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Installed Performance of Heat Pump Water Heaters in a Cold Climate

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Acknowledgements

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GLOSSARY AND NOMENCLATURE

BTU	British thermal unit
COP	Coefficient of performance
DOE	U.S. Department of Energy
EF	Energy Factor
EF_{field}	Energy factor as determined under field conditions
ERWH	Electric resistance water heater
HPWH	Heat pump water heater
kWh	Kilowatt hour
Q_{hot_water}	Hot water energy delivered from tank
$Qe_{controls}$	Electric energy supporting the HPWHs controls
$Qe_{heatpump}$	Electric energy delivered to the heat pump (compressor and fan)
$Qe_{resistance}$	Electric energy delivered to electric resistance heaters
Qe_{total}	Total electric energy input
$Q_{standby}$	Thermal energy lost from tank to surroundings
$Q_{refrigerant}$	Energy delivered from heat pump refrigerant loop to water tank
Q_{air}	Energy delivered from room air to heat pump refrigerant system
Q_{stored}	Hot water energy stored in tank
$fe_{resistance}$	Fraction of total output supplied by electric resistance input
Vol_{hot_water}	Volumetric use of hot water, gallons
T_{hot}	Delivered hot water temperature, degrees F
T_{cold}	Delivered cold water temperature, degrees F
T_{inlet_air}	HPWH inlet air temperature, degrees F

NOMENCLATURE

Heat pump water heater: The water heaters discussed in this report are electric appliances that have integral heat pump systems as well as electric resistance heating elements, and can also be termed “hybrid water heaters”.

Control setting, or Setting: The user-selected controls option determining how the water heater will behave in heating water. Selections usually include

- Heat pump, or Efficiency: Heat pump (compressor) heating only
- Hybrid: Heat pump, with electric resistance heat added as needed
- High Performance: Heat pump and electric resistance, emphasizing fast recovery
- Electric: Electric resistance only
- Vacation: Reduces water temperature setting for a pre-determined number of days

Many reports and owner’s manuals use the term Mode rather than Controls Setting

Operating mode, or Mode: The internal operating state of the HPWH, which can include:

- Heat pump
- Electric resistance
- Heat pump and electric resistance operating simultaneously
- Controls only[1] (no operation of heat pump or electric resistance elements) *Some reports call this the "standby" mode – we use the term as described below.*

In the context of our report, we might use phrasing such as "*The **hybrid** control setting of allows for operation in the **electric resistance operating mode** and **heat pump operating mode**.*

Standby heat loss, or Standby loss: Heat lost from the storage tank to the surrounding environment. *In other contexts, standby may have other meanings*

Coefficient of Performance (COP): The ratio of useful energy output to electrical energy input for the heat pump subsystem.
Some reports use the term COP to mean the ratio of useful hot water energy output to electrical energy input as derived from field data - we use the term EF_{field} for this.

[1] Heat pump water heaters, unlike most older gas and electric water heaters, draw a small amount of power continuously for controls operation.

EXECUTIVE SUMMARY

Interest in heat pump water heaters (HPWHs) has grown over the last few years with improved performance and an increased emphasis on electrifying HVAC and water heating. Based on the interest of MECA and EO member organizations in the technology, Slipstream performed a study of the latest generation of HPWHs in the upper Midwest. Research objectives addressed performance, economics, space heating impacts, and user satisfaction.

The project included a field study of measured performance of HPWHs in nine homes, and a survey of a larger group of HPWH owners—both groups drawn from MECA HPWH incentive program participants.

Selected sites were all in the western part of the lower peninsula of Michigan, in rural or village settings. All the HPWHs were installed in full basements that were partially conditioned by primary heating equipment installed in the basement but with no direct control of basement space temperature. HPWHs from three manufacturers (Bradford White, Rheem, and AO Smith) were represented. All had a nominal storage tank capacity of 50 gallons, and Uniform Efficiency Factor (UEF) ratings between 3.39 and 3.56.

Slipstream installed monitoring systems at each site; measurements included hot water flow, hot and cold water temperatures, electric power consumption, basement environmental temperature, heat pump inlet air temperature, and variables related to space heating including gas valve status, main living space temperature, outdoor temperature, and temperature near auxiliary heating devices. Data was gathered at 1-second intervals (1-minute for electric power) for 11 to 14 months at each site.

Field study household size ranged from one to five people, average hot water use across the sites from 14 to 68 gallons per day, and average delivered hot water energy from 7,500 to 40,000 BTU per day.

The primary performance indicator used in the analysis was Field Energy Factor, the ratio of delivered hot water energy to electrical energy input, calculated on approximately a daily basis. This factor is analogous to rated energy factor but based on uncontrolled operating conditions. Across the nine sites, field energy factor values for periods of exclusively heat pump operation ranged from 1.95 to 3.56. Over periods of hybrid (combined heat pump and electric resistance) operation, field energy factor (for seven sites with adequate data) ranged from 1.13 to 2.28, and in purely electric resistance operation, from 0.68 to 0.91.

Using observed relationships between performance and operating conditions, Slipstream developed factors for use in predictive modeling of performance under assumed conditions. Standby heat loss rate (rate of heat loss from tank to environment) was evaluated at an average of 59.9 BTU/hr °F. Coefficient of performance (COP) of the heat pump system was defined as useful energy delivered to the storage tank divided by electrical energy input. Average values across the systems studied ranged from 2.99 to 3.59. The effect of inlet air temperature was

captured using linear regression. The fraction of total system output supplied by electric resistance input, relevant during hybrid operation, was characterized using regression against total load.

Modeling for conditions that approximate DOE test conditions and assuming no electric resistance operation yielded model-specific energy factors of 2.85 to 2.94, lower than manufacturer's rated UEF in each case, a difference we cannot readily explain. Modeling comparison of HPWH models to an electric resistance water heater with an energy factor of 0.95, assuming a relatively cool basement temperature typical of the upper Midwest and 50 gallons per day of hot water use, showed annual energy savings of 2040 to 2,640 kWh, with annual operating cost savings (at a constant rate of $0.125/kWh) of $255 to $330.

To investigate the space heating impact of HPWH use, Slipstream used energy balance calculations to estimate the net uptake of energy by each HPWH from the surrounding environment. This value and indoor-outdoor temperature difference were used as independent variables in regression, with primary heating system output as the dependent variable. The results provided no evidence of increased space heating as a result of HPWH operation. We cannot draw a firm conclusion of zero heating impact, however, as the HPWH energy uptake is small compared to the total space heating load, and scatter in regression results may mask some effect.

While this study did not allow estimation of long-term basement temperature depression associated with HPWH operation, an array of four temperature sensors spaced between floor and ceiling provided a clear view of short-term temperature changes. Across the sites, the average temperature drop from start to end of a cycle was 2.3 °F, and the temperature after a four-hour recovery period averaged 0.1 °F lower than the temperature at the start of the cycle.

Evaluation of electric power use by hour of day for the water heaters studied, normalized to the usage at each site, showed peaks at around 9:00 AM to noon and 6:00 to 10:00 PM. Carbon emissions for the scenario evaluated were significantly less for HPWHs than electric resistance, propane, or natural gas water heaters.

A survey of the nine field study households and other participants in EO HPWH incentive programs yielded 81 responses. Sixty-four respondents (80%) reported installing a HPWH as a replacement for an electric resistance appliance; the remainder had previously used propane or natural gas. Large majorities of respondents reported that rebates, energy or cost savings, and the age of an existing water heater as significant or very significant factors in the purchase decision, while contractor recommendation and health and safety were generally insignificant.

Seventy-nine respondents said they were satisfied or somewhat satisfied with their HPWH, with just two reporting a neutral reaction and none reporting dissatisfaction. Seven respondents experienced an increase in hot water shortage compared to a previous water heater; four of these reported using the heat pump control setting rather than the hybrid setting.

In 69 cases, the HPWH was installed in the basement of the home. When asked about the temperature and humidity effects of the HPWH during the summer and winter, a majority reported no opinion for either season, while 34 reported a positive reaction to summer changes, and 17 reported a positive reaction to winter changes. There were nine respondents who reported negative reactions to winter changes, and four to summer changes. Twenty-four respondents said the noise of HPWH was noticeable.

One unexpected finding was that 32 respondents (40%) reported that they had not used a professional installer for their system. Among respondents who used a professional installer, instruction received from installers varied. The most common assistance was receiving a user's manual, reported in 39 cases; the least common was receiving an explanation of the controls settings, reported in 24 cases.

INTRODUCTION AND BACKGROUND

The new generation of heat pump water heaters (HPWHs) have Uniform Energy Factors (UEFs) well above three. They also have different control settings that allow users to choose how much to rely on the heat pump or the electric resistance elements to heat the water. Slipstream conducted a field monitoring project to quantify the performance of HPWHs installed in several homes in MECA member utility service territory.

MECA ENERGY OPTIMIZATION AND WATER HEATING

Since 2009, MECA's 13-member cooperative and municipal utilities have offered cash incentives for energy efficient products and equipment through the Energy Optimization (EO) program. Beginning in 2017, EO's residential efficiency program began placing more emphasis on reducing energy use from water heating.

Heat pump water heaters have evolved over several decades, with manufacturers developing improved models after the introduction of national Energy Star standards in 2008. EO began offering a $200 incentive for HPWHs in 2013. Incentives for HPWHs remained at $200 through 2017 and then were increased to $300 in 2018 and finally up to $700 by October 2019 to motivate more customers to replace their electric resistance water heaters with the more efficient HPWH. As seen in Figure 1, the EO program saw limited adoption of HPWHs from 2013 through 2018 and then a significant increase when the incentive was raised to $700.

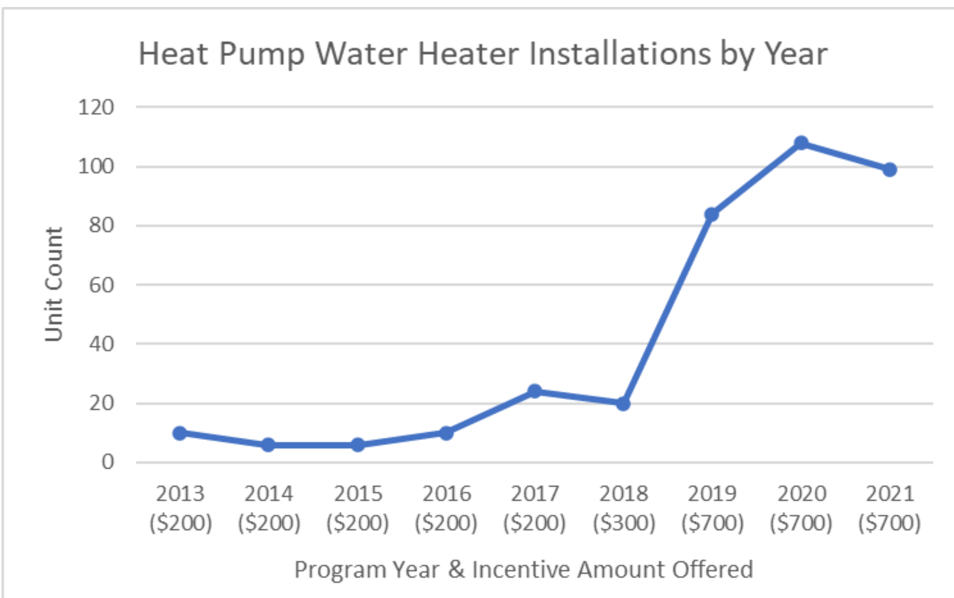

Figure 1. Heat Pump Water Heat Installation by Year and Incentive

MECA member Great Lakes Energy (GLE), the third largest electric utility in Michigan, added an additional rebate of $400 for their members who installed a HPWH, amounting to $1,200 and nearly covering the entire cost of the equipment. This combined incentive also had an impact on the HPWH market: two HPWH distributors, Ferguson Enterprises and Alpena Supply, marketed the combined incentive to contractors in GLE's territory and used it to advocate for higher HPWH incentive offerings from utilities outside the EO program.

Marketing Heat Pump Water Heaters

Heat pump water heaters with an EF/UEF of 2.0 or greater are eligible for incentives through the EO program. They are available in tank capacities from 40 gallons to 80 gallons, though only 8 percent of EO program applications have been for 65 gallon or larger capacity.[2] In 2019, the EO program began marketing HPWHs directly to members of MECA's co-ops and municipal utilities through ads in Country Lines magazine, the EO program website, and with an instant discount coupon for an AO Smith HPWH purchased from Lowe's. This direct-to-customer marketing approach was a change for EO programs, which mostly promoted high efficiency products to the contractors and retailers (trade allies) who sell and install the products.

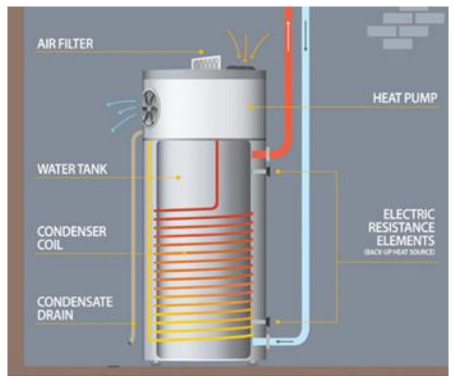

Figure 2. HPWH Ad in Country Lines Nov/Dec 2019, HPWH diagram on EO website.

<u>Lowe's HPWH Discount Coupon</u>

Lowe's was selected as the retailer for the instant discount coupon because their point-of-sale system could process unique barcodes for each coupon recipient and invalidate the coupon after first use. Lowe's was also willing to participate in the discount coupon promotion without passing administrative costs onto the EO program. Additionally, A.O. Smith, whose water heaters are sold at Lowe's, was instrumental in connecting Lowe's with EO program staff, and provided up to 50% of the coupon printing and postage costs.

In October 2020, Lowe's/EO co-branded coupons were sent to 7,396 members of four MECA co-ops/utilities (Alger Delta, GLE, Homeworks Tri-County, Marquette Board of Light and Power). The purpose of the discount coupon promotion was three-fold: educate customers on the benefits of HPWHs, convey the higher incentive, and test customer redemption rates and experience with the coupons.

[2] Most manufacturers suggest 65- or 80-gallon models for high demand households to ensure tanks can recover from high usage episodes without relying too heavily on inefficient electric resistance backup. Selection of these larger tank sizes for higher-usage households can be important in making heat pump water heaters acceptable to consumers.

A.O. Smith anticipated a coupon redemption rate between 0.1% and 0.3%. The Lowe's/EO co-branded HPWH coupons had a redemption rate of .37%, exceeding expectations.

Members of GLE and Homeworks Tri-County who redeemed their coupons soon after they were sent out were more likely to have a positive experience: store associates had the coupon information fresh in their minds and were able to complete orders without issue while products remained in stock at local stores and the warehouse. A GLE member specifically noted that his coupon directly led to the preemptive replacement of his 20-year-old electric water heater.

In contrast, a HomeWorks Tri-County member who redeemed their coupon in December 2020 had a less pleasant experience due to depleted stock. Because the HPWH wasn't in stock, a Lowe's department manager had to place a special order and the customer waited upwards of 12 weeks for the product to arrive.

Trade Ally Engagement

EO program staff decided to try the direct-to-customer marketing approach because mechanical contractors and plumbers were not very familiar with HPWHs and often gave their customers incorrect information. To help trade allies become better advocates for HPWHs and reduce misinformation they gave to customers, the EO program held three HPWH trainings for trade allies in 2020 with AO Smith, Bradford White, and Rheem.

To further educate trade allies on the benefits of HPWH and help them promote HPWHs, the EO program created fact sheets about the three largest brands of HPWH and offered a $100 contractor reward for each HPWH installed.

And a serendipitous outcome from the EO's direct-to-customer promotion of HPWHs happened when a GLE member, who owns an HVAC and plumbing business, was motivated by the advertising and incentives to replace their existing electric water heater with an HPWH. Their positive, personal experience with the HPWH prompted them to begin offering HPWHs to customers of their HVAC and plumbing business.

STUDY OBJECTIVES

Slipstream conducted a field monitoring study on HPWH's in MECA territory to increase our understanding of the technology's potential as an energy saving measure. The research objectives are as follows:

1. **HPWH Performance:** characterize measured energy factor and effective capacity at different operating modes.
2. **Economics:** calculate cost and energy savings compared to an electric resistance water heater.
3. **Space heating impacts**: quantify changes in basement temperature and estimate HPWH's impact on space heating and cooling operation
4. **Customer satisfaction:** survey on experience and satisfaction with installation and performance

METHODOLOGY

We designed a field study of HPWH's in homes in MECA service territory, sought participation, installed and maintained monitoring for about a year, and analyzed the resulting data. A survey of HPWH owners was carried out as a separate task.

SITE SELECTION

We sought homes for the field study that met the following primary criteria:

- An installed heat pump water heater with an EF/UEF rating of 3.0 or greater, preferably of varying manufacturer across sites
- Space heating supplied by a one- or two-stage furnace, with minimal use of auxiliary heating

The space heating criteria were put in place to allow direct calculation of the heating energy supplied to the home, important for estimating the impact of HPWHs on space heating. Furnace gas valves are easily monitored, and the thermal efficiency of furnaces can be assumed to be fairly constant over a season, in contrast to the variable COP of air-source and geothermal heat pumps. Auxiliary heating equipment such as gas fireplaces and wood/pellet stoves offer much greater challenges in terms of monitoring inputs and measuring or estimating heating energy output, and we tried to avoid them.

We screened records of MECA water heater rebate program participants to select those that appeared to meet the criteria. Slipstream staff then called potential candidates and conducted site visits to do the final screening and formalize participation agreements.

Participants were offered cash incentives of $300 ($100 paid after installation of monitoring equipment, $200 on equipment removal) plus up to $200 over the course of the study if they allowed use of their home internet service for data collection. Our team found it particularly difficult to satisfy the space heating criteria – many of the members participating in the rebate program use heat pumps for space heating, and many, regardless of the primary heating system type, make significant use of secondary or auxiliary heating systems. To improve space heating analysis in homes with heavy use of auxiliary heat, we offered a further incentive to those willing to forego its use for periods of about four weeks at a time.

We were able to recruit nine households to participate in the field study (Table 1).

Several characteristics were common to all the participant households and properties.

- All the HPWHs were installed in full basements
- None of the HPWHs used ducted airflow on either intake or exhaust side
- All the homes had a private water well

Additional information on heating systems and on basement size and construction can be found in other sections of this report.

Table 1. Summary information on field study households.

Site	County	Number of full-time occupants	HPWH manufacturer & model	Rated UEF
01	Mason	3	AO Smith (HP1050H45DV 130)	3.45
02	Charlevoix	5 (2 adults, 3 children)[3]	Bradford White (RE2H50S10-1NCWT)	3.39
03	Antrim	4 (2 adults, 2 children)	Richmond[4] (10E50-HP4D)	3.56
04	Oceana	2	Bradford White (RE2H50S10-1NCWT)	3.39
05	Oceana	1	Bradford White (RE2H50S10-1NCWT)	3.39
06	Oceana	2	Bradford White (RE2H50S10-1NCWT)	3.39
07	St. Joseph	4 (2 adults, 2 children)	Rheem (XE50T10HD50U1)	3.55
08	St. Joseph	1	Rheem (XE50T10HD50U1)	3.55
09	Oceana	2	Bradford White (RE2H50S10-1NCWT)	3.39

MONITORING APPROACH

Our approach to monitoring was intended to capture, as directly as possible, the inputs, outputs, and environmental conditions that were expected to be important to HPWH performance. Table 2 lists the primary sensors used, Figure 3 shows sensor positions.

The digital electric metering device (manufactured by egauge) was installed by an electrician at the electric distribution panel in each home, and the water meter and hot and cold water sensors were installed by plumbers contracted for the work – the remainder of each measurement system was installed by Slipstream staff. Except for the power meter, sensors located in the basement of each home were connected to a Campbell Scientific CR1000X data acquisition system. Electric power data was recorded at one-minute intervals; other values were measured and recorded at one-second intervals. We downloaded stored data from the egauge and Campbell Scientific systems on a daily basis through remote internet connections. The

[3] This reflects occupancy through about May 31, 2021, when the house was sold. Since the sale, the house has two to five occupants, generally on weekends.
[4] Richmond-branded heat pump water heaters are manufactured by Rheem, and this water heater is classified as a Rheem where manufacturer-specific information is provided.

stand-alone temperature logging devices were not accessible through a remote connection. More information on the monitoring system can be found in Appendix A.

Table 2. Monitoring system components.

Measured variable	Term used in report	Units	Sensor or meter type
HPWH power consumption	Qe_{total}	W or kWh	Digital electric meter
HPWH current flow	-	-	Current sensor
Water volume at HPWH inlet	Vol_{hot_water}	Gallons	Utility-type water meter with pulse output
Cold water temperature at HPWH inlet	T_{cold}	°F	Immersion thermistor
Hot water temperature at HPWH outlet	T_{hot}	°F	Immersion thermistor
HPWH inlet air temperature	T_{inlet_air}	°F	Packaged linear temperature/ humidity sensor
Temperatures in basement environment	$T_{basement}$ (average of four sensors	°F	Thermistors and linear temperature sensors
Primary furnace gas valve status	-	-	Current sensor
Main living space temperature	$T_{thermostat}$	°F	Self-contained temperature logger
Air temperature near auxiliary heating devices	-	-	Self-contained temperature logger
Outdoor air temperature	$T_{outdoor}$	°F	Self-contained temperature logger

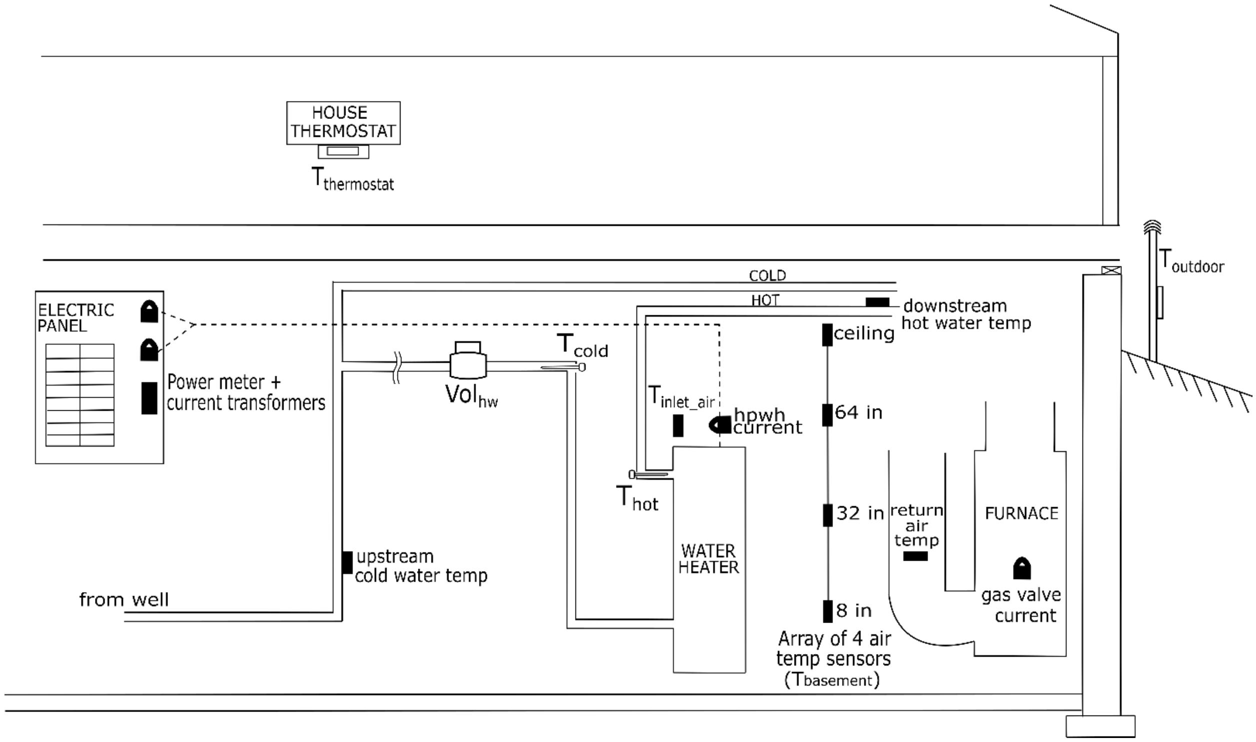

Figure 3. Monitoring system component positions.

Figure 4. Water heater and monitoring components.

OPERATION, MODE CHANGE EXPERIMENTS

The project team asked each participating household to use the electric resistance control setting on their HPWH for a period of about two weeks in the winter and again in the summer. The data collected during these periods allowed calculation of the standby heat loss rate from the water heaters. The participants who normally used the hybrid controls setting were also asked to use the heat pump-only setting for a period.

As part of our objective of analyzing the space heating impacts of HPWH operation, we made agreements with some households to limit the use of auxiliary heating systems over certain time periods, as mentioned in the site selection section above.

ANALYSIS OVERVIEW

We analyzed performance, net savings, indirect impacts on space temperature and heating/cooling loads, and reported satisfaction for each participating household, and in aggregate across all sites.

Energy Analysis Concepts

The energy flows to and from self-contained storage water heaters can be characterized as shown in Figure 5, where the following terms apply:

> Q_{hot_water} is the useful energy delivered from the water heater to fixtures in the building.
> $Qe_{heatpump}$ is the electrical energy used to operate the heat pump compressor and fan.
> $Qe_{resistance}$ is the electrical energy delivered to electric resistance coils to heat water directly.
> $Qe_{controls}$ (not shown in the figure) is the electrical energy delivered to the controls circuitry in each water heater.
> Q_{air} is the heat extracted from air surrounding the water heater during compressor operation, primarily heat absorbed by the evaporator, offset to some degree by heat loss from the compressor motor and from the condenser coils back to the surrounding environment.
> $Q_{standby}$ is the continuous loss of heat from the tank to the surrounding environment.
> Q_{stored} is the energy stored in the tank in the form of hot water.

Each of these values is treated as positive when energy is flowing in the usual direction (as shown by the arrows), and with the exception of Q_{stored}, typically represent a daily total flow of energy.

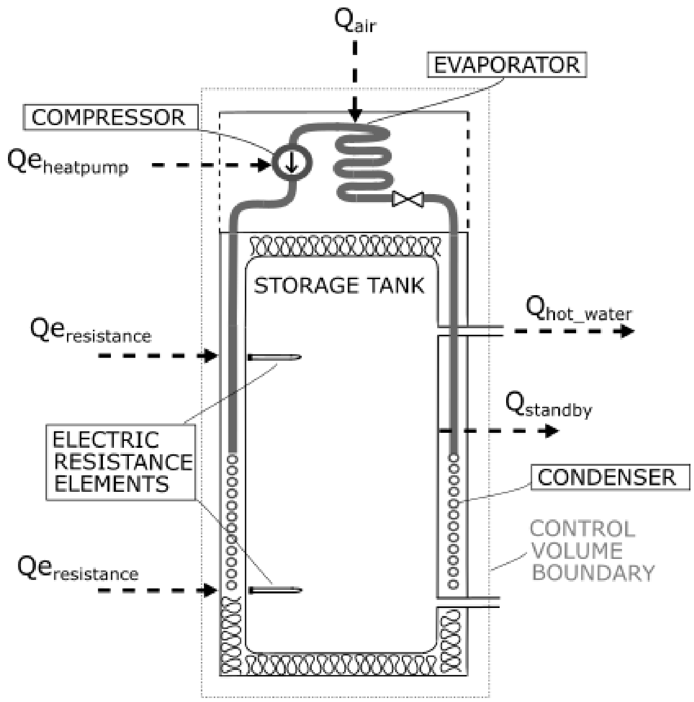

Figure 5. Energy entering and leaving a heat pump water heater, with control volume.

Control volumes are a useful way to apply the conservation of energy to the system being studied: over any given time period, the energy going into the volume plus the net change in energy stored must equal the energy leaving the volume. Applied to the control volume boundary around the tank:

$$Q_{in} = Q_{out} + \Delta Q_{stored}$$

Where Q_{in} and Q_{out} represent total energy flows over a time period, and ΔQ_{stored} is the net change in energy stored within the control volume (or water storage tank) over the same time period. A common assumption in water heating analysis is that stored energy is nearly constant at the end of any 24-hour period that has given the system time for complete reheating to its setpoint[5]. This allows dropping the ΔQ_{stored} term from energy balance calculations. We use a baseline 24-hour period (with the break at 3:00 AM, when active hot water use is low), but also adjust daily energy output to recognize hot water energy drawn from the tank during the previous period that has not been replenished at the 3:00 AM break. The result is the following energy balance that can be applied over daily periods:

$$Q_{in} = Q_{out}$$

or

[5] Alternatively, intervals that end immediately after a reheat cycle should provide for constant energy storage.

$$Qe_{heatpump} + Qe_{resistance} + Q_{air} = Q_{hot\_water} + Q_{standby}$$

Sources of energy values

Q_{hot_water} is calculated directly from measured water volume and temperatures. Our monitoring system measured total electric power delivered to each HPWH, and we developed an algorithm to separate the total into the components, $Qe_{heatpump}$, $Qe_{resistance}$, and $Qe_{controls}$[6]. Recognizing typical line losses between the point where power is measured at the electrical panel and the HPWH, we apply a factor of 99% to the measured power classified as providing electric resistance heating. We assume controls power, $Qe_{controls}$, stays outside the control volume and doesn't contribute to the energy balance across the boundary. Based on this, we ignore controls energy in calculations that balance input and output energy but add it back in when considering overall Energy Factor (EF), operating energy, and operating cost. Q_{air} is derived indirectly from measured values and energy balance calculations. $Q_{standby}$ is derived indirectly from input and output as measured during periods of electric resistance heating.

Performance Indicators

The overall performance of water heaters is most commonly described using EF, or the updated UEF, the ratio of the useful hot water energy output to purchased energy input, as measured under specific test conditions. While our study could not duplicate the test conditions needed to formally derive EF, we used the ratio of useful energy output to electric energy input in our data to calculate a "Field Energy Factor" (EF_{field})[7].

$$EF_{field} = \frac{Useful\ output}{Electric\ input} = \frac{Q_{hot\_water}}{Qe_{heatpump} + Qe_{resistance} + Qe_{controls}}$$

Another fundamental performance indicator is Coefficient of Performance (COP), which characterizes performance of the heat pump sub-system. Applied to a HPWH, COP is the ratio of energy delivered from the compressor-driven refrigerant system to the water storage tank divided by the electrical energy input used for heat pump operation[8]:

$$COP = \frac{Q_{refrigerant}}{Qe_{heatpump}}$$

[6] Power disaggregation made use of the very different levels of current draw in controls, heat pump, and electric resistance operating modes, and the characteristic rise in current draw to detect heat pump operation occurring simultaneously with resistance heating.

[7] Some reports on HPWHs use the term "COP" to describe the value we call EF_{field} – we've held to the more conventional engineering definition of COP.

[8] This usage of COP aligns with the common engineering definition, and should not be confused with Field Energy Factor (EF_{field}).

The heat pump control volume boundary in Figure 6 identifies the relevant energy flows.

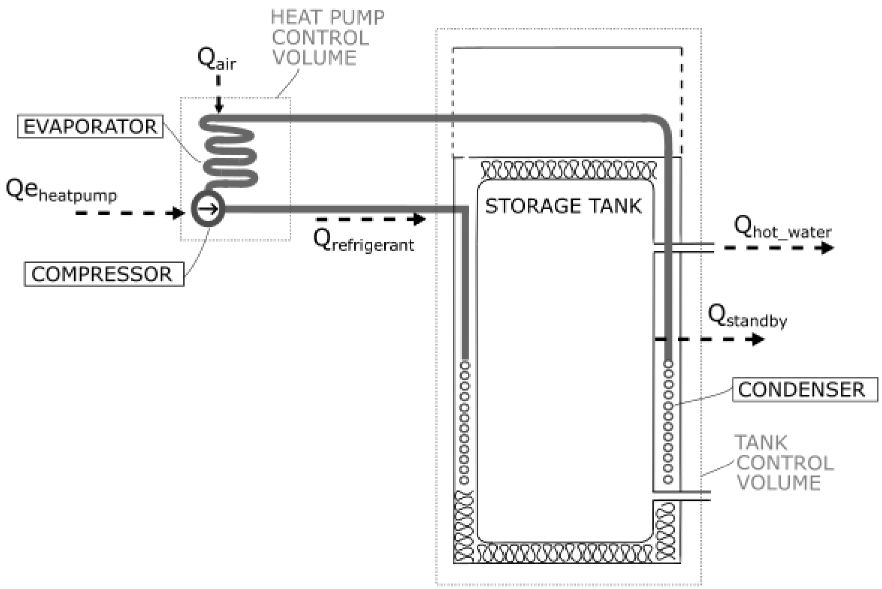

Figure 6. Energy entering and leaving the heat pump control volume, used in COP calculation.

HPWHs using the hybrid controls setting use a variable amount of electric resistance input energy, determined by the manufacturer's control algorithms. We derived an empirical trend in the fraction of the output supplied by resistance heating for each system and use the term $fe_{resistance}$ for this quantity.

We applied these basic principles to our field data in calculating the overall performance of each HPWH system, and in modeling system performance under conditions not observed in the field.

Space heating and basement temperature impacts

The fact that heat pump water heaters extract heat from intake air means that, when installed within conditioned space (including partially conditioned basement space) there are two possible impacts: an increase in space heating requirements, and/or a reduction of space temperatures. We looked at both these outcomes.

We used the widely accepted method of regression of space heating system output against the difference between the indoor and outdoor temperature to evaluate the characteristic space heating trend in each study home, with the energy extracted by the HPWH as an added regression variable. Some study homes have and use secondary heating systems in addition to a primary furnace, and operation of these systems was considered. Basement space temperature analysis made use of air temperatures measured at four heights in each home to evaluate changes during and after HPWH operating cycles.

An expanded section on the theory and methodology of analysis can be found in Appendix B.

Survey

The project team surveyed two groups of HPWH owners. The first group consisted of the nine households participating in the field study, and the second group included other participants in the EO incentive program for HPWHs. The surveys focused on perceived performance of and satisfaction with HPWHs as installed in respondent's homes. Since our team had detailed information on many aspects of the field study homes, slightly different survey instruments were developed for the two groups: both can be found in Appendix C.

PERFORMANCE MONITORING RESULTS

Our team gathered data for about 11 to 14 months at each of the nine field study sites between August 2020 and September 2021. Our data collection system was generally reliable, but we lost data in several limited cases, which led to excluding about 11 days in total from our analysis.

There was a significant occupancy change at site 02 when the home was sold and the owners moved out on about June 1, 2021. The new owners allowed our team to continue collecting data, but they typically occupied the home on weekends only, with long periods of no hot water use and some use of the vacation controls setting. Since this use pattern is outside the norm (and the ideal) for use of a HPWH, we've excluded data for June 1 and beyond from our overall performance analysis of site 02.

HOT WATER USAGE

Not surprisingly, average daily hot water usage varied greatly across the study homes, in terms of both total volume and volume per occupant, ranging from 14 gallons per day for a household of two adults to 68 gallons per day for a family of four (Table 3). The table excludes the period of new occupancy at site 02, but otherwise includes day of zero hot water consumption. Usage per occupant ranged from 7 to 35 gallons per day. Hot water energy delivered ranged from about 7,500 to 40,000 BTU per day.

Table 3. Average monthly hot water usage and temperature by site across the monitoring period.

Site	Average daily hot water use (gal)	Average daily hot water use per occupant (gal)	Average daily delivered hot water energy (BTU)	Median daily maximum flow rate (gpm)	Avg Incoming Cold Water Temperature (F)[9]	Avg Delivered Hot Water Temperature (F)[9]
01	32	11	20,466	1.35	59	127
02	28	8	14,045	2.66	62	109
03	68	23	40,154	2.27	50	118
04	23	12	14,049	1.90	54	117
05	35	35	18,401	1.90	56	112
06	27	13	15,119	1.52	60	111
07	45	15	24,732	2.00	58	122
08	25	25	13,480	1.81	61	119
09	14	7	7,512	1.05	63	113
Avg	***33***	***17***	***18,662***	***1.75***	***58***	***117***

We also found high day-to-day variation in hot water use at each site (Figure 7), with peaking of hot water demand in early-to-mid-morning hours and again in the evening at most sites (Figure 8). Both trends are consistent with the findings of previous studies.

For comparison to values in the table above, the DOE water heater test standard calls for a cold water temperature of 58 F, a hot water temperature of 125 F, and (for water heaters in this class) 55 gallons of hot water use in a one-day period.

[9] Temperature readings are weighted by water flow at each 1-second data interval.

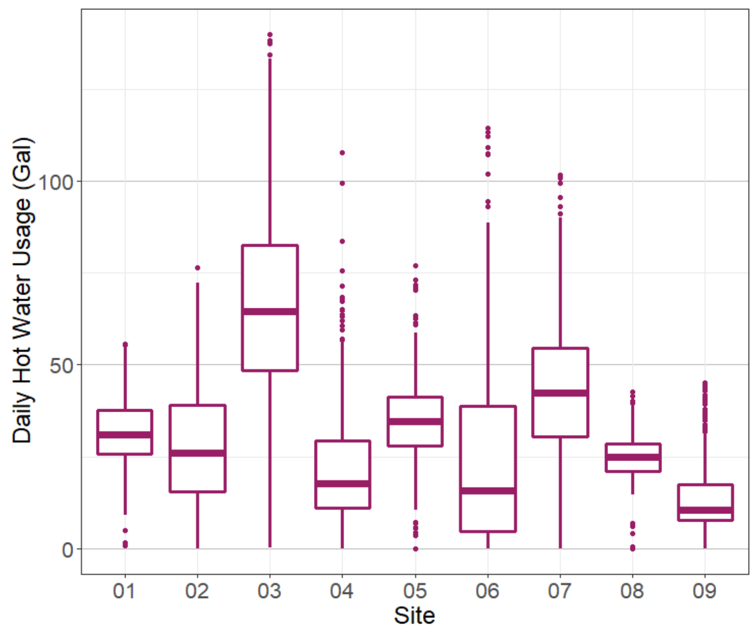

Figure 7. Distribution of daily hot water use by site. The boxes represent the 25th to 75th percentiles, and the heavy line is the median value. For readability, plots exclude the highest one percent of observations. Days of no hot water use are included.

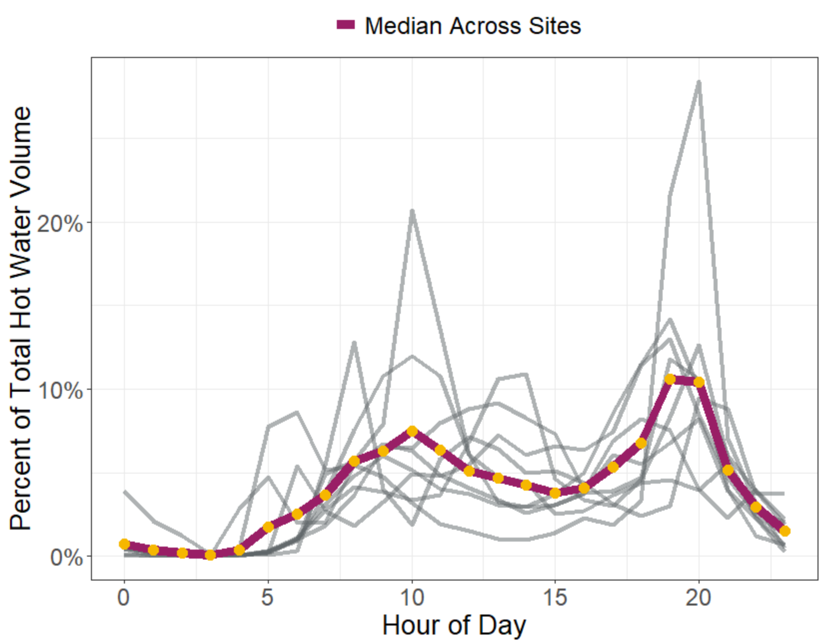

Figure 8. Relative hot water consumption by hour of day. Hour is based on local time at the sites in Michigan, including the daylight savings time shift in March and November. The prominent morning peak is at site 05, a household of 1 person, and the prominent evening peak is site 08, also a household of 1 person.

The temperature of cold water entering the water heater follows a roughly annual cycle at each site and in the median across sites (Figure 9).The temperature of water delivered from the well at each site probably follows a smooth annual curve, but the temperature entering the water heater is influenced by the uncontrolled addition of heat between the well and the water heater due to time spent in the pressure tank and piping.

Hot water temperature at each site should be fairly constant over time, but is influenced by several factors, including system dynamics (water in the storage tank can't be precisely heated to a uniform temperature), episodes of high usage (when the temperature drops off), and setpoint changes (Figure 10).

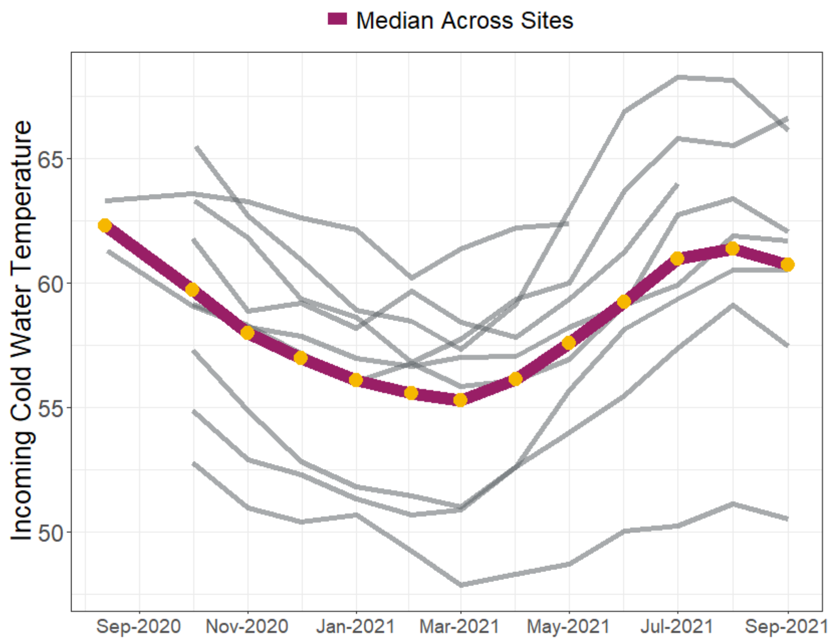

Figure 9. Average monthly incoming cold water temperature by site over the monitoring period. Hot and cold water temperatures are weighted by flow.

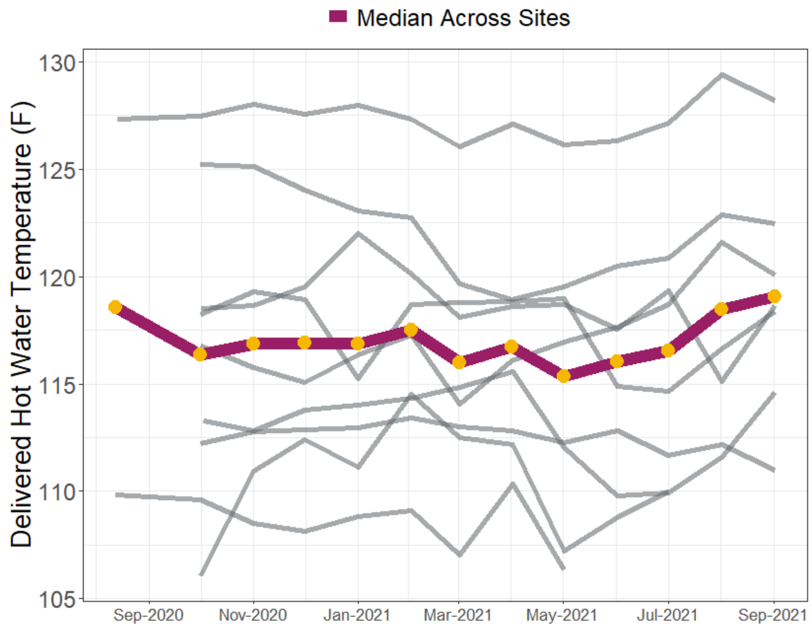

Figure 10. Average monthly hot water temperature by site over the monitoring period. Hot and cold water temperatures are weighted by flow.

The annual trend in delivered hot water energy is irregular, but generally shows a wintertime peak, with a secondary summer peak at some sites. The winter peak is likely due to the combined effects of higher volumetric use and colder incoming water (so more energy added per gallon). The summer peak is driven by higher usage volume in some of the homes.

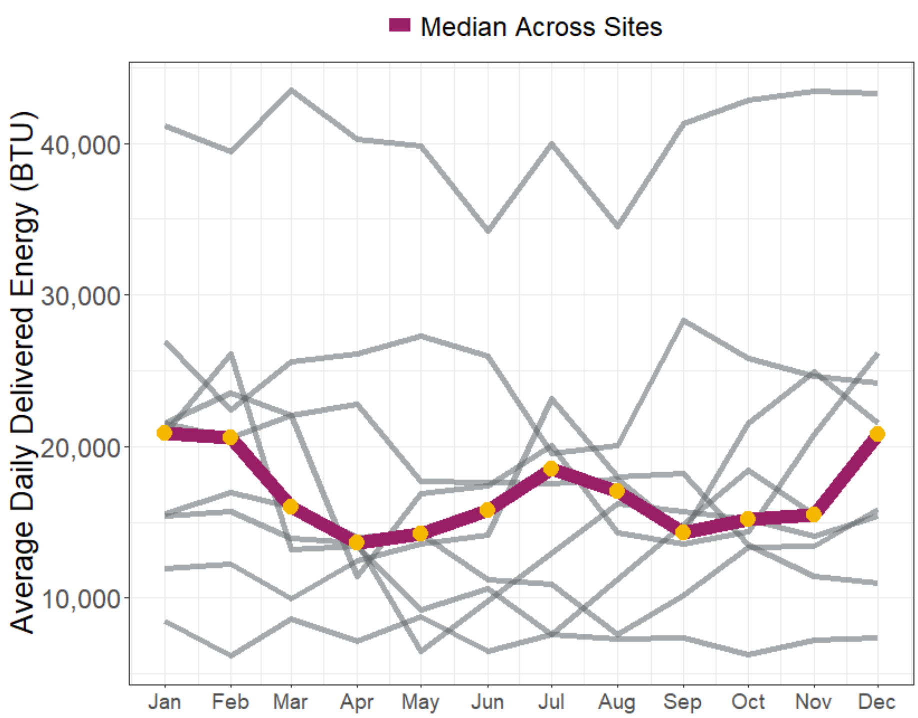

Figure 11. Average daily delivered hot water energy by month for each site.

OVERALL ENERGY USE

Figure 12 shows the daily average input and output energy flows for each field study site. The inputs include the energy extracted from ambient air by the heat pump system (Q_{air}) and the three components of electric power ($Qe_{resistance}$, $Qe_{heatpump}$, and $Qe_{controls}$), while outputs include hot water energy (Q_{hot_water}) and standby heat loss ($Q_{standby}$). By definition, the sum of inputs (except $Qe_{controls}$) balances total outputs.[10] The differing overall magnitude among the sites is largely the result of differing hot water usage.

The extraction of heat from ambient air for delivery to the water is the core principle that gives heat pump water heaters an efficiency advantage over conventional electric resistance water heaters. This efficiency advantage can be seen in the relative lengths of the green bars in Figure 12, where energy from ambient air is generally half or more of the total input energy and is always substantially greater than the electric energy powering the heat pump. The relationship between these quantities is related to heat pump COP, discussed later.

The fraction of input energy from electric resistance is determined to a large degree by the controls settings used by the home occupants. The water heater at site 01, for example, was kept in the efficiency (heat pump) setting for most of the study period. Use of the hybrid setting of course allows electric resistance heating, and the fraction of electric resistance depends on hot water draw patterns and the manufacturer's control algorithms. Site 06 shows the highest fraction of electric resistance input energy and we suspect this is driven by hot water use patterns that may draw the tank temperature down more quickly than is the case at other sites.

[10] As mentioned earlier, we assume controls power does not contribute to heating water, so $Qe_{controls}$ appears as an excess quantity on the input side.

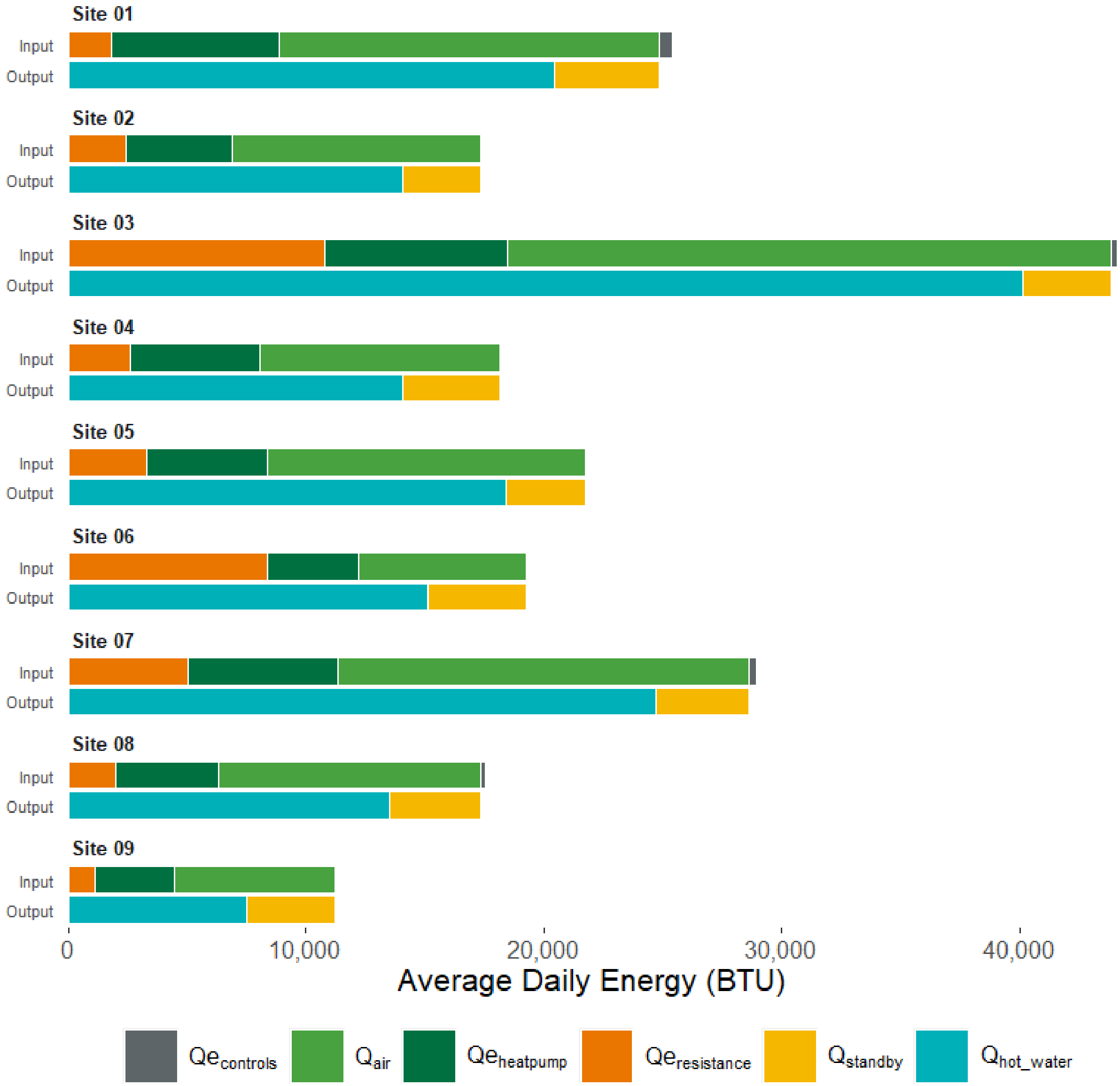

Figure 12. Input and Output average daily energy flows by site.

The power of the heat pump compressor and fan varies widely, typically increasing (after a brief start-up spike) over time within each individual operating cycle. Electric resistance power is more predictable, but resistance element power varies with line voltage, plus some water heaters have upper and lower resistance elements of different wattage. Controls power is generally low, but with significant differences between the models represented in the field study (Table 4).

Table 4. Typical power consumption by electric power component.

Manufacturer	Sites	Median heat pump compressor & fan power (W)	Electric resistance upper/lower element rating (W)	Median electric resistance power (W)	Median controls power (W)
AO Smith	01	426	4500 / 4500	4356	7
Bradford White	02, 04, 05, 06, 09	377	4500 / 4000	4386	1
Rheem[11]	03, 07, 08	347	5000 / 5000	5120	3

OVERALL PERFORMANCE

We calculated field energy factor (EF_{field}) on a daily basis for the HPWHs we monitored. These calculations exclude days when the electric resistance controls setting was used at our request. Figure 13 and Figure 14 demonstrate several trends in daily energy factor as daily hot water consumption varies. The group of mostly dark purple points in Figure 13 show a classic pattern, driven by the effect of approximately constant standby heat loss that pulls energy factor down toward zero as hot water demand decreases. (A very similar pattern will be found in conventional gas and electric resistance water heaters). With the heat pump control setting, the upper points on this curve will be limited by the efficiency of the heat pump system. With controls set to hybrid, electric resistance heat will be added in at times, and is expected to provide an increasing fraction of reheat energy as hot water loads increase. The more yellow points represent days with a high fraction of electric resistance heat and show greatly reduced energy factor. We're not certain why the two groups of points are largely isolated from one another, but we see some evidence that the controls on this and other Bradford White water heaters may trigger more electric resistance heating earlier under some usage conditions than other water heaters, with the result that it plays a disproportionate role in reheating.

Figure 14 shows results for site 03, the household with the highest hot water use in our study. Here we see a more continuous pattern of points, with energy factor peaking at around 50 to 75 gallons per day and decreasing with higher usage as the fraction of electric resistance heating increases. This site has a Rheem HPWH, and the controls were generally set in either hybrid or "high performance" that emphasizes electric resistance heating to maintain capacity.

Similar EF plots for all sites are found in Appendix D. As a generalization, the energy factor of HPWHs can be expected to peak on days with moderate water usage, say around 50 gallons per day, high enough to reduce the effects of standby loss, yet low enough to avoid much use of resistance heating. We study these trends further in the modeling section below.

[11] Rheem includes the water heater labeled as a Richmond.

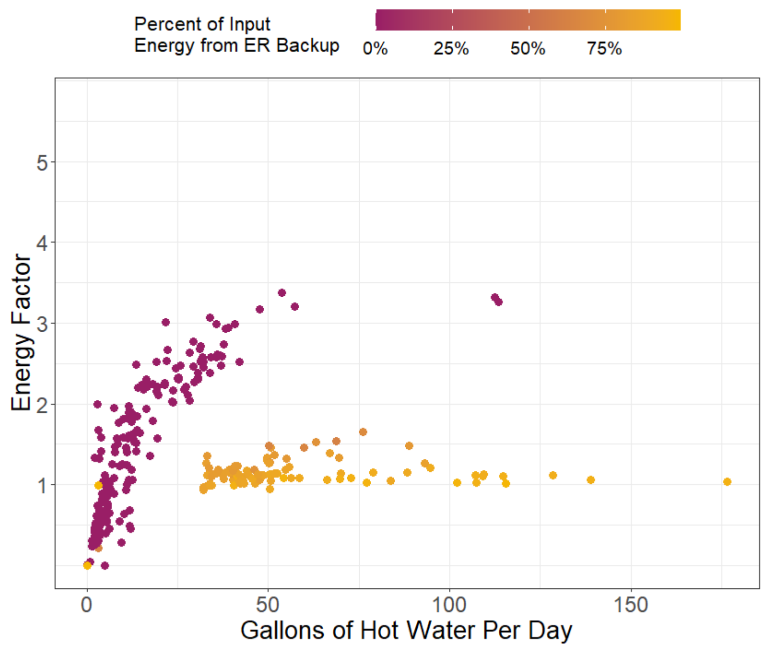

Figure 13. Daily energy factor by daily water consumption for site 06, with colors scaled to the percent of input energy from electric resistance backup.

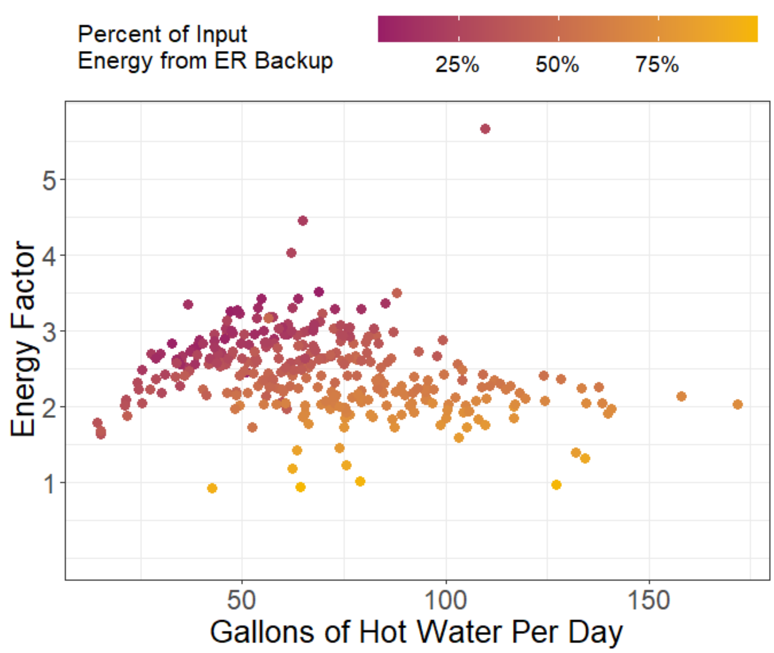

Figure 14. Daily energy factor by daily water consumption for site 03, with colors scaled to the percent of input energy from electric resistance backup.

The performance of the heat pump water heaters as derived from field data is summarized in Table 5. The field energy factor values are significantly lower in each case than the manufacturer's rated UEF for the same model of water heater; several factors contribute to this. First and most obvious is the low average daily hot water use in many of the field study homes. With lower hot water use, standby heat loss has a larger effect on energy factor, pulling it down. The second factor is the amount of electric resistance heat that's used under the DOE standard test protocol as compared to real-world operation. Although the DOE protocol advises that HPWHs controls be placed in a hybrid setting, we suspect that the specified draw pattern allows many HPWHs to complete the test with no resistance heat, resulting in high energy factors. In contrast, use of the hybrid setting in real homes generally results in the use of electric resistance operation, with resistance use increasing as hot water load increases. The increased use of resistance heat at high usage may in part explain the lower-than-rated energy factor at site 03, where average hot water usage was higher than called for in the test protocol. Finally, varying water use over time has an effect on average energy factor that may not be intuitive. Specifically, the energy factor over multiple days of varying use will be lower than the energy factor predicted for any single day with the same average use.

Table 5. Overall performance of systems studied. EF_{field} is the output/input performance derived from field data over the monitoring period.

Site	Rated UEF from AHRI database	EF_{field} in various operating modes			
		All modes[12]	*Heat Pump*	*Hybrid*	*Electric Resistance*
01	3.45	2.46	2.50	-	0.81
02[13]	3.39	2.19	2.52	1.59	0.78
03	3.56	2.34	3.56	2.28	0.91
04	3.39	1.96	2.12	1.45	0.74
05	3.39	2.51	3.04	1.24	0.85
06	3.39	1.29	1.74	1.13	0.78
07	3.55	2.49	3.05	2.05	0.86
08	3.55	2.39	2.57	1.45	0.88
09	3.39	1.94	1.95	-	0.68
Avg	***3.45***	***2.17***	***2.56***	***1.60***	***0.81***

The control setting is a significant factor in performance and operating costs. We requested that each household set their HPWH controls to electric resistance for a period of about two weeks during the winter, and two weeks during the summer. This was done to give us data for the calculation of standby losses. At other times, occupants could use the settings of their choice, and did occasionally change them. We don't know specifically what control setting was in use at

[12] Excludes periods when the HPWH was set to use electric resistance only at the request of the study team.
[13] For period before occupancy change

any given time but can classify each day according to the observed operation (Table 6). Heat pump and electric resistance refer to days with 100% of operation in those modes; hybrid refers to days with a mix of heat pump and electric resistance. These observed operating modes are indicative of the control settings in use, except that 100% heat pump operation may be observed for water heaters with controls set to hybrid.

Table 6. Days in observed operating mode by site.

Site	Days in Each Observed Operating Mode			
	Heat Pump	*Hybrid*	*Electric Resistance*	*No operation*
01	361	7	27	1
02	238	39	16	1
03	29	305	24	4
04	318	23	28	1
05	300	25	27	11
06	212	95	18	1
07	193	124	31	1
08	284	20	37	7
09	313	8	27	0

STANDBY HEAT LOSS

During periods of exclusively electric resistance heating, we can assume that all the power delivered to the resistance heating elements goes directly to heating water in the tank (or equivalently, that the effective COP of electric resistance heating is 1.0). Using the energy balance around the water heater, and considering only periods of 100% electric resistance heating, we see that output energy delivered in hot water subtracted from electric resistance input energy provides an estimate of standby energy loss. Our request to each participating household to set the water heater controls to the electric resistance setting for periods of about two weeks in the winter and again in the summer generated the data needed for this calculation. As mentioned earlier, we assume that losses in electric wiring led to a 1% reduction in the power delivered to the water as compared to the power measured at the distribution panel in each home. A summary of standby loss calculation results appear in Table 7.

Table 7. Standby loss results by site.

Site	Manufacturer	Average difference between basement and tank temperature (°F)[14]	Daily Standby Loss (BTU)[15]	Avg standby loss rate (BTU / Day °F)
01	AO Smith	73	3908	53
02	Bradford White	55	4237	70
03	Rheem	62	2837	49
04	Bradford White	69	4857	70
05	Bradford White	56	3211	56
06	Bradford White	69	4590	64
07	Rheem	66	3618	56
08	Rheem	64	4488	65
09	Bradford White	62	3751	60
Avg	**-**	***64***	***3944***	***60***

We assume standby loss is a simple function of temperature difference between the tank and the surrounding environment and use regression to estimate a standby loss coefficient. This coefficient can then be used to estimate standby loss at any time outside the short period of testing, and under assumed conditions in modeling. We performed regressions for each site, with the average delivered hot water temperature representing tank temperature, and the average of basement air temperature at four heights as the environmental temperature. Because of variability in results for individual sites, we settled on using a single regression that combines data across all sites (Figure 15). Since standby loss should drop to zero when the temperature difference is zero, the regression intercept is fixed at this point.

[14] This is estimated by subtracting the daily maximum delivered hot water temperature from the basement air temperature averaged over sensors at four heights, placed 5 to 10 feet from the water heater.
[15] This is field derived standby loss calculated exclusively on days where HPWHs were configured to the electric resistance control setting.

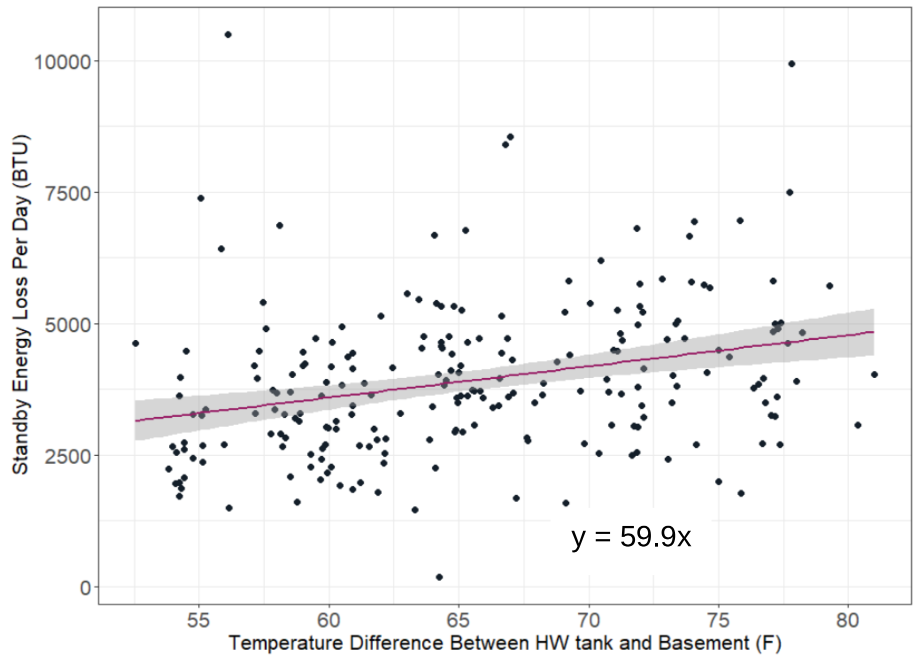

Figure 15. Standby loss vs tank - basement temperature difference for all sites, with regression line.

COP

Coefficient of performance (COP), as mentioned earlier, is the ratio of useful heat output of a heat pump system (heat delivered to the tank in this case, or $Q_{refrigerant}$) to the power used by the heat pump (the compressor and fan in this case, or $Qe_{heatpump}$).[16] We estimate COP from data on days that used exclusively heat pump reheating of the water (no electric resistance). On these days, we can assume $Q_{refrigerant}$ is the only input to the storage tank, and (with the usual assumption of no net change in stored energy), that it exactly balances the total output of delivered hot water plus standby losses. Thus, though we can't measure $Q_{refrigerant}$ directly, we can calculate it from Q_{hot_water} and $Q_{standby}$. Average COP values calculated from data are shown in Table 8.

Heat pump COP is influenced by the temperature difference between the evaporator and condenser (the "temperature lift")—higher lift results in lower COP. We used linear regression to explore this relationship. While temperature lift would be the ideal independent variable, we don't have a direct method for estimating condenser temperature (which will vary with hot water draw patterns), so we used evaporator inlet air temperature (