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NEEA Report: Laboratory Assessment of AirGenerate ATI66 Hybrid Heat Pump Water Heater

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Table of Contents

List of Figures

List of Tables

Executive Summary

The Northwest Energy Efficiency Alliance (NEEA) contracted with Ecotope, Inc. and Cascade Engineering Services Inc., to conduct a laboratory assessment of the AirGenerate ATI hybrid heat pump water heater (HPWH) for northern climate installations. Using a testing plan developed by Ecotope to assess heat pump water heater performance, Cascade Engineering evaluated the 66-gallon version of the ATI.

The goals of the work were three-fold: to support development of the Northern Climate Heat Pump Water Heater Specification; to find products on the market compliant with the specification; and to assist manufacturers in their product development efforts by sharing test results.

The testing plan included characterizing the fan airflow; measuring heat pump efficiency over a range of ambient temperatures while focusing on low temperature performance; conducting the standard 24-hour and 1-hour rating tests; measuring noise output levels; and quantifying the number of efficient showers delivered at 50°F ambient. Overall, the results demonstrated that the ATI66 is well-designed to effectively exploit heat pump efficiency and is compliant with the Northern Climate Specification. Specific findings include:

- Both the Coefficient of Performance (COP) and 24-hour Energy Factor (EF) tests demonstrated the equipment design preserves performance over a range of low operating temperatures. The Northern Climate Energy Factor is slightly above 2.0.

- The heating component controls are designed in a simple and elegant way to both be efficient and meet high demand periods. The 66-gallon tank provides three consecutive 16-gallon showers before switching to resistance heat. Further, in the "Auto" operating mode, the 1-hour tests showed approximately 72% of the stored hot water needs to leave the tank before the resistance element engages.

- The fan measurements showed the equipment is suitable for connecting to an exhaust duct system. The fan maintains the air flow level across any reasonable duct scenario. The fan gives the installer the flexibility of ducting the cooler exhaust air away from the location where the unit is installed without compromising HPWH performance

- The active defrost and wide ambient temperature operating range makes the unit well-suited for Pacific Northwest buffer space installations. Notably, the compressor, under default settings, operates until 32°F.

1 Introduction

Using the measurement and verification (M&V) plan developed by Ecotope to assess heat pump water heaters (HPWH), Cascade Engineering Services, Inc. evaluated the AirGenerate AirTap Integrated (ATI) HPWH. This model has two tank sizes available: 50 gallons and 66 gallons. Cascade Engineering tested the larger 66-gallon tank, referred to as the ATI66. The M&V plan consists of a series of tests to assess equipment performance under a wide range of operating conditions. Cascade Engineering also conducted further tests as specified in the appendices to the Northern Climate Heat Pump Water Heater Specification. The tests included measurement of basic characteristics and performance including first hour rating and Department of Energy (DOE) Energy Factor (EF), description of operating modes, measurement of heat pump system efficiency and the effects of restricted airflow. For a detailed description of the tests and conditions, refer to the M&V plan document and to the report prepared by Cascade Engineering, which documents the test equipment and procedures. This report focuses primarily on the equipment operation and performance itself and not on the interactions with the building in which it is installed.

Ecotope examined two revisions of this particular model of HPWH. Cascade Engineering conducted the majority of testing on a unit delivered to its labs in early 2011 (referred to as rev1) and conducted additional testing on an updated version delivered in the summer of 2011 (referred to as rev2). AirGenerate made changes to the equipment partially based on results observed in testing the rev1 unit; the two most significant physical changes between rev1 and rev2 consisted of improvements to the insulation of the tank and moving the condenser lower inside the tank to heat the water volume at the very bottom. Appendix A lists the tests performed on each version. Given the small and well-understood nature of the changes between revisions, much of the testing output on rev1 is still applicable to performance on rev2. This report distinguishes between the two revisions where relevant.

2 Methodology

Cascade Engineering collaborated with Ecotope and NEEA to devise methods and protocols suitable for carrying out the testing plan. Cascade Engineering incorporated the following documents into its procedures:

- The heat pump water heater measurement and verification protocol developed by Ecotope http://www.bpa.gov/energy/n/emerging_technology/pdf/HPWH_MV_Plan_Final_012610.pdf
- Northern Climate Specification for Heat Pump Water Heaters http://neea.org/northernclimatespec
- Department of Energy testing standards from Appendix E to Subpart B of 10 CFR 430
- American Society of Heating, Refrigeration, and Air Conditioning Engineers Standard 118.2-2006 for the Method of Testing for Rating Residential Water Heaters

The general approach and methodological overview is provided here. All figures and schematics in this section are courtesy Cascade Engineering.

In alignment with the type of test conducted, Cascade Engineering carried out the testing at three different locations within its facility:

- Inside an ESPEC Model # EWSX499-30CA walk-in, thermal chamber;
- In a large lab space which was not thermally controlled but was kept at room temperature conditions; and
- In a room with low ambient noise.

The DOE, COP and Draw Profile tests require tight controls on the ambient air conditions, so those tests were all conducted in the thermal chamber. The chamber is capable of regulating both temperature and humidity over a wide range. For this testing, the chamber created environmental temperatures from 30°F to 95°F. The chamber independently monitors and records temperature and humidity conditions at one-minute intervals. Figure 1 shows the HPWH installed inside the thermal chamber. The test plan did not require tightly-controlled conditions for the verification of the operating modes so those tests were conducted in the large lab space at whatever conditions were encountered at the time (typically 55°F-70°F). Additionally, Cascade Engineering conducted the airflow measurements and any one-time measurements of system component power levels under these conditions. Lastly, Cascade Engineering moved the HPWH to a room with ambient noise levels below 35dBA to measure the noise emanating from the operating equipment.

Figure 1. HPWH Test Unit Installed Inside Thermal Chamber

Figure 2 is a schematic of the general test setup. Cascade Engineering installed an instrumentation package to measure the required points specified by the DOE test standard as well as additional points to gain further insight into HPWH operation. A tree of six thermocouples positioned at equal water volume segments measured tank water temperature (**Error! Reference source not found.**). For both the ATI66 rev1 and rev2 tests, Cascade Engineering augmented the DOE-required six thermocouples with seven more at equal spacing, giving a total of thirteen thermocouples in the tree. Cascade Engineering measured inlet and outlet water temperatures with thermocouples immersed in the supply and outlet lines. Three thermocouples mounted to the surface of the evaporator coil at the refrigerant inlet, outlet, and midpoint monitored the coil temperature to indicate the potential for frosting conditions. Power for the equipment received independent monitoring for the entire unit, the compressor, and the resistance elements (**Error! Reference source not found.** and Figure 5). Cascade Engineering made a series of one-time power measurements for other loads including the control board and the fan. Appendix C provides a complete list of sensors, which includes more than those mentioned here, plus their rated accuracies.

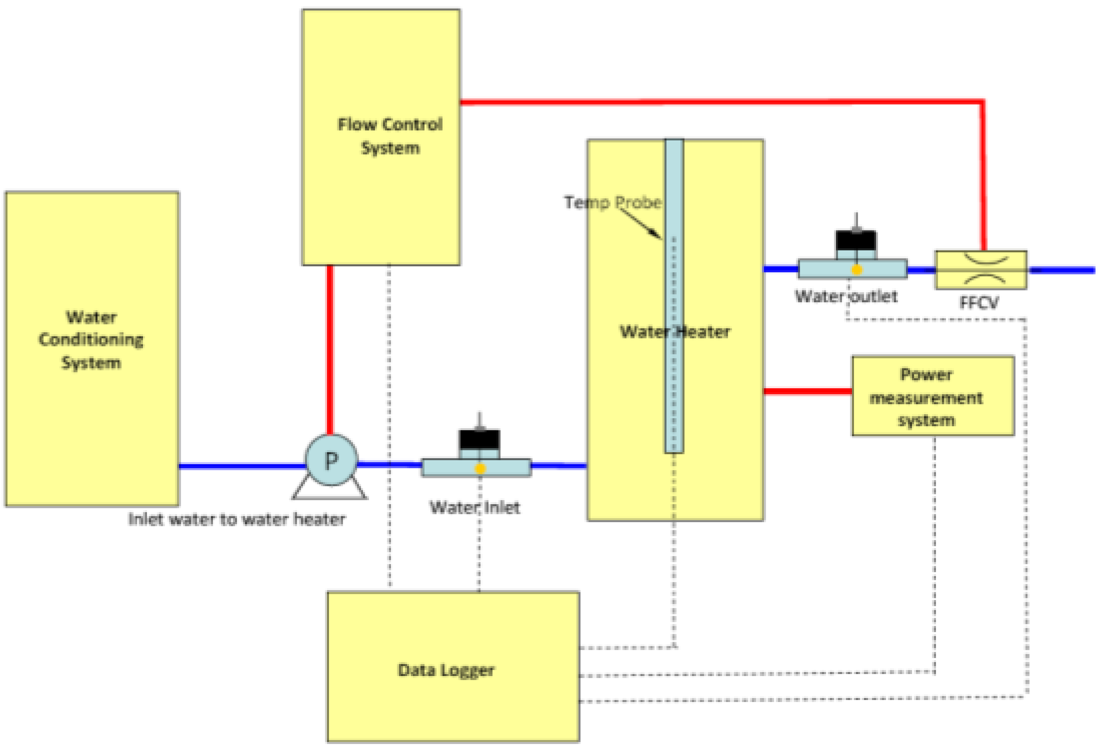


Figure 2. General Test Setup

Figure 3. Thermocouple Temperature Tree

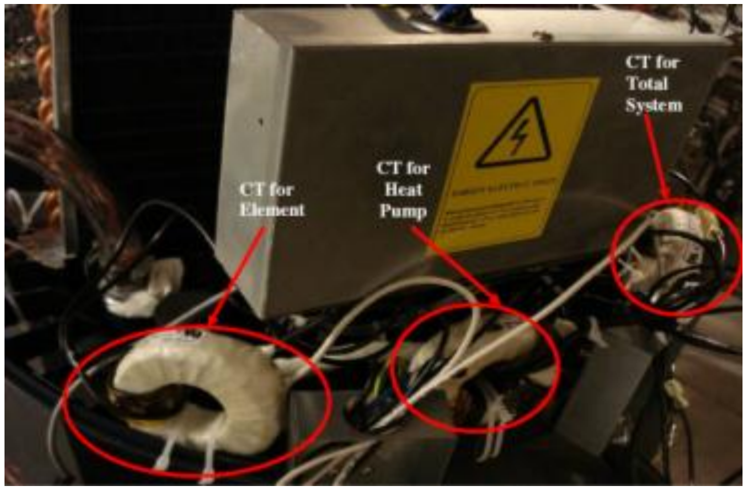


Figure 4. Power Measurement Current Transducers

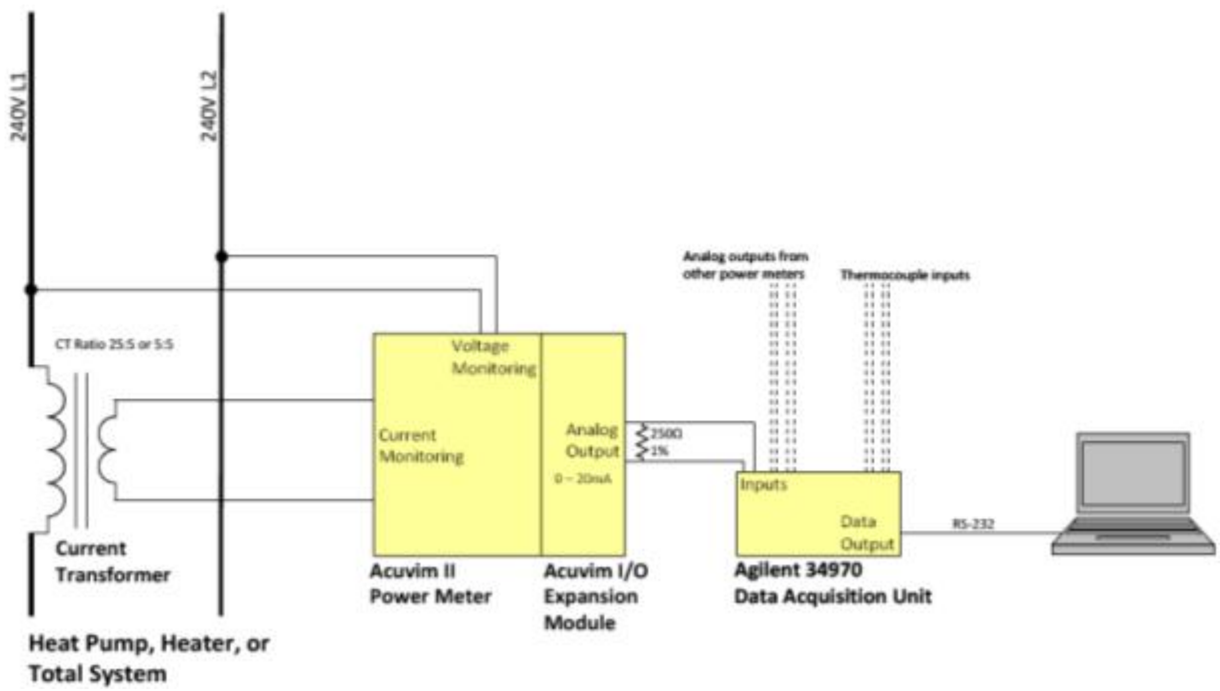


Figure 5. Power Measurement and Data Acquisition Schematic

Cascade Engineering conditioned and stored tempered water in a large tank to be supplied to the water heater at the desired inlet temperature. A pump and a series of flow control valves in the inlet and outlet water piping control the water flow rate. A flow meter measures and reports the actual water flow.

