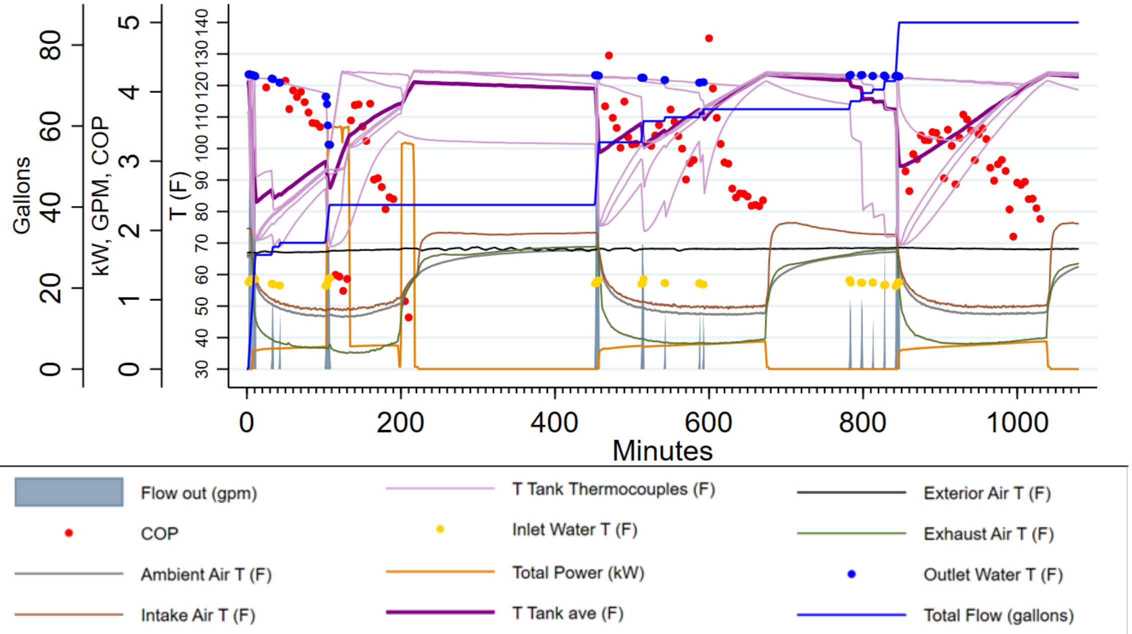
A.2.7 Closed-High-1000



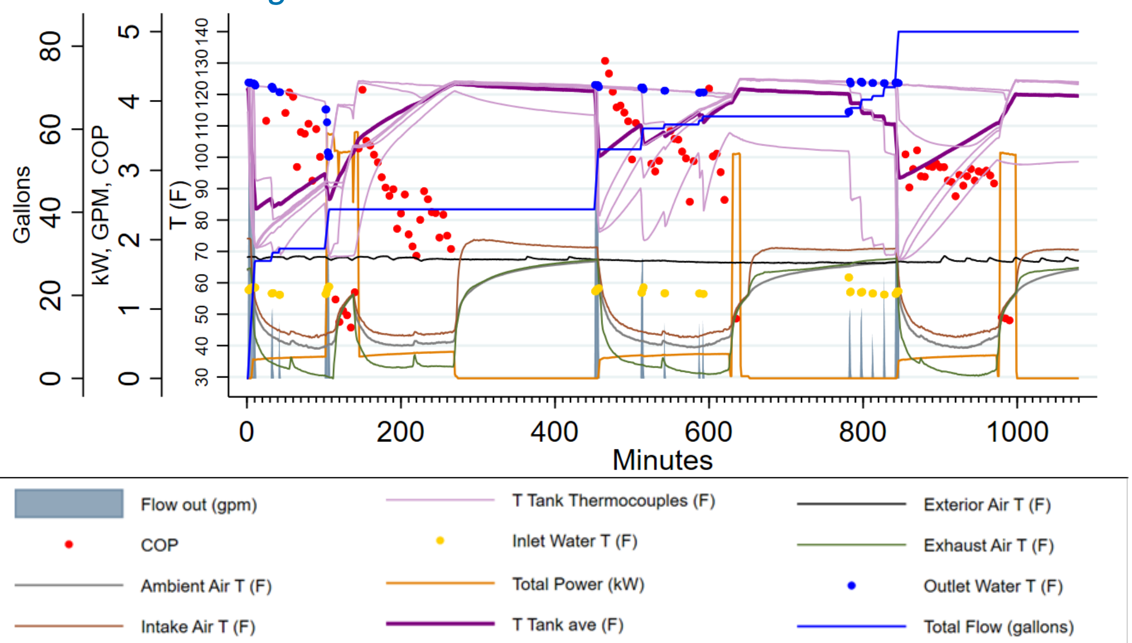
A.2.8 Closed-High-700



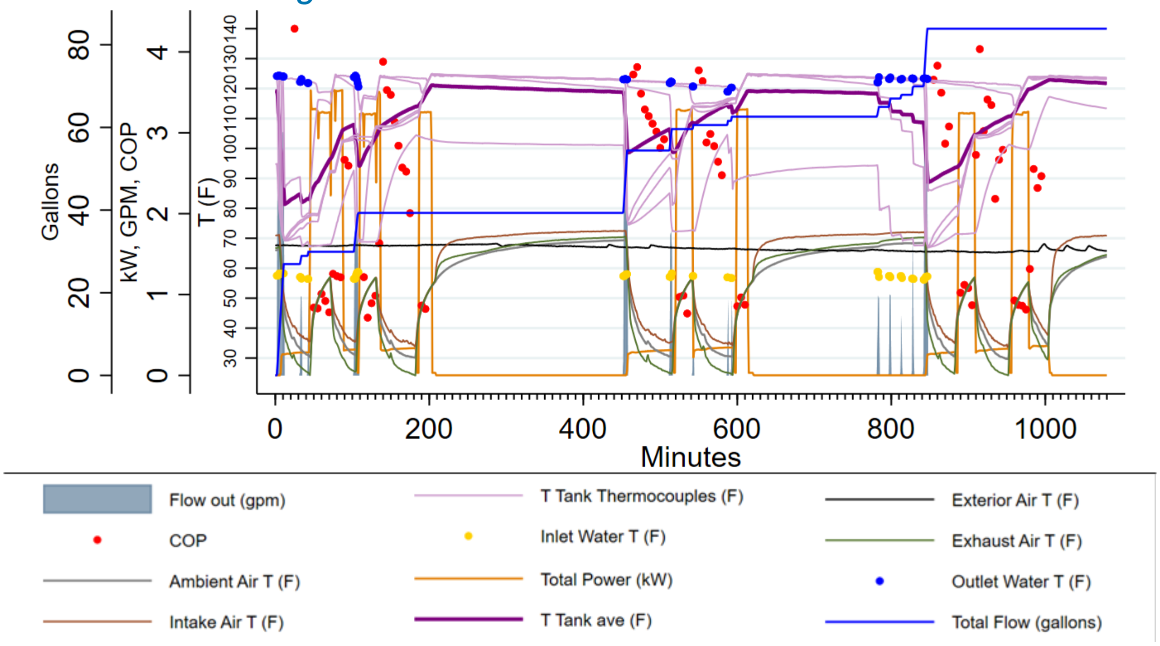
A.2.9 Closed-High-450



A.2.10 Closed-High-200

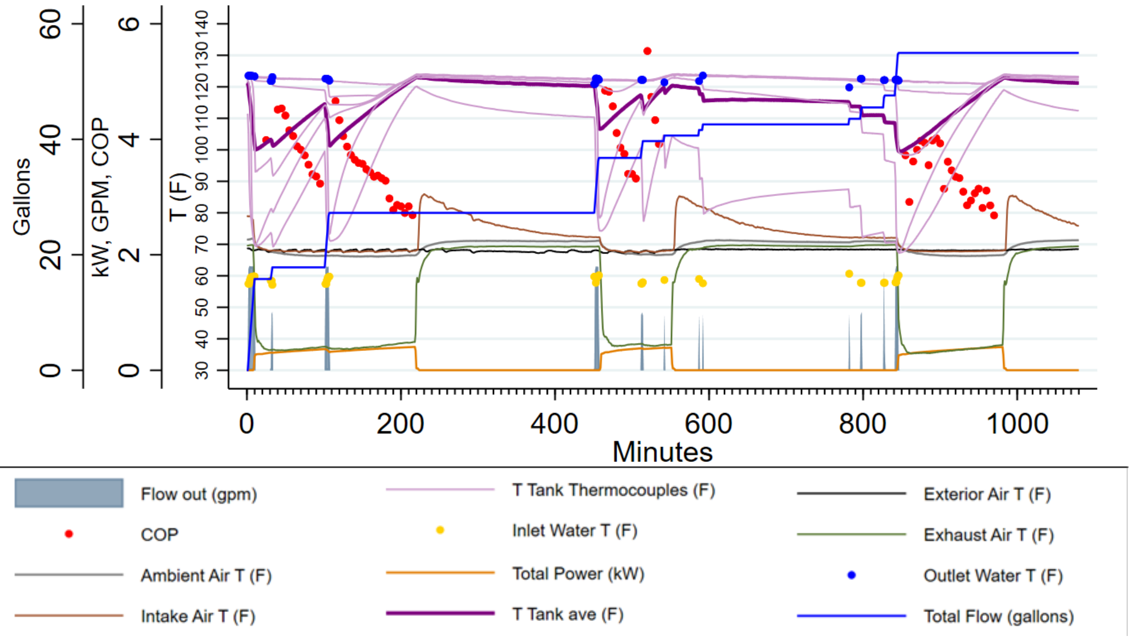


A.2.11 Closed-High-84

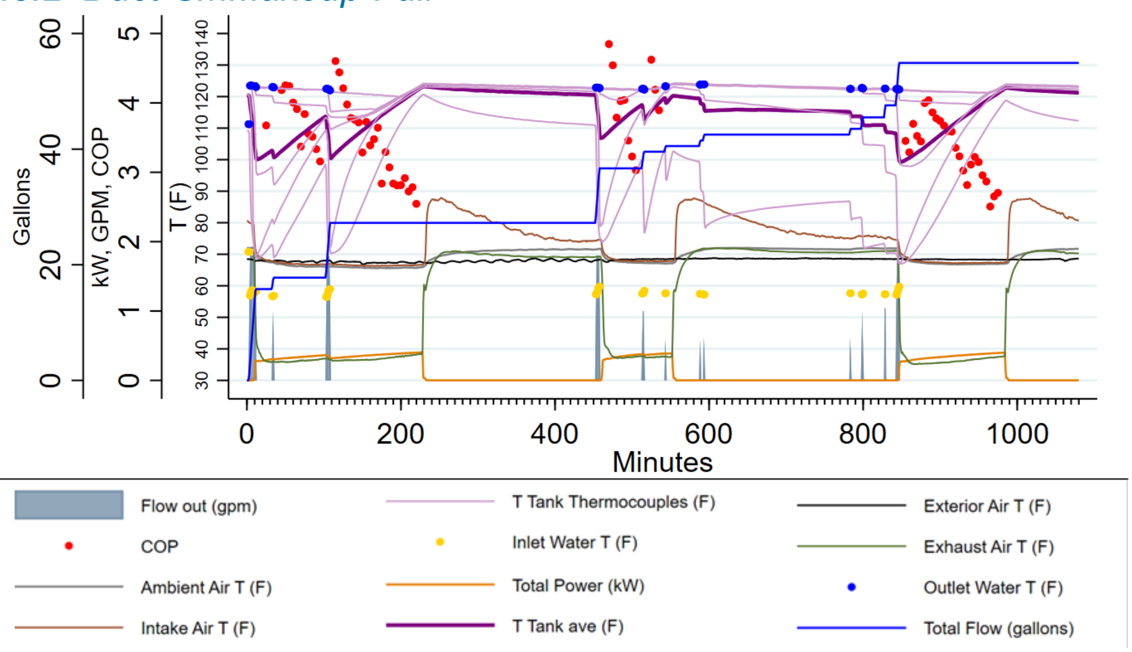


A.3 Interventions

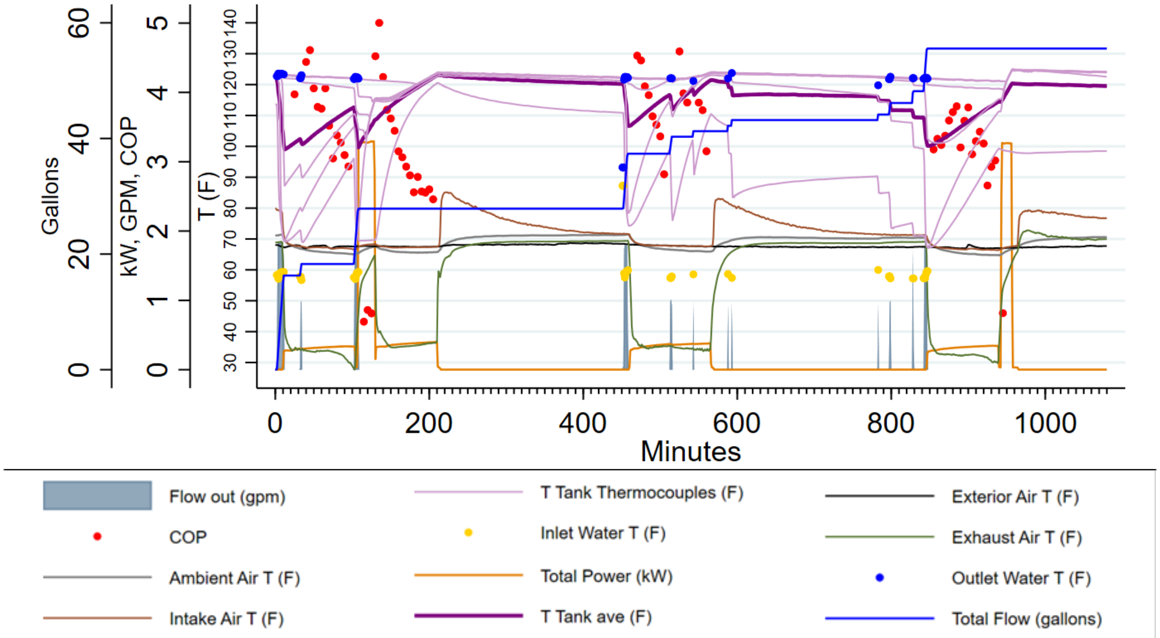
A.3.1 Duct-LgMakeup-Full



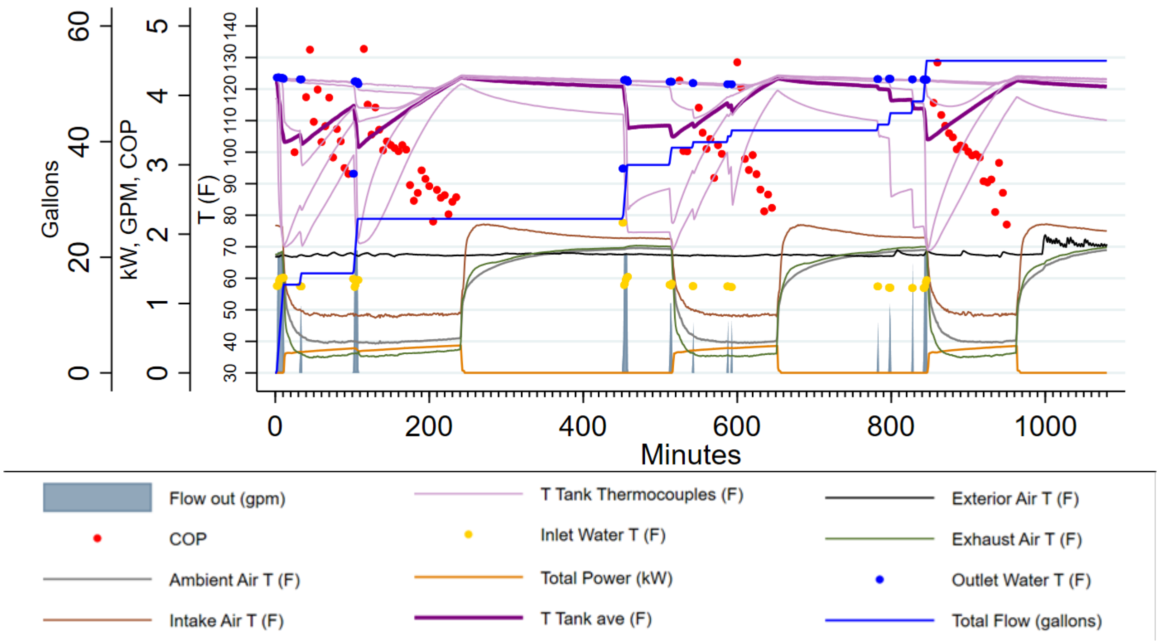
A.3.2 Duct-SmMakeup-Full



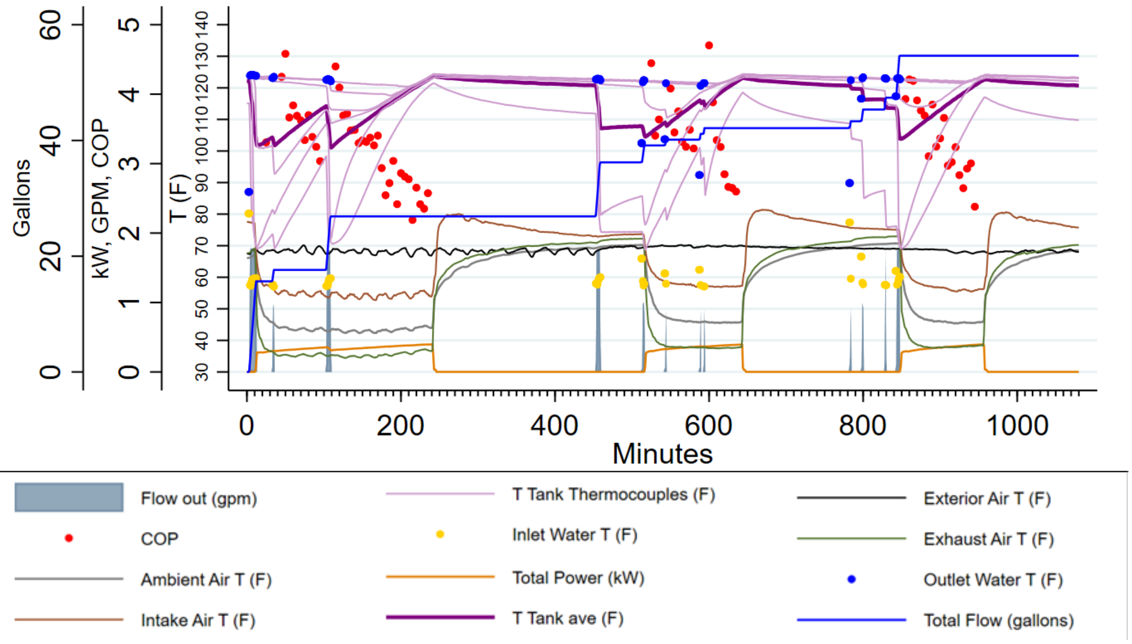
A.3.3 Duct-LgMakeup-Half



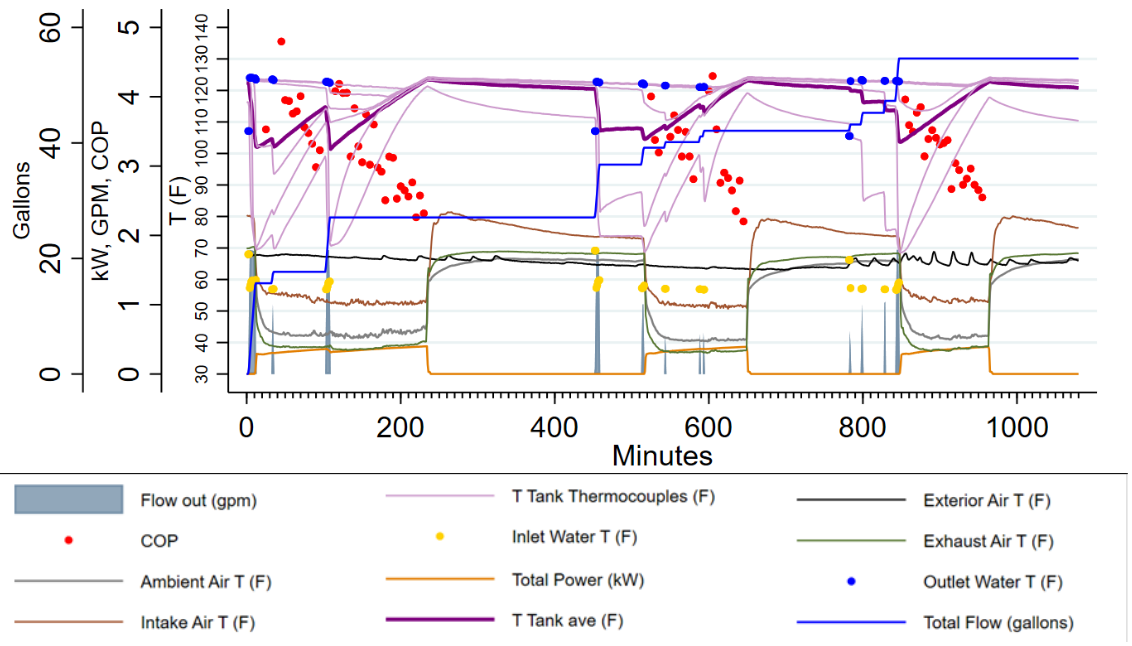
A.3.4 DirectedExhaust



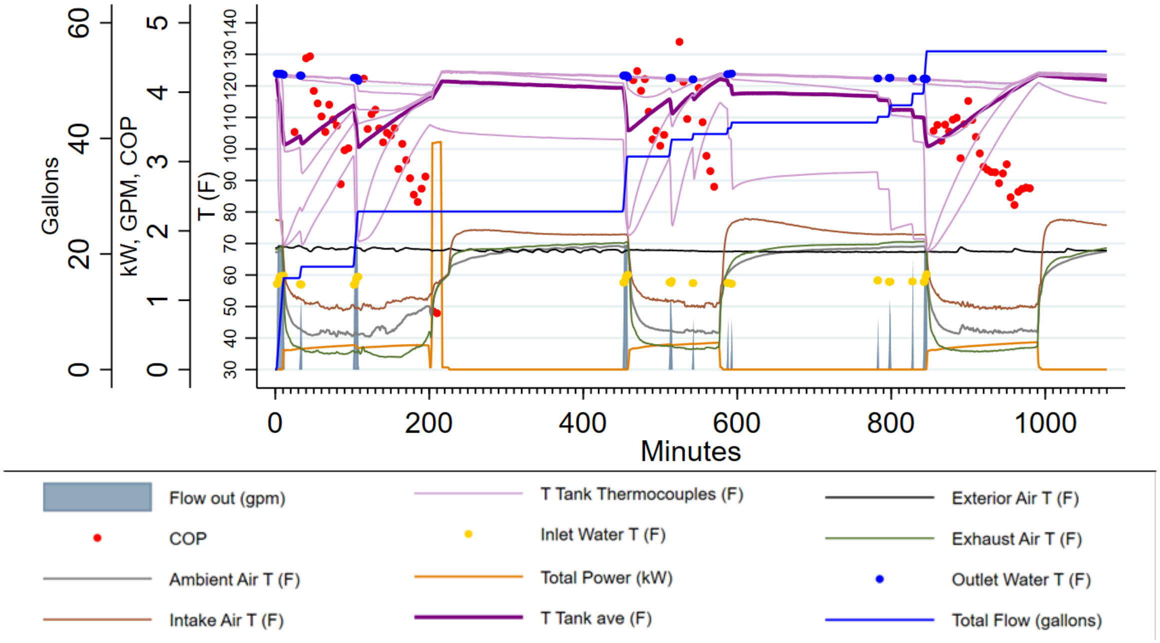
A.3.5 Shelf



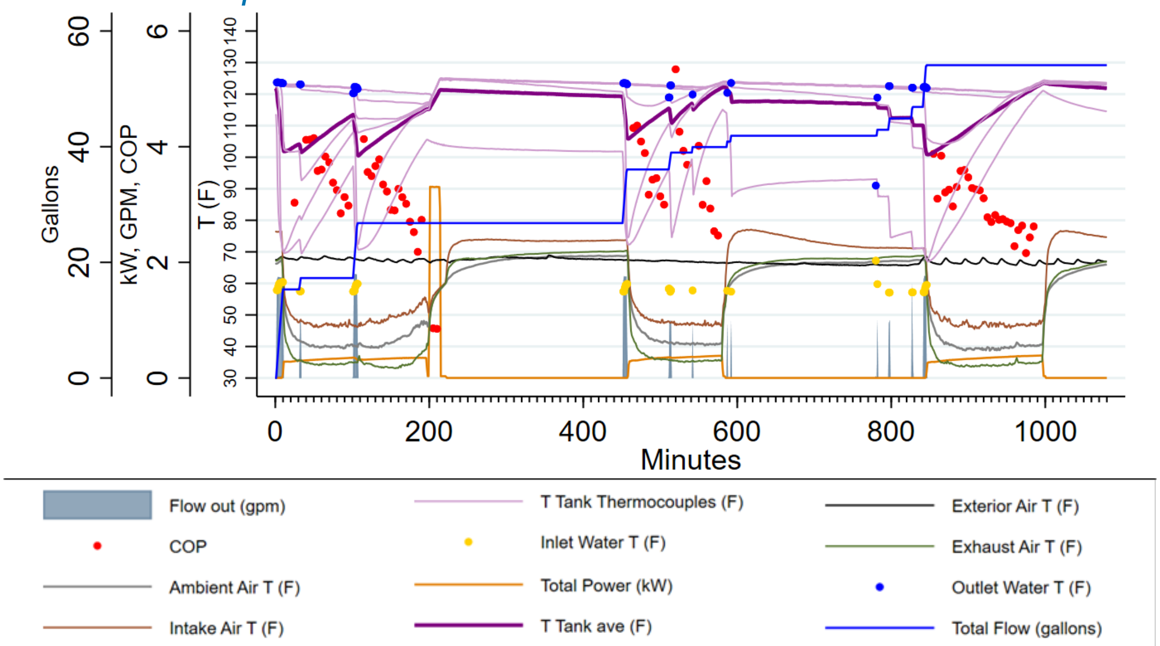
A.3.6 Louvers-Full



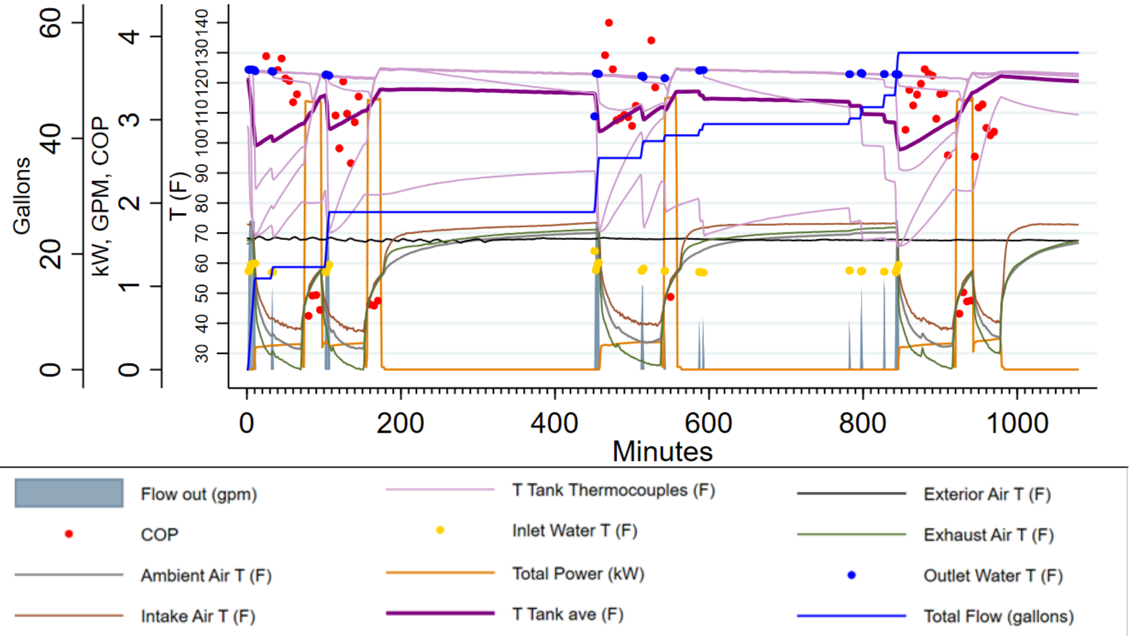
A.3.7 Louvers-Half



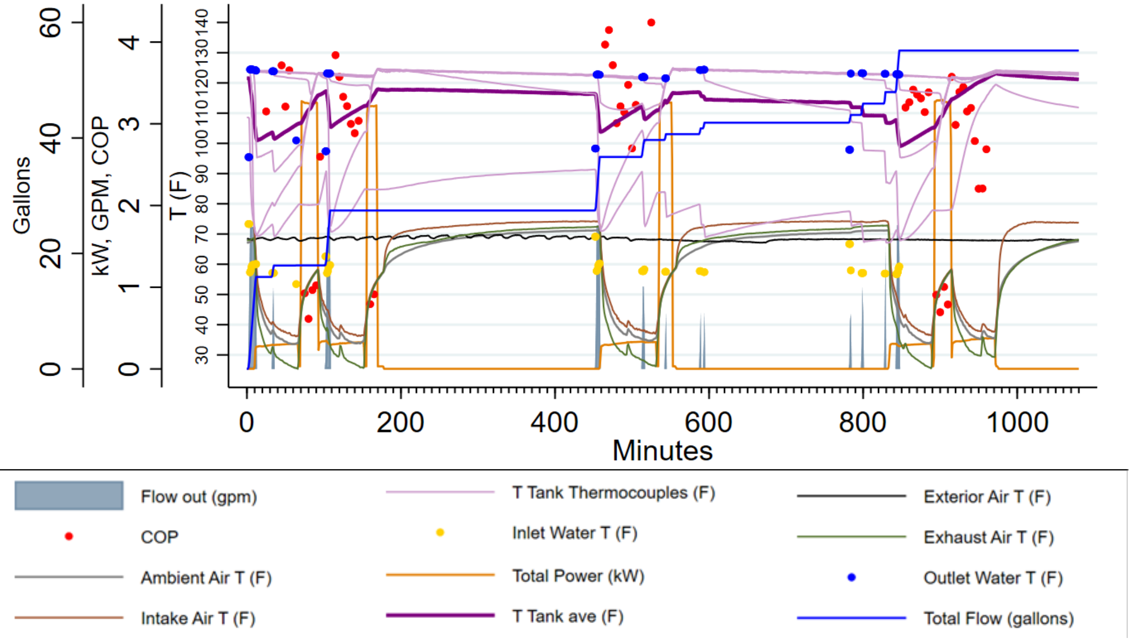
A.3.8 Doorstop



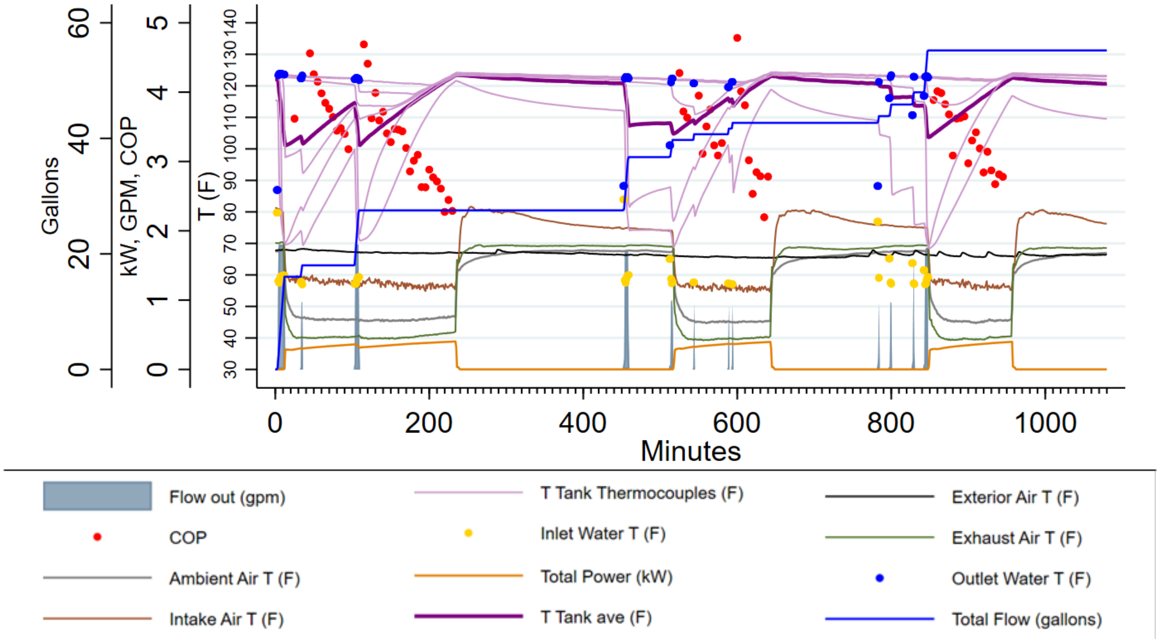
A.3.9 Grille-Upper



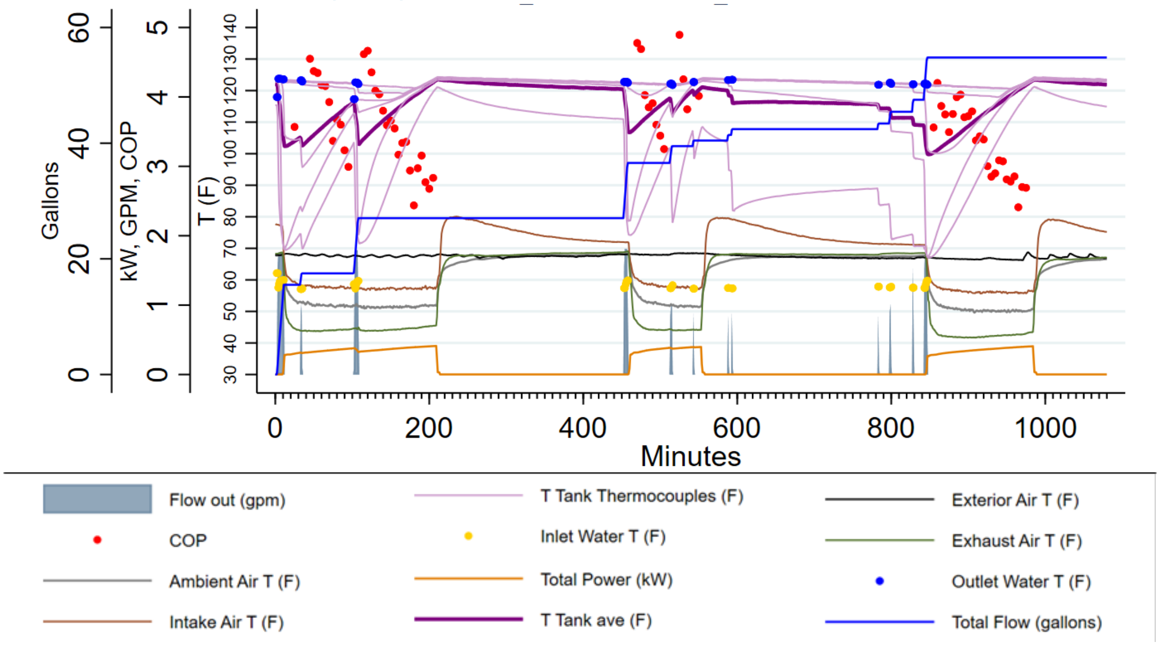
A.3.10 Grille-Lower



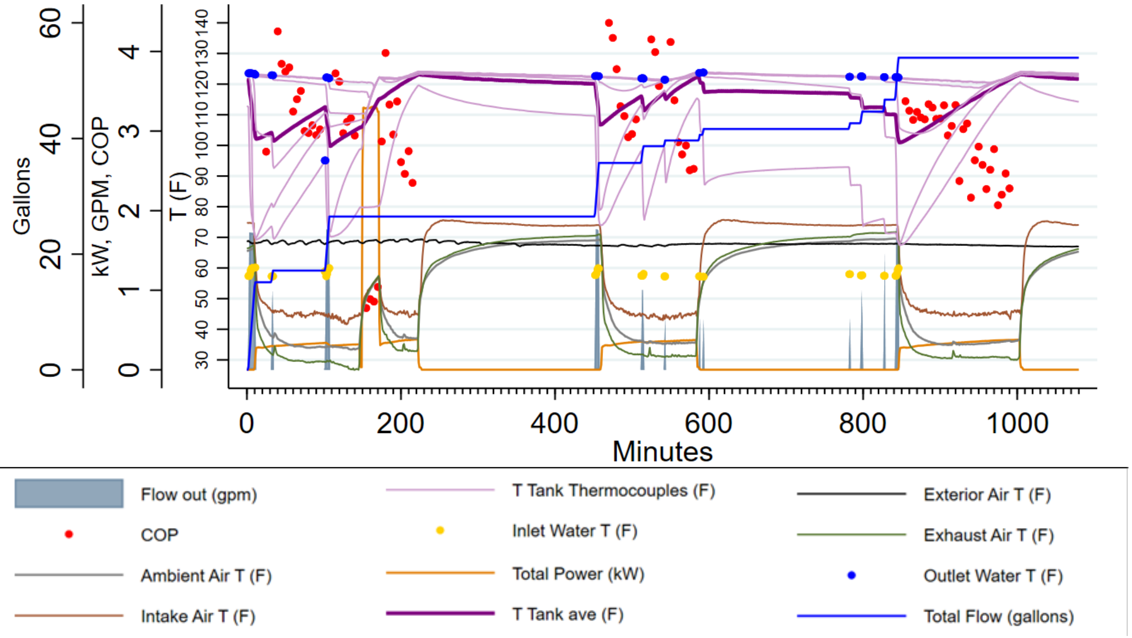
A.3.11 Grilles-Both



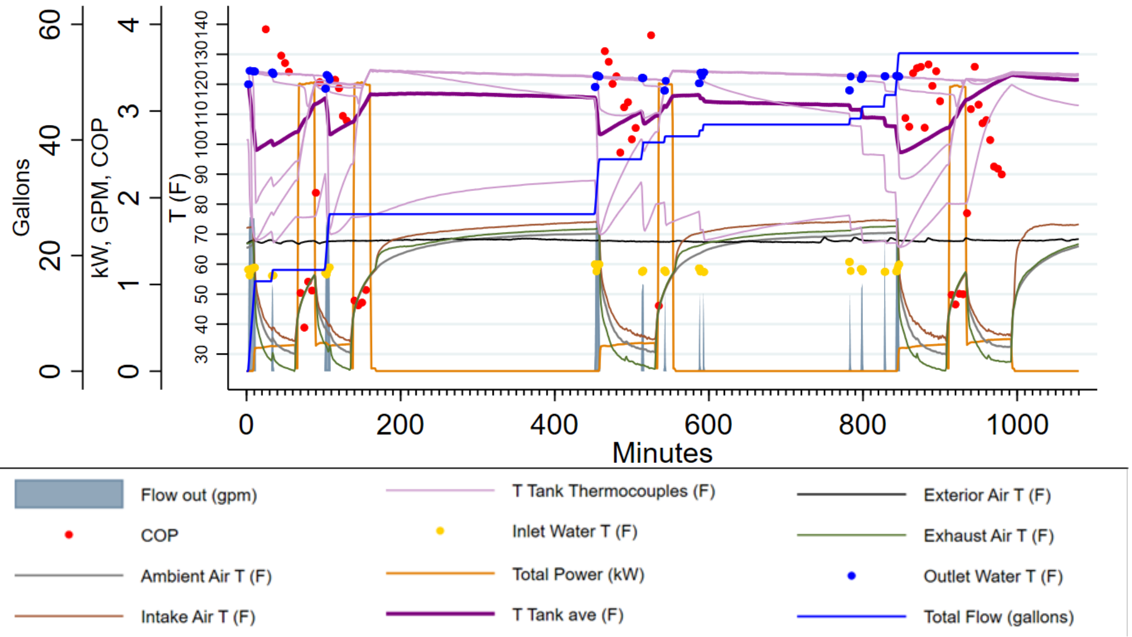
A.3.12 Grilles-Both(200)



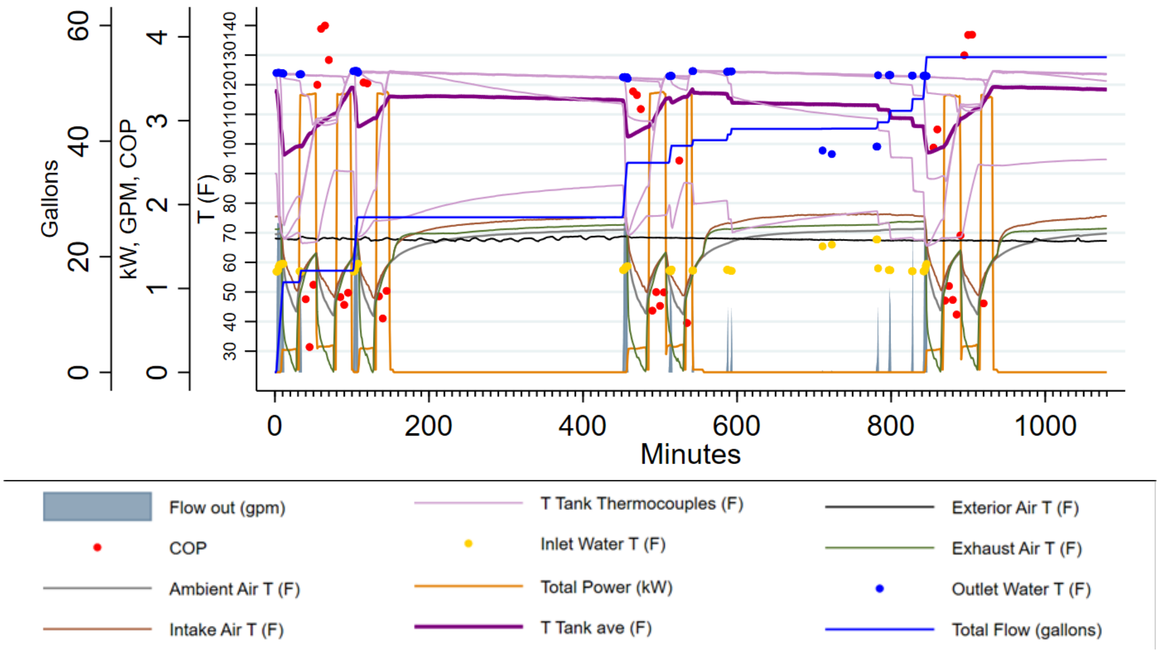
A.3.13 VentCaps-HighNFA



A.3.14 VentCaps-LowNFA



A.3.15 DownElbow



Appendix B: NFA Location Visualization