A data acquisition (DAQ) system collects all the measurements at five-second intervals and logs them to a file. In a post processing step, Ecotope merged the temperature log of the thermal chamber with the DAQ log file to create a complete dataset for analysis.

The lab measured the airflow through the evaporator coil fan using a flow station in line with the exhaust duct. The flow station provides a physical average pressure of four points facing into the airstream and four points facing away from the airstream. The stations are calibrated to known airflows so that the differential pressure between the up and down stream measurements determines the airflow. Cascade Engineering conducted the airflow measurements once to establish an equipment fan curve. Therefore, by measuring only the power in other situations, the airflow can be determined without continuous flow monitoring.

Cascade Engineering conducted all tests to align with the DOE specifications, with exceptions described as follows:

- The rev1 tests placed the unit directly on the floor of the thermal chamber while the rev2 tests placed the unit on top of a plywood and foam insulated test pad. Neither used the prescribed ¾” plywood and three 2x4 platform.
- The pump for conditioned water maintained the supply pressure near 20psi and not the 40+psi of the spec.
- Water inlet and outlet supply piping was of the PEX variety and not copper.
- The lab took inlet and outlet water temperature measurements ~15 feet from the tank for rev1 (Ecotope subsequently corrected for the actual temperatures in the post-processing phase to remove time lags caused by added distance) but took measurements 2 feet from the tank for rev2.
- As discussed elsewhere, the supply voltage differed from the equipment specified value but, as was the case for the water temperature measurement, a data processing step corrected for the anticipated differences.

In all, the deviations from the standard protocol are expected to produce minimal differences in testing outcomes. If anything, the difference in platform and piping could be expected to slightly reduce the heat loss rate of the tank.

3 Findings: Equipment Characteristics

3.1 Basic Equipment Characteristics

The AirGenerate AirTap Integrated HPWH is an all-electric water heater consisting of a heat pump integrated with a hot water tank. The equipment has two methods of heating water:

(1) Using a heat pump to extract energy from the ambient air and transfer it to the water, and
(2) Using a resistance heating element immersed within the tank.

The heat pump compressor and evaporator are located on top of the tank. A single-speed centrifugal fan draws ambient air from the right side of the unit, pulls it through the filter and across the evaporator coils, and exhausts colder air out the top. The unit is designed to easily duct the exhaust air to a six-inch round duct. The refrigerant condenser, which transfers heat to the water, is submerged inside the tank toward the bottom.

The lab conducted a series of measurements comprising a basic descriptive characterization of the equipment. These are shown in

Table 1 and are discussed in the rest of this section. For reference purposes, the table also shows the values given by AirGenerate's equipment specifications.

As with traditional electric tank water heaters, the ATI contains two electric resistance heating elements. Unlike most traditional tanks with one element at the top and one element at the bottom of the water column, the ATI has one element at the top and a backup element in the middle. The backup element does not activate during normal operating modes and is designed to be activated only in the event the heat pump system stops functioning. The AirGenerate spec sheet lists resistance element power draw as 4 kW with a 220V supply.[1] The primary resistance element may operate either by itself or in conjunction with the compressor.

The controls for the ATI are configured to operate either the compressor by itself, the upper element by itself, or both concurrently. Measurements show that the compressor draws 450 to 1000W depending on both tank water and ambient air conditions, resulting in a maximum power draw of 5.7 kW at 240V. For the heat pump, lower temperatures for both water and air result in lower power draws while higher temperatures result in larger power draws. Obviously, resistance element power draw is constant. Two other components of the equipment also consume power: the fan, which moves ~ 370CFM of air with no obstructions to flow and draws 100W, and the control circuits, which use a constant 2.5W.

[1] The laboratory supply voltage for the rev1 testing was 209V, which effectively reduced the power output of the resistance element (~12.5Ω) to 3.5kW. Cascade Engineering, Ecotope, and NEEA assumed that the compressor power draw, an inductive load, remained unaffected by the slightly lower supply voltage. For testing the rev2, which occurred months later, the lab had installed a transformer to supply the equipment at 240V. Again, the only assumed effect consisted of a change in resistance element power output, now observed at 4.6kW. The only tests influenced by this difference are those in which the resistance element is used, namely the one-hour test. In order to compare revisions, Ecotope corrected the test results for differences in input voltage. The power output of the element is either corrected up (rev1) or down (rev2) to the equivalent power at 220V. This power difference is translated into energy and gallons of water heated based on the runtime of the elements in the test.

The ATI66 has a nominal 66-gallon capacity but measurements showed the unit in the lab held 64 gallons. National guidelines on the sizing of equipment allow a 10 percent variation in nominal versus actual size; this water heater falls within those guidelines. The difference in nominal size versus actual size is not unique to HPWHs and occurs with traditional electric resistance tanks as well.

The ATI uses R-410a refrigerant. R-410a has lower condensing temperatures than R-134a, which is used by some other HPWH manufacturers. This can lead R-410a systems to experience difficulties in heating water to high setpoints. The ATI66 testing, however, showed that the heat pump successfully heated water to 135°F. Cascade Engineering did not test higher setpoints; they may or may not be attainable through heat pump operation. Regardless, 135°F is sufficiently hot for most conceivable applications.

Table 1. Basic Characteristics for AirGenerate ATI66

	Laboratory Measurement	**Manufacturer's Specification**
Power @ 220V		
Upper Element (W)	4000	
Lower Element (W)	4000	
Compressor* (W)	450-1000	790
Standby (W)	2.5	--
Fan (W)	100	--
Airflow Path	Inlet right side. Exhaust out the top.	
Airflow unobstructed (cfm)	370	400
Airflow @ .25in (cfm)	340	--
Refrigerant	R-410a	
*range depends on water T and ambient T. Power increases with each.		

The convenient exhaust air ducting option produced a need to determine airflow for both unobstructed exhaust and under a ducting scenario. Cascade Engineering measured the fan flow with no duct at 368CFM. Assuming ducts with approximately 0.25 inches of water in static pressure reduces the airflow to 340CFM. Figure 6 shows the results of the fan testing.

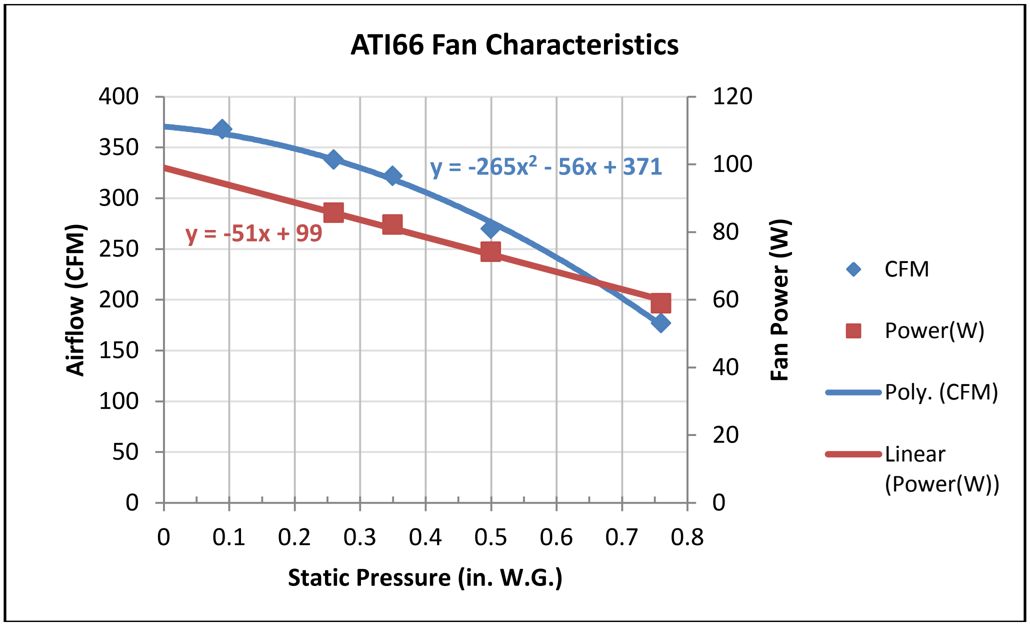


Figure 6. Fan Performance

3.2 Operating Modes and Sequence of Heating Firing

The HPWH has an integrated circuit control board which may be programmed in a number of ways to control when the heating components turn on and off. AirGenerate has developed several control strategies, referred to as operating modes, to determine equipment operation. The ATI HPWH has three basic modes of operation, shown below in order of most efficient to least efficient:

- "Econ" – compressor only during user-defined time intervals
- "Auto" – combination of compressor and resistance elements
- "Heater" – primary resistance heat element only

AirGenerate provided detailed information for the operating modes, which are controlled by two temperature sensors: an upper sensor to control resistance element operation and a lower sensor to control compressor operation.

The M&V plan called for a test to explore the control strategies for the Auto mode of operation. The test began with the water heater at a setpoint of 135°F and initiation of a three-gallon-per-minute (gpm) draw. The ATI66 allows monitoring of water temperature at the heat pump coil and water temperature at the resistance element; these readings came from the ATI66's built-in sensors, not from sensors installed by the lab. Cascade Engineering recorded the temperature at each when a heating component activated during the 3 gpm draw, and terminated the draw upon activation of both heating types. The tank was then allowed to recover. Cascade Engineering initiated a 5.5 gpm draw and performed a similar procedure. Cascade Engineering performed the tests at conditions found in the lab on that day (not inside a thermal chamber): 62°F ambient temperature and 30 percent relative humidity.

Cascade Engineering undertook this detailed testing to describe only the Auto mode of operation. The test results matched exactly the operating mode information provided by AirGenerate. Summaries of behavior in all modes are described below.

The equipment operating logic for all modes is governed by the following set of parameters:

F11: Water setpoint temperature. Factory default is 135°F
F12: Temperature difference from setpoint for heating activation. Factory default is 10°F[2]
T1: Water temperature measured by upper temperature sensor (adjacent to resistance element)
T2: Water temperature measured by lower temperature sensor (adjacent to heat pump coil)

Econ Mode: The heat pump activates when the lower temperature sensor T2 falls below F11-F12. Under factory default settings, this means that the heat pump activates when the surrounding water temperature falls below 125°F. The heat pump runs until the water around it as measured by sensor T2 meets setpoint. The resistance element does not operate in this mode. Additionally, the heat pump is only operational during user-defined time intervals. No default setting exists for these time intervals, so switching to Econ mode without defining the operating time settings will result in the heat pump remaining off.

Auto Mode: The heat pump activates when the lower temperature sensor T2 falls below F11-F12 and the resistance element activates when the upper temperature sensor T1 falls below F11-F12. Under factory default settings, this means that the heat pump activates when the surrounding water temperature falls below 125°F and the resistance element activates when the surrounding water temperature falls below 125°F. Both heating types are allowed to run concurrently. The heat pump and resistance element shut off when their respective temperature sensors read that the water has re-attained setpoint.

Heater Mode: The resistance element activates when the upper temperature sensor T1 falls below F11-F12. Under factory default settings, this means that the resistance element activates when the surrounding water temperature falls below 125°F. The heat pump does not operate in this mode. The resistance element shuts off upon re-attaining setpoint at its temperature sensor.

[2] Information provided by AirGenerate on the rev2 unit indicates that the temperature differential to activate the resistance element was increased to 20°F while the heat pump activation dead band remained the same. The rev2 tests did not attempt to characterize this change.

4 Findings: Testing Results

4.1 First Hour Rating and Energy Factor

The Department of Energy has established two tests to rank the comparative performance of heat pump water heaters. The first test produces a first hour rating that determines how much useable hot water the heater makes in one hour. The second, a 24-hour simulated use test, produces an energy factor (EF) that identifies how much input energy is needed to generate the 64.3 gallons of hot water used in the simulated 24-hour period. For tank-type water heaters, the first hour rating depends largely on tank volume and heating output capacity while the EF depends on the heating system efficiency and the heat loss rate of the tank. The normative performance characteristics of the equipment are shown in Table 2 and discussed in the rest of this section. Although the lab carried out the tests to align with the DOE specifications, the outputs here should be considered advisory only – any official ratings are those reported by the manufacturer.

The lab conducted the tests with the ATI66 in Auto mode – the default setting on the equipment when shipped by AirGenerate. The results are also shown in Table 2. Changes in the tank design between rev1 and rev2 are the reasons for higher 1-hour and 24-hour test ratings for the standard test conditions. For the 1-hour test, the rev2 tank configuration is able to heat more of the water at the bottom of the tank; therefore, the tank starts with more hot water and has more available to deliver during the test. For the EF test, rev2 has a better-insulated tank, which partially explains the increased rating.

In addition to performing the tests at the standard rating conditions, Cascade Engineering conducted several other tests using the same methods and draw patterns but different environmental conditions. These included the 24-hour test at 50°F ambient air / 50°F inlet water and the 1-hour test at 30°F ambient air / 45°F inlet water. The second 1-hour test, at 30°F ambient air / 45°F inlet water, shows for rev1 the expected much lower output volume. The output is reduced primarily by the colder inlet water (compared to 58°F) and secondarily by the lower compressor capacity at lower ambient temperatures.

Table 2. Performance Characteristics for AirGenerate ATI66

	Laboratory Measurement		**Manufacturer's Specification**
	rev1	**rev2**	
Tank Volume (gal)	64	64	66
First Hr Rating - Standard (gal)[3]	65.1	67.9	75
First Hr Rating @ 30°F Ambient	51.9	-	-
Energy Factor (std conditions)	2.06	2.19	2.4
Energy Factor @ 50°F Ambient	-	1.96	-
Northern Climate Energy Factor	-	2.03	-
Tank Heat Loss Rate (Btu/hr°F)	3.8	3.4	-

[3] Test results corrected to 220V equivalent power for resistance element.

4.1.1 1-hour Test

The data from the 1-hour test at 135°F setpoint are plotted in Figure 7. The test begins with a 3gpm draw. Approximately 6 minutes into the first draw, the heat pump activates (green line showing 0.7kW). As the draw continues past 12 minutes, the water temperature at the resistance element falls enough to engage the upper heating element, and at 16 minutes the outlet temperature has fallen enough that the draw is terminated. For the next approximately 27 minutes, the resistance element and compressor are operating in conjunction with total power just over 5 kW, as shown on the green line. At 44 minutes, the upper portion of the tank has recovered to setpoint, so the equipment switches to compressor only. Per the DOE test method, this triggers another draw since the water at the top of the tank is now hot. During the second draw the resistance element reactivates. At minute 52 the draw is terminated and the unit is in recovery for the remainder of the 60-minute test.

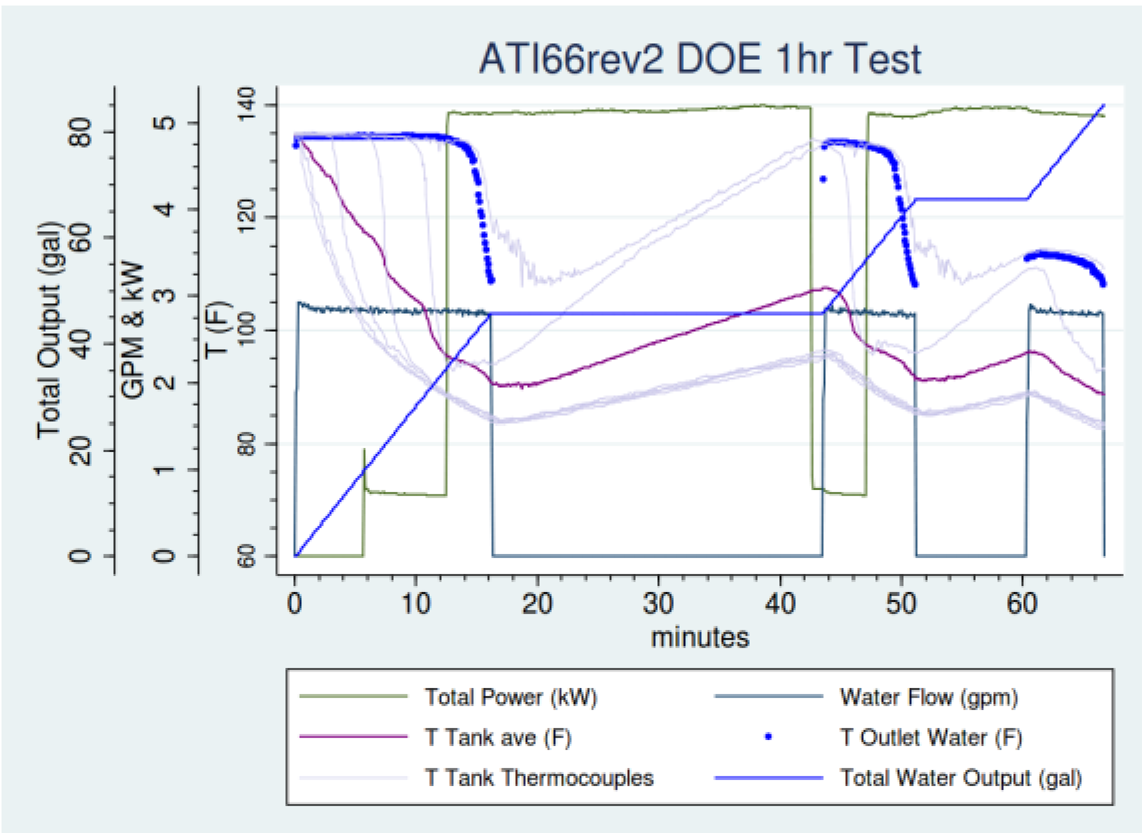


Figure 7. DOE 1-Hour Test

The bright blue line shows the cumulative water drawn during the test. The green line plots the total equipment power consumption. The thick purple line displays the average tank temperature while the thin lavender lines show the temperatures reported from the six thermocouples placed at different heights (corresponding to equal volume segments) within the tank (in effect a temperature profile of the tank at any point in the test). Lastly, the blue dots plot the output water temperature.

4.1.2 Energy Factor Tests

At the most basic level, an energy factor (EF) is the ratio of total useful energy output to total energy input. The DOE test method prescribes a standard set of operating conditions to use for the test and for normalization purposes in the calculation of the EF. The 24-hour simulated use test consists of six 10.7-gallon draws equally spaced over six hours, followed by 18 hours of standby. The standard test conditions are 67.5°F, 50% RH ambient air, 135°F tank setpoint and 58°F incoming water temperature. As with the 1-hour test, the equipment operating mode was set to Auto. Figure 8 shows the first seven hours of the test so the draw events and recovery can be examined in more detail. Figure 9 shows the full 24 hours which also demonstrates the tank heat loss rate.

Figure 8 plots the same type of data as Figure 7. One distinction is the exclusive use of the compressor for heating, unlike the 1-hour test which shows both compressor heat and resistance element heat to meet the high demands of the test. For the 24-hour simulated use test, the large tank capacity and efficient compressor operation more than sufficiently meet the hot water demand so no resistance heating is needed. In fact, the tank volume and control logic are such that the first draw does not trigger any heating at all. The compressor activates at the second draw, and by the end of each hour is able to more than recover the average tank temperature from before the draw.

Figure 8 also plots the instantaneous coefficient of performance (COP), which is a measure of how much heat is added to the hot water in a given time interval divided by the energy used to create or deliver that heat in that interval (in this case five minutes). For electric resistance heat, the COP is generally assumed to be 1. In contrast, the COP for heat pumps can vary greatly depending largely on the ambient air conditions (heat source) and the tank temperature (heat sink). The downward trend of the COP in Figure 8 with each recovery cycle reflects the changing tank temperature. The scatter in the COP plots is due to uneven, short-term fluctuations in the tank temperatures, but the general trend is clear. The COP varies between 2 and 3 throughout each recovery period, decreasing as the tank temperature warms (the heat pump is less efficient when working against a larger temperature difference).

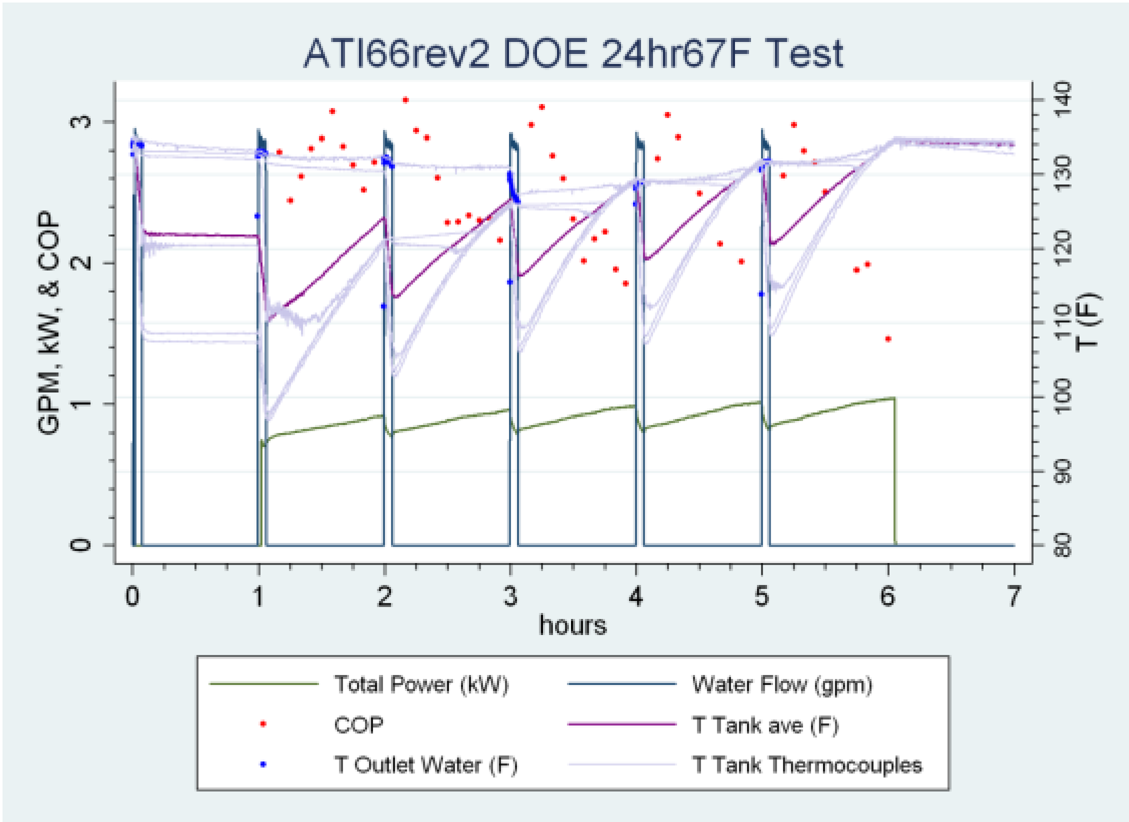


Figure 8. DOE 24-Hour Simulated Use Test, First Seven Hours

Figure 9 shows the full 24 hours of data. From shortly after hour 6 for the remainder of the test, the tank is in standby mode with the only power draw being 2.5W for the control circuits. From the change in average water temperature over this period, Ecotope calculated a heat loss rate of 3.4 Btu/hr°F (0.98 W/°F) for the tank. This heat loss amounts to 430 kWh/yr for a tank installed inside a house and set to 120°F. If installed in a garage with an average year-round temperature of 50°F, the loss amounts to 600 kWh/yr. Unlike traditional electric tanks that recover the standby loss with a COP of 1, Figure 8 shows the AirGenerate ATI66 HPWH, using the compressor, will recover standby losses with a COP near 2, thereby reducing that portion of annual energy use by half.

Figure 9 shows that the water heater performs no standby firings during the test. Instead, it lets the average tank temperature fall from 135°F to 128°F, which follows from the control logic given. In a few more hours, the tank would perform a standby recovery. Because the same control logic is used for a setpoint of 120°F, the average tank temperature will fall 10°F before a standby recovery occurs. This still leaves the hottest water at the top of the tank usable at 110°F.

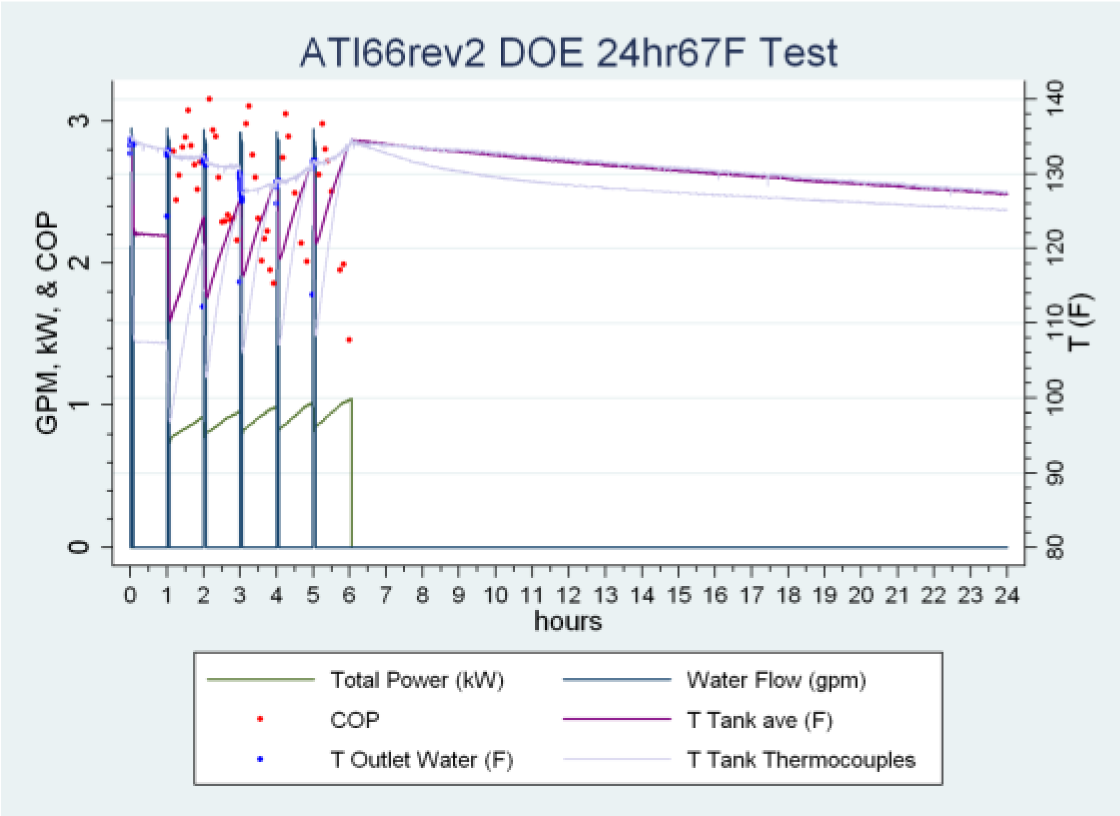


Figure 9. DOE 24-hour Simulated Use Test. Full 24 hours.

The 24-hour test at 50°F ambient air and 50°F inlet water is plotted in Figure 10. In contrast to the test at 67°F ambient air, the unit takes until hour 7.5, 1.5 hours longer, to recover the tank – to be expected given the difference in air temperature. The outlet water temperature difference for the last three draws is also notable. Due to the lower ambient air temperature, the compressor is unable to reheat the tank as quickly, causing lower outlet water temperature as the test progresses. Water temperatures are still above 118°F. In neither test does the resistance heat element turn on. A final note on the 50°F test is that the increased heat loss through the tank is observable through the slightly lower average tank temperature at the end of the test.

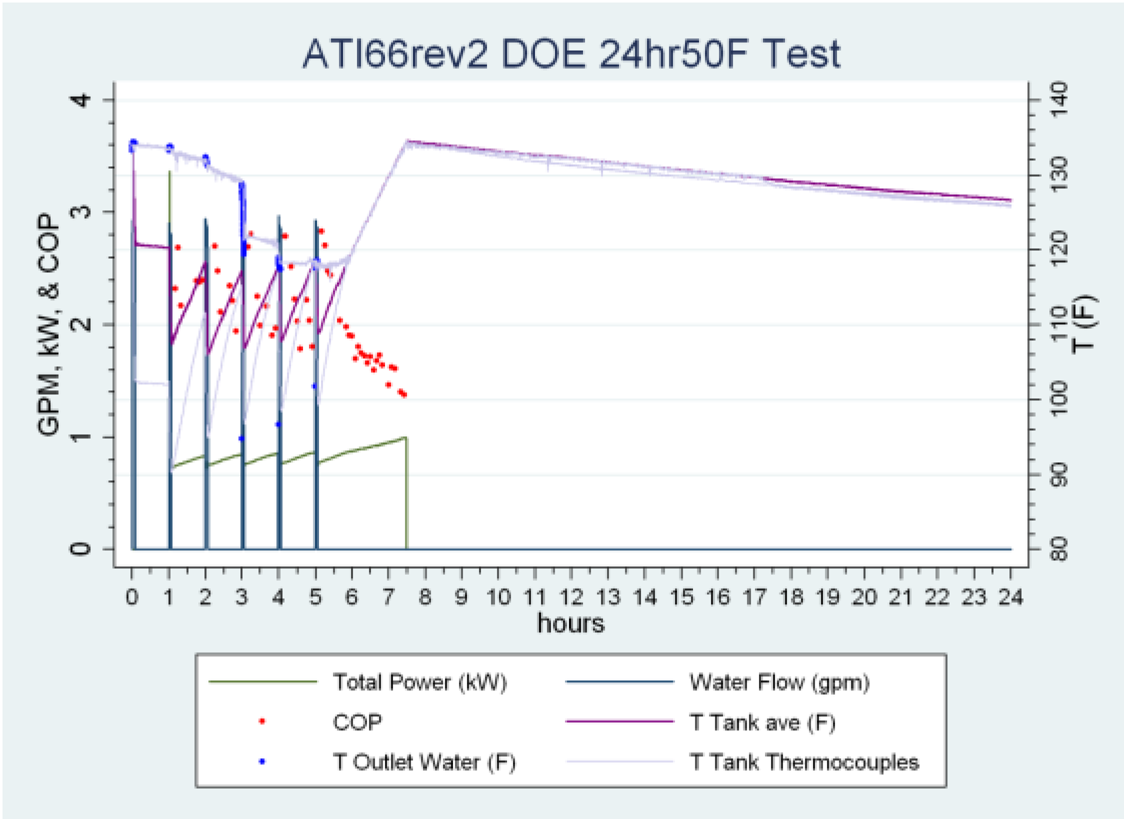


Figure 10. DOE 24-hour, 50°F Ambient Air 50°F Inlet Water. Full 24 hours.

4.2 Compressor Performance

To fully understand the HPWH performance, the M&V plan called for mapping equipment COP at varied tank temperatures and ambient air conditions. These COP measurements reflect how efficiently the heat pump components of the HPWH are operating under any given set of conditions. These COP calculations do not apply when the resistance elements are operating, in which case the COP is assumed to be nearly 1. The performance map is extremely useful in understanding how well the equipment will operate in conditions encountered in garages and unconditioned basements. The COP tests start with a full tank of cold water and the equipment off. The equipment is then switched on and data are recorded as the tank heats up to setpoint. Table 3 lists the set of conditions for all COP tests.

Table 3. Test Conditions for COP Mapping

Test Name	Ambient Conditions		Operating Mode	Fan Static Pressure (in water)
	Temp (F)	RH		
COP-30	30	80	Econ	0.25
COP-40Auto	40	95	Auto	0.25
COP-40Auto-0.75	40	95	Auto	0.75
COP-50	50	58	Econ	0.25
COP50-w	50	95	Econ	0.25
COP-67	67	50	Econ	0.25
COP-95	95	40	Econ	0.25

The lab performed two of the tests in Auto mode, allowing resistance heat operation, as a supplemental check on operating modes. It performed one test with increased static pressure on the fan to simulate a clogged air filter. It performed the rest of the tests in Econ mode with 0.25 inches of water in static pressure at the fan to provide representation of a wide range of ambient conditions.

On all the COP tests the lowest thermocouple resides beneath the condenser, thus the lowest ~ twelfth (about 5 gallons) of the tank is not directly heated. The result is an effective hot water capacity reduction of the rev1, one that was corrected in the rev2 of the ATI66. The lab performed the COP tests on the original version, so the lowest thermocouple reports a much lower temperature than do all the others. This does not affect the results of the COP characterization because AirGenerate did not change components affecting compressor efficiency between rev1 and rev2. Ecotope used only the temperature of water in contact with the condenser coils for the curve-fitting exercises.

Various specification and brochure documents from AirGenerate show variety in the low ambient temperature cutoff limit for compressor operation. The default is listed in the Installation and Operating Instructions as 32°F. With changes to the operating parameters, the COP-30 test showed robust operation even at 30°F. This unit is unique compared to other units tested as it has an active defrost cycle. When low ambient temperatures lead to coil icing, the ATI66 shuts down its fan for two minutes and reverses the refrigeration cycle, turning the evaporator into the condenser and removing the ice. This allows compressor operation at much lower temperatures than units lacking an active defrost cycle.

The COP tests nicely illustrated the coil defrosting behavior of the ATI66. During the COP-30 test performed at 30°F, active defrost cycles occurred regularly every 20 minutes. The default factory settings invoke a defrost event when the evaporator temperature is below 28°F and these defrost events may occur no more frequently than once every 20 minutes (the factory setting for this operating parameter). Since the evaporator temperature was below 28°F for the entirety of the COP-30 test, the unit performed defrost cycles at this regular interval, shown in Figure 11.

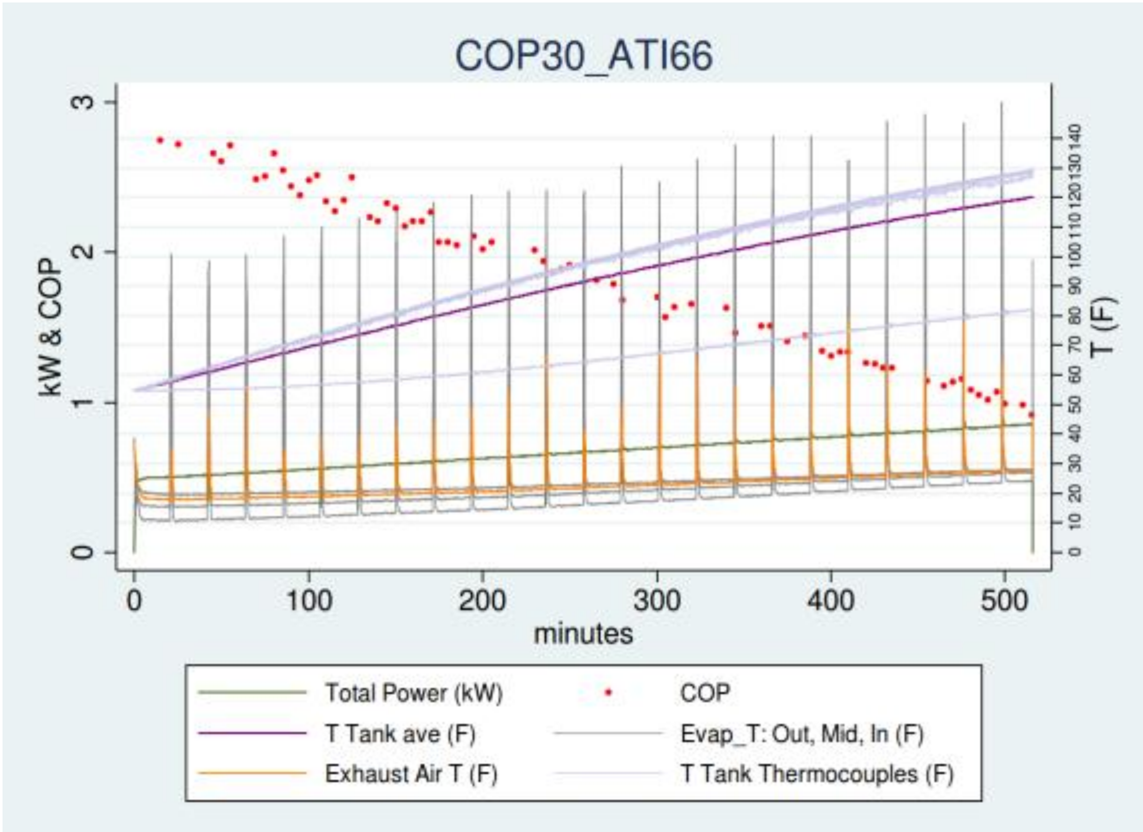


Figure 11. COP-30 Test

Of note in the control logic is that, in addition to limiting defrost events to once every 20 minutes, a 20-minute lag exists between cold evaporator temperatures tripping the logic and the start of the defrost cycle. The 20-minute lag at the beginning of the COP-30 test minimally affected the outcome. The calculated COP is essentially a steady-state COP penalized for defrost cycling. However, during the 40°F and 50°F tests, the behavior was not as clean. The results of the COP-50w test are shown in Figure 12.

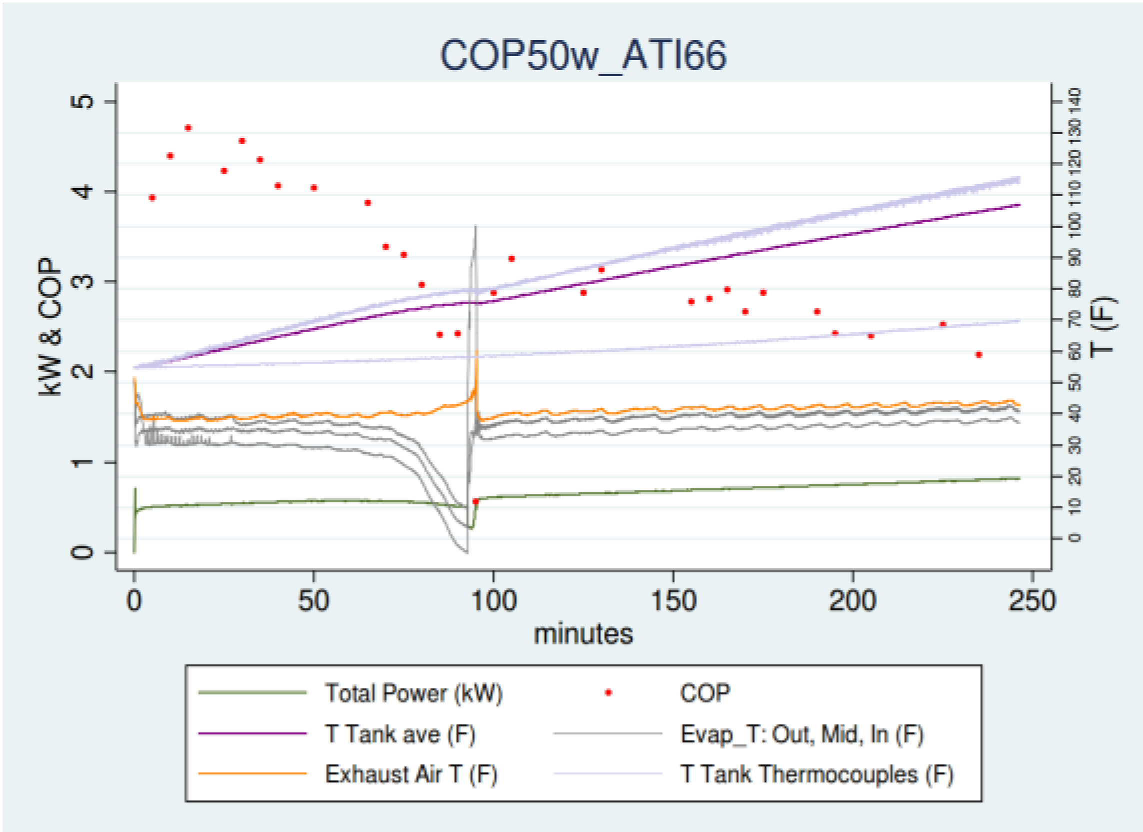


Figure 12. COP-50w Test

Around minute 75 the evaporator coil begins to frost. The equipment must wait 20 minutes, until minute 95, before activating the defrost cycle. In the intervening time, the coil ices severely, the evaporator temperature dives, and the COP dives accordingly. This behavior confounds the curve-fitting exercise of producing steady-state efficiencies.

This phenomenon is a real performance penalty, especially with high ambient humidity ratios, occurring at ambient temperatures between roughly 35°F and 55°F. Two means of dealing with this phenomenon exist. One is to remove the segment where COP dives preceding the overdue defrost, regress the censored data to find a steady-state no-defrost COP, then reduce that COP later with a defrost cycle penalty. The other is to regress the raw data and let the COP dive pull down the regression line. Both methods are crude; however, the second method is more straightforward and simultaneously captures the real effect of frosting. The COP curve fit is plotted along with raw data in Figure 13, which also shows COP dives in the COP-50 and COP-50w tests when the defrost cycle waits 20 minutes to start after coil icing begins.

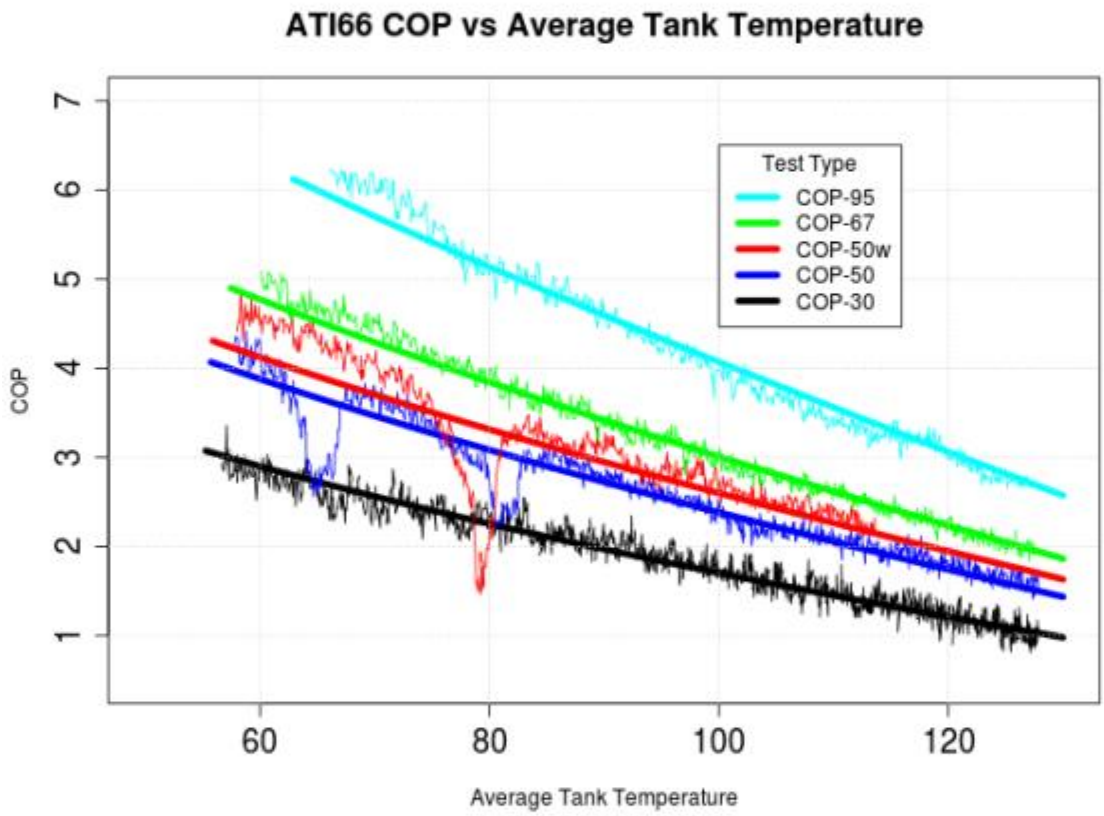


Figure 13. COP versus Tank Temperature

1.1.1. Equipment COP

Equipment efficiency depends on the water temperature in the tank, ambient air temperature, and ambient air moisture content. Ecotope performed curve fitting on the COP data with a penalized regression method known as the "lasso"—least absolute shrinkage and selection operator. The lasso is basically ordinary least-squares regression, except the sum of coefficient absolute values is constrained by some constant. That constant is typically chosen to minimize cross-validation error rate: the error observed when training the model on one portion of the data and testing it on the remainder.

Ecotope chose this method in the absence of a convenient, physically-grounded model for any individual HPWH with the objective of producing a simple, reliable and general equation describing COP. Different terms may become significant for different HPWHs, as the "lasso" is an unsupervised, machine-learning algorithm. Using an unsupervised algorithm to "learn" the patterns in the data better captures equipment-specific nuances of operation, and using a penalized regression algorithm helps avoid the pitfall of over-parameterization. The curve fits will be particularly useful in developing water heater performance simulations.

For the ATI66, Ecotope used the following equation to describe COP (this is the equation visualized above in Figure 13):

$$COP = 10.84 + .041T_{db} + 0.0001258T_{db}^2 - 0.0003505T_{db}T_{tank} - 0.2217WT_{tank} + 0.09913\ln(T_{db}) + 0.4257\ln(W) - 1.485\ln(T_{tank}) + 0.1405\ln(T_{db}W)$$

where T_{db} = ambient air dry bulb temperature (F)
W = humidity ratio (mass water/mass air)
T_{tank} = average tank temperature (F)

4.2.1 Air Flow Effects on Performance

To examine the performance effect of a dirty or clogged air filter, the lab conducted two otherwise-identical tests with the exhaust fan working against differing static pressures. Essentially, it followed twice the COP-40 test procedure with the equipment in Auto mode: once with 0.25 inches of water in static pressure and once with 0.75 inches of water in static pressure. From the measurements of fan flow, this becomes 338 CFM and 177 CFM of air across the evaporator. The COP section above describes the conditions for these tests.

Remarkably, cutting the airflow nearly in half degraded the COP only slightly. During the parallel COP-40 tests, the average COP for tank temperatures between 80°F and 120°F was 1.99 with the higher airflow and 1.78 with the lower airflow, illustrated below in Figure 14. The periodic dips in COP represent defrost events as discussed above.

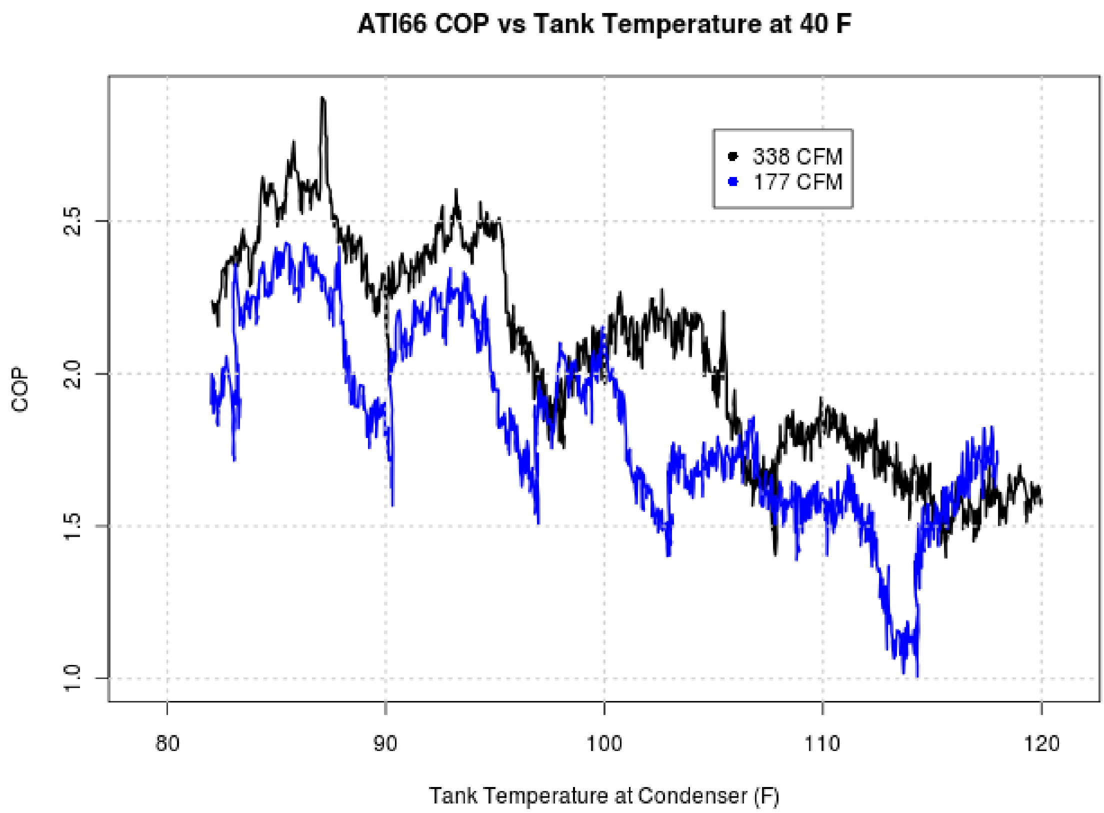


Figure 14. Airflow Effects on Compressor Performance

4.3 Supplemental Tests

In addition to recreating the standard DOE ratings tests and performing a battery of COP tests to describe efficiency, Cascade Engineering conducted several supplemental draw profiles to better understand the ATI66's performance.

The first is a simulated-use "Shower Test," which describes the number of efficient hot showers the HPWH is capable of providing. The test is performed at 50°F ambient air and the tank starts at a setpoint of 120°F. To mimic a series of morning showers, the lab conducted repeated eight-minute draws at two gallons per minute. The draws are separated by a five-minute lag time and continued until either the resistance element activates or the outlet temperature falls below 105°F. When one of these events occurs, the current draw is allowed to finish and the tank is allowed to recover, concluding the test. The test yields a useful rating: the number of consecutive, efficient showers available. The ATI66 water heater provides three consecutive efficient showers. The results of the test are displayed in Figure 15.

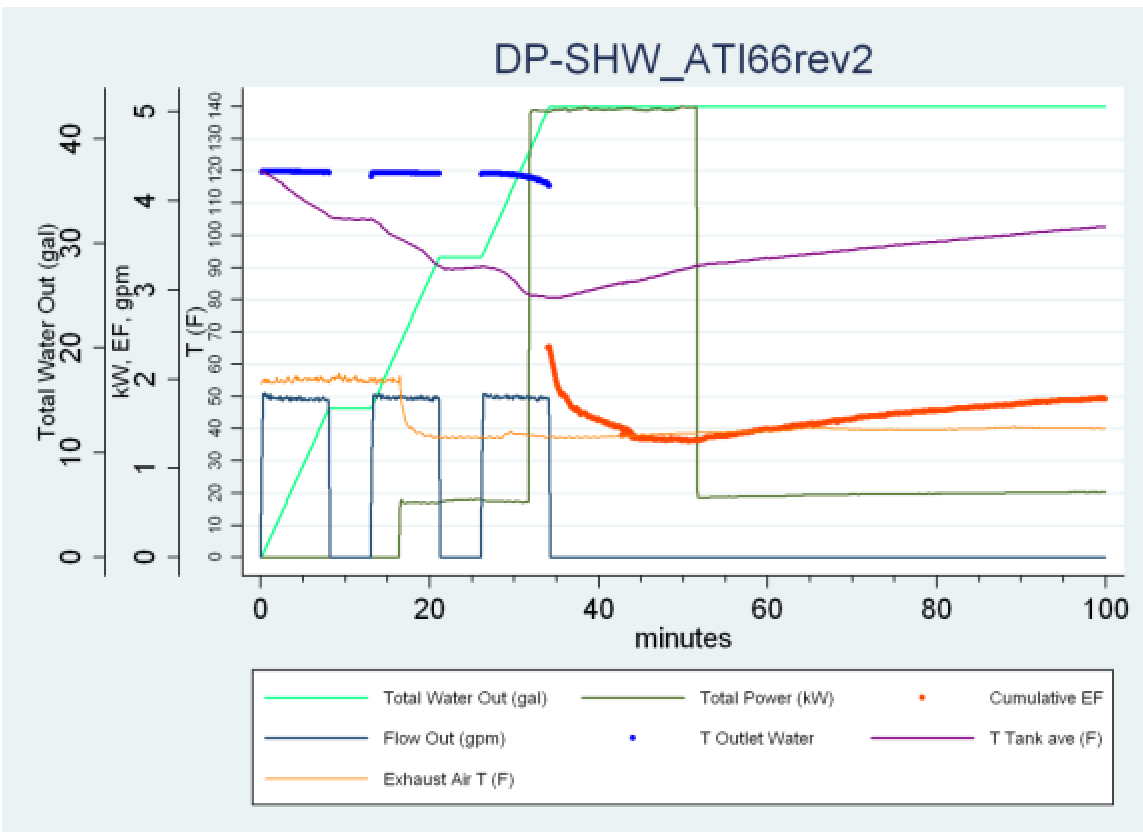


Figure 15. Shower Test Supplemental Draw Profile

The second supplemental test is referred to as DP-4 (Draw Profile 4), its name a relic of previously-used and discarded draw profiles from earlier rounds of testing. DP-4 is a light-use draw profile totaling 30 gallons. The illustrative utility of this test comes from repeating it at two different ambient temperatures. DP-4 was conducted at 40°F and 67°F. This is analogous to demonstrating how the HPWH would respond to the draw profile in a wintertime unconditioned

Pacific Northwest buffer space versus inside conditioned space. The differences in capacity and efficiency are stark. At 40°F the overall energy factor of the test was 1.5; at 67°F the overall energy factor was 2.2. The results of both tests are depicted below in Figure 16 and Figure 17. Note the defrost events and greatly extended runtime in the 40° test. The draw profile itself is also represented through the “Flow Out (gpm)” line and the “Total Draw (gal)” line.

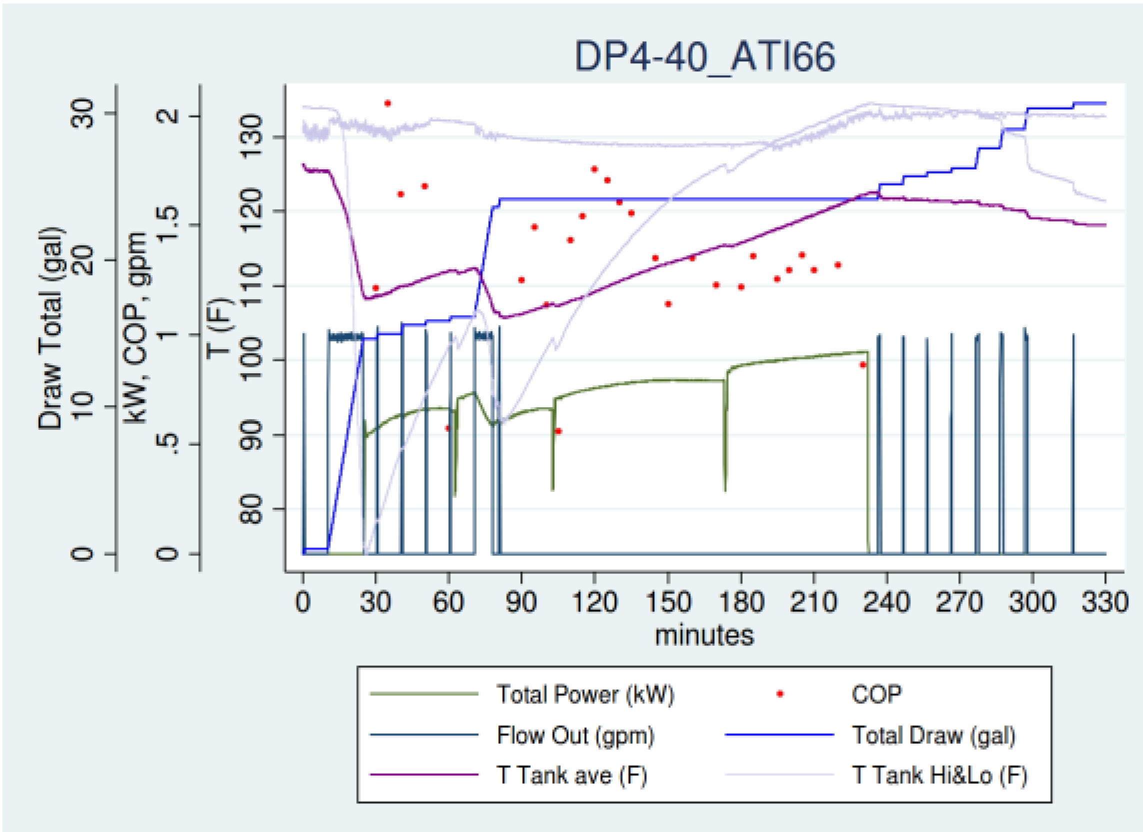


Figure 16. DP-4 Test at 40 degrees

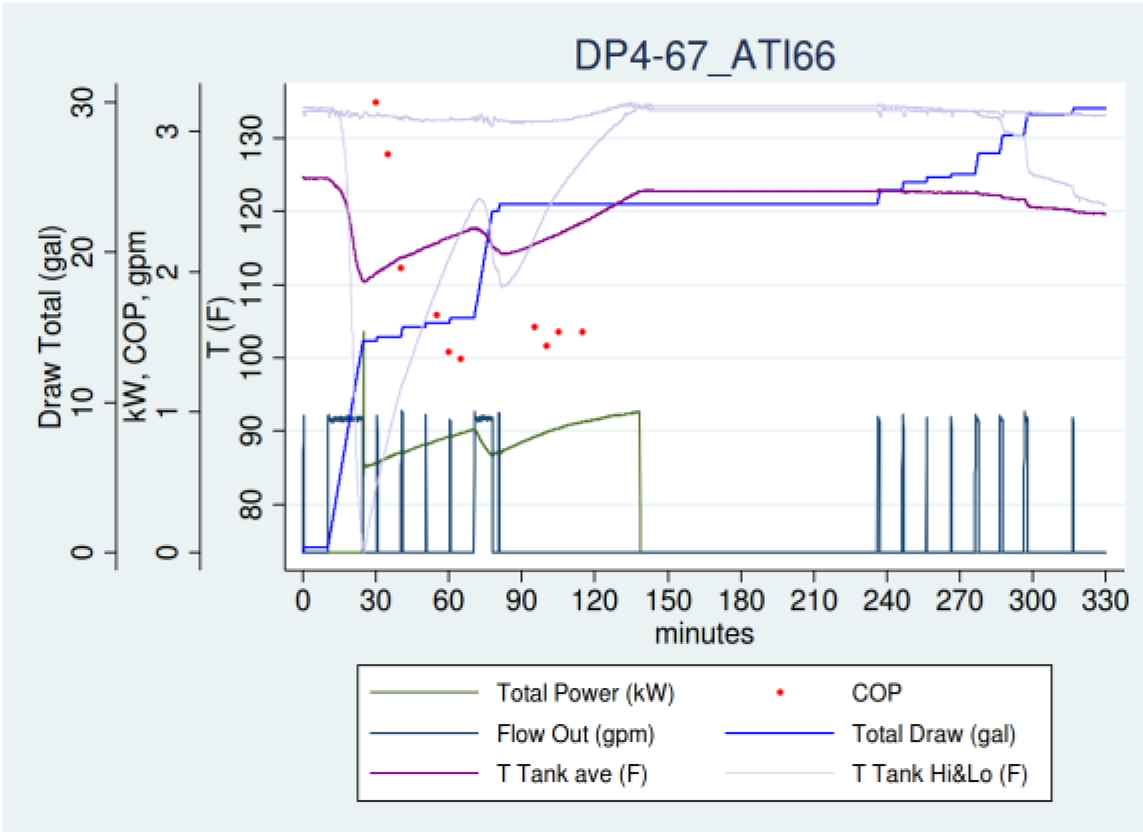


Figure 17. DP-4 Test at 67 degrees

5

5.1 Freeze Protection, Additional Observations and Noise

To test the ability of the water heater to withstand extreme cold temperature events, the lab subjected the ATI66 to 24 hours at 30°F temperatures. The test began with the tank at setpoint and then all power to the unit was disabled for the test period. At the end of 24 hours, the lab inspected the unit for any obvious leaks, cracks or ice formation. None was found, so the unit was powered on and observed to be fully functional, thus passing the freeze protection test.

During testing, the lab monitored the evaporator coil for icing conditions by mounting three thermocouples to the coil surface. Temperatures dropped below freezing on numerous occasions, which allowed for the formation of ice. Subsequently, the equipment would enter defrost mode to clear the coil. Cascade Engineering and Ecotope observed no deleterious effects, aside from expected drops in COP, due to ice buildup.

The lab also observed the condensate collection pan and drainage path throughout the testing process. The pan collected and drained condensate as expected. The lab observed no blockage, overflows or adverse outcomes.

Using the Northern Climate Spec, the lab also measured the sound level of the equipment. It made five measurements around the circumference of the water heater with the unit placed against one wall of a room (ambient dBA of 33.6). In one case, the lab connected an 18-inch length of 6-inch diameter duct to the air exhaust port to see if the duct would dampen any sound. The averages of the five measurements were:

- 58.5 dBA, with no ducting attached
- 58.2 dBA, with short ducting attached

6 Conclusions

The last section in this report discusses observations, in no particular order, on the equipment design and their implications for operation and performance.

- The compressor and tank size are large enough to adequately exploit heat pump efficiency. At 64 gallons (nominally 66) the unit is able to meet higher peak loads than a 50-gallon tank and, because of the large storage capacity, it can generally spend more recovery time using the compressor only while still being able to satisfy hot water demand. Likewise, the compressor is sized large enough to recover the tank in a reasonable period of time following peak draws.

- The heating component controls are designed in a simple and elegant way to both be efficient and meet high demand periods. In Auto mode, the independent controls of the resistance element and compressor allow one or both to run. For most draws, the lower temperature sensor triggers the compressor on for efficient heating, while for deep draws, the upper element activates the resistance element to heat the upper portion of the tank as quickly as possible. Allowing simultaneous operation of the heat pump and resistance element increases the overall COP during periods of high demand. The controls also succeed in delaying the time when the resistance element engages. During the first draw of the 1-hour test, ~72% of the tank volume was withdrawn before the element activated.

- The Econ mode timer may dissuade users from using the most efficient setting, as an operating schedule must be programmed in or the HPWH will not heat any water at all.

- The active defrost and wide ambient temperature operating range makes the unit well-suited for Pacific Northwest buffer space installations. However, despite the effectiveness of the defrost cycle at lower temperatures (~30°F), the controls could be altered to trigger a defrost more readily at moderately cold ambient temperatures (~40-50°F). As observed in the COP tests, the 20-minute delay in defrost cycle activation causes a precipitous drop in evaporator temperature and COP under these conditions.

- The user can change many equipment operating parameters, including settings for the defrost cycle—a nice feature to optimize performance, but it is doubtful that many homeowners would actually adjust these settings.

- Accessing the filter inside the plastic housing on the top of the unit is difficult, especially if the unit is ducted. The homeowner would have to remove the ducting to get to the filter, decreasing the likelihood of filter cleaning.

- Using R-410a refrigerant can cause problems when heating the water to higher setpoint temperatures, although Ecotope observed the ATI66 heating to 135°F with no difficulties.

- Fan selection makes the equipment suitable for connecting to an exhaust duct system, which gives the installer the flexibility of ducting the cooler exhaust air away from the location where the unit is installed. The ability to duct the airflow, however, comes at the price of a more energy-intensive fan.

Appendix A: Testing Matrices

Testing Matrix AirGenerate Integrated ATI66 rev 1

Test Name	Ambient Air Conditions					Inlet Water		Outlet Water		Airflow	Operating Mode
	Dry-Bulb		Wet-Bulb							inch. static pressure	
	F	C	F	C	RH	F	C	F	C		
COP Curve Development - Performance Mapping											
COP-30	30	-1	28	-2	80%	55	13	130	54	0.25"	Compressor Only
COP-50	50	10	44	7	58%	55	13	130	54	0.25"	Compressor Only
COP-67	67.5	20	57	14	50%	55	13	130	54	0.25"	Compressor Only
COP-95	95	35	75	24	40%	55	13	130	54	0.25"	Compressor Only
COP-40-auto	40	4	39	4	95%	55	13	130	54	0.25"	Factory Default
COP-40-auto-0.75	40	4	39	4	95%	55	13	130	54	0.75"	Factory Default
DOE Standard Rating Point Tests											
DOE-1-hour	67.5	20	57	14	50%	58	14	135	57	0.0"	Factory Default
DOE-24-hour	67.5	20	57	14	50%	58	14	135	57	0.0"	Factory Default
DOE-1-hour-30	30	-1	28	-2	80%	45	7	135	57	0.0"	Factory Default
Operating Mode Tests											
OM-67	67.5	20	57	14	50%	58	14	135	57	0.0"	Factory Default Mode
Airflow Measurement											
AM	Temperature and humidity need not be tightly controlled. They can be room conditions which might approximate DOE standard conditions.									0.0" to 0.75"	Factory Default
Draw Profiles											
DP-4	67.5	20	57	14	50%	58	14	135	57	0.25"	Factory Default
DP-4-40	40	4	39	4	95%	45	7	135	57	0.25"	Factory Default
Freeze Protection Test											
FRZ	30	-1	28	-2	80%	55	13	130	54	0.25"	Factory Default
Noise Measurement											
NOI	Measure combined fan and compressor noise									0.0"	Heat Pump running

Testing Matrix AirGenerate Integrated ATI66 rev 2

DOE Standard Rating Point Tests

Test Name	Ambient Air Conditions					Inlet Water		Outlet Water		Airflow	Operating Mode
	Dry-Bulb		Wet-Bulb							inch. static pressure	
	F	C	F	C	RH	F	C	F	C		
DOE-1-hour	67.5	20	57	14	50%	58	14	135	57	0.0"	Factory Default
DOE-24-hour	67.5	20	57	14	50%	58	14	135	57	0.0"	Factory Default
DOE-24-hour-50	50	10	44	7	58%	50	10	135	57	0.0"	Factory Default

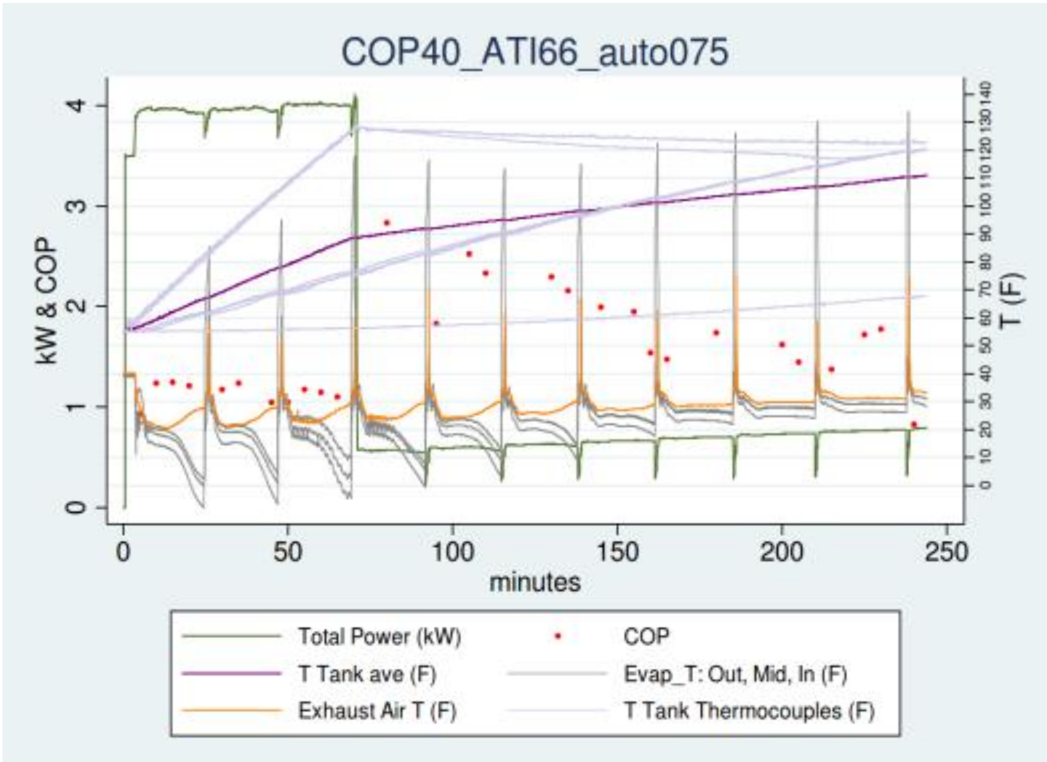
Compressor Cut-off Temperature

CMP-T	*	*	*	*	60%	58	14	135	57	0.0"	Factory Default

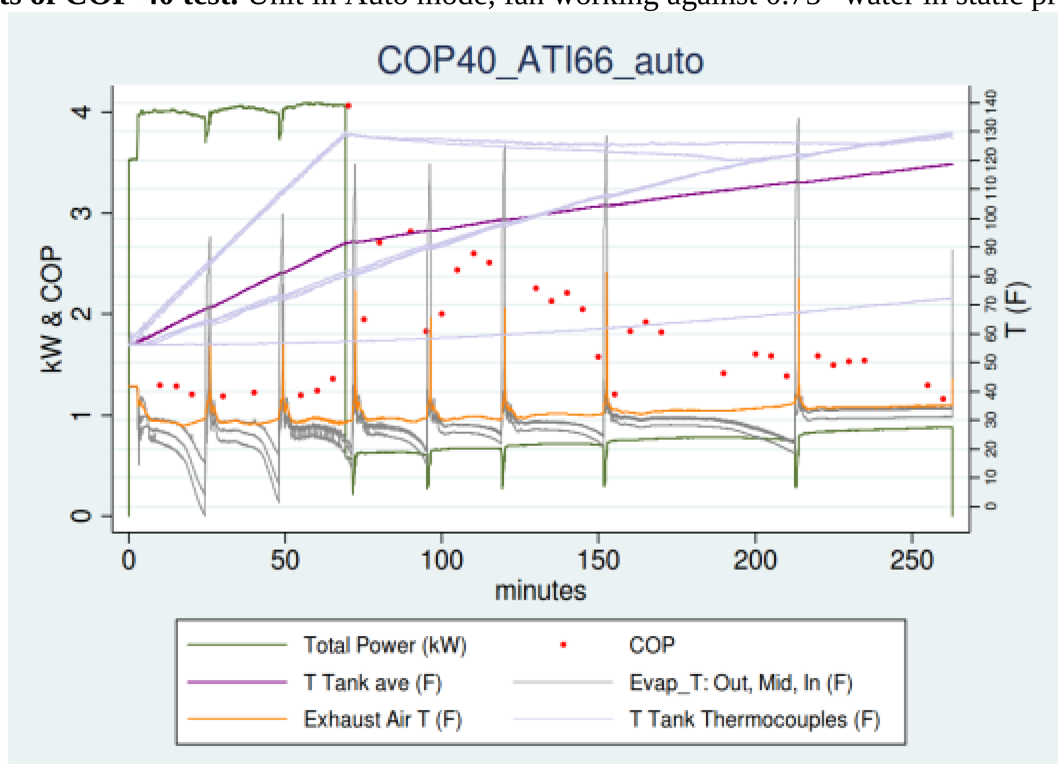
Draw Profiles

DP-SHW-50	50	10	44	7	58%	50	10	120	49	0.0" - No Duct Kit	Factory Default

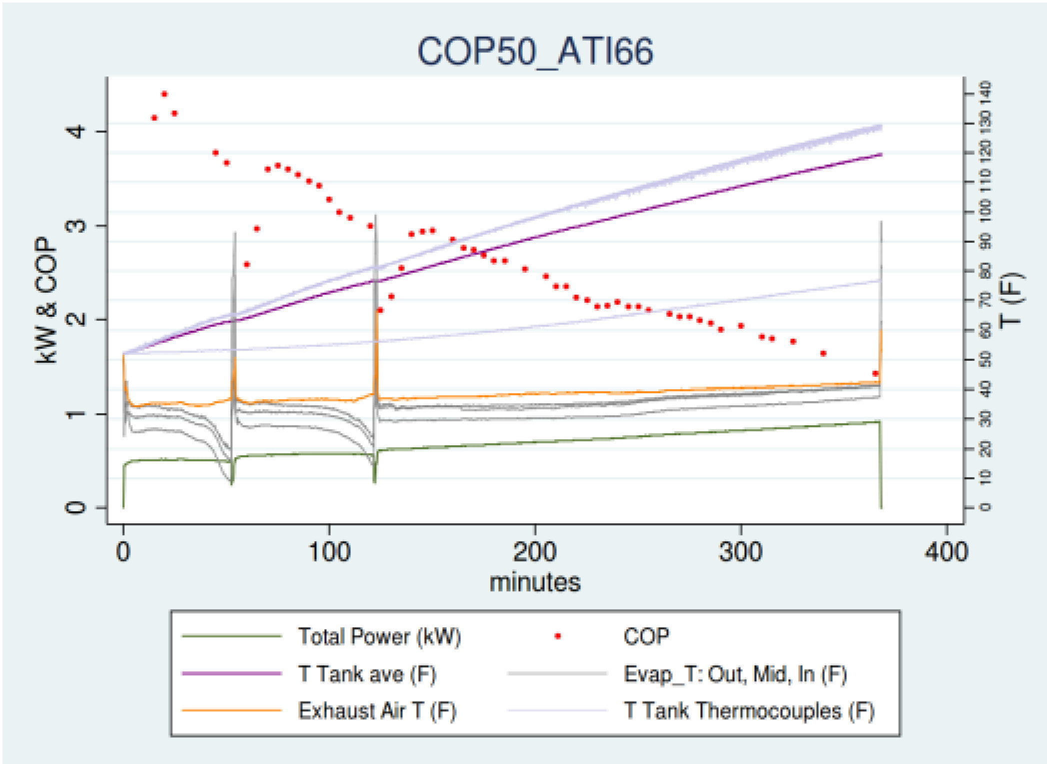
Appendix B: Additional Graphs



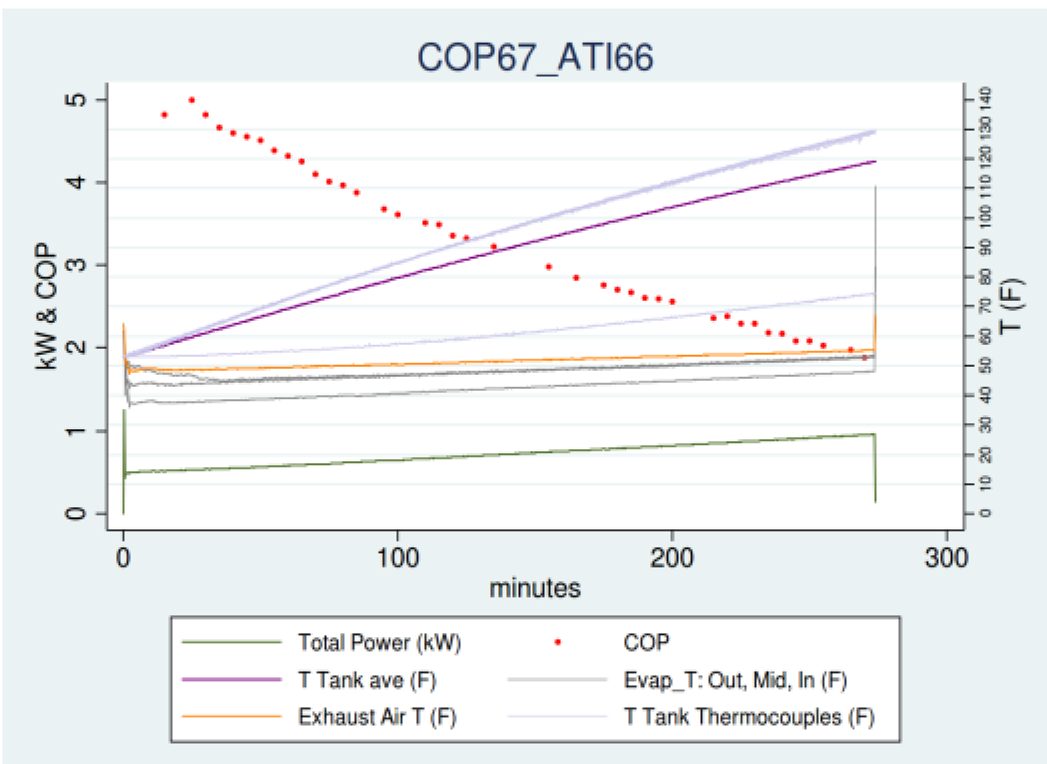
Results of COP-40 test. Unit in Auto mode, fan working against 0.75" water in static pressure.



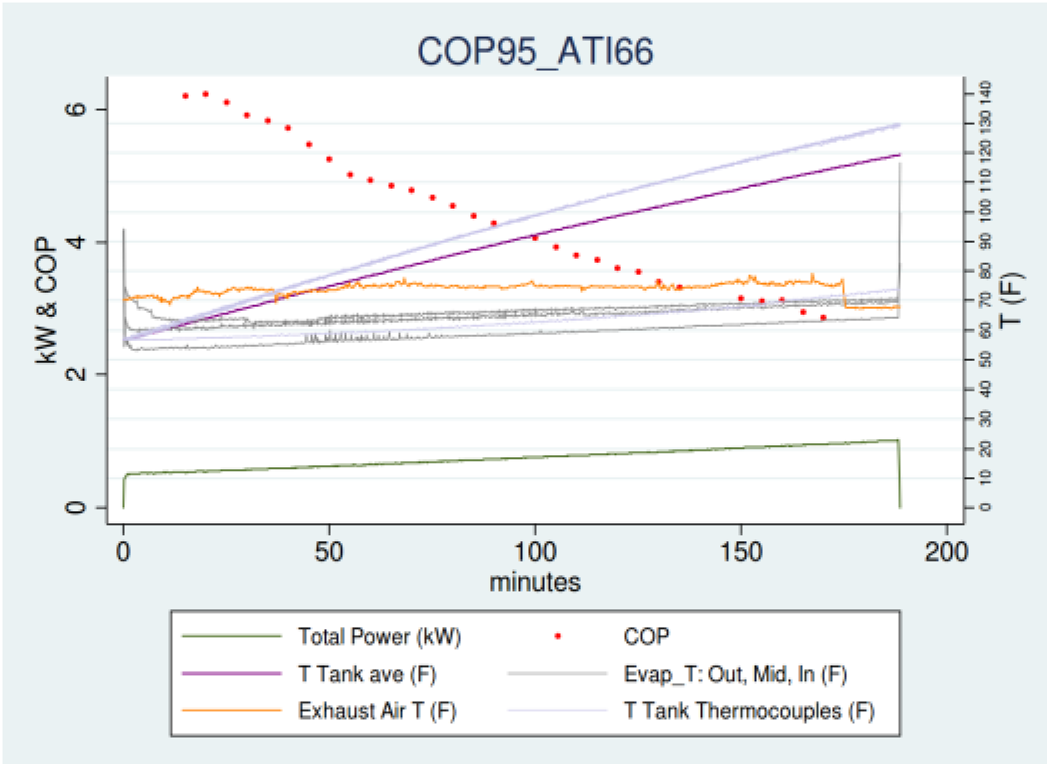
Results of COP-40 test. Unit in Auto mode, fan working against 0.25" water in static pressure.



Results of COP-50 Test.



Results of COP-67 Test.



Results of COP-95 Test.

Appendix C: Measurement Instrumentation List

Equipment	Make and Model	Function	Accuracy
Walk-in Thermal Chamber	Make: ESPEC, Model No.: EWSX499-30CA	Control temperature and relative humidity in test environment	
Data Acquisition System	Agilent Technologies Model No.: 34970A	Log temperature, power and flow rate data	Voltage: 0.005% of reading + 0.004% of range. Temperature (Type T): 1.5°C
Thermocouple	Omega, T type	Temperature measurement	1.0°C
Power Meter	Acuvim II - Multifunction Power Meter with AXM-I02 I/O Module	Power measurement, PF measurement of system, Resistance Heater, and Heat Pump	Main Unit: 0.2% full scale for voltage and current. AXM-I02 Analog Output: 0.5% full scale + 1% resistor tolerance
Current Transformer (25:5)	Midwest CT model 3CT625SP	Use with Acuvim Power Meter for Total UUT power and heater power measurement	0.4% at 5VA
Current Transformer (5:5)	Midwest CT model 3CT205SP	Use with Acuvim Power Meter for Total UUT power and heater power measurement	0.6% at 2VA
Flow Control System	Systems Interface Inc	Water draw rate and volume control	
Flow meter	Signet 2537 paddlewheel Flow Meter	Use with Flow Control System	+/- 1% linearity +/- 0% repeatability
Inlet Water Conditioning System	Pro Refrigeration	Conditioning of UUT inlet water temperature	
Water pressure gauge	Noshok 25.100-100	Inlet water pressure measurement	+/- 2.5% full scale
Hand-held temperature and humidity meter	Omega RH820W	Lab environment temperature and humidity measurement	
Electronic Scale	OXO "Good Grips" Scale	Measurement of water mass	5.0 Kg full scale with 1g increment
Electronic Scale	Pelouze Model: 4040	Measurement of water mass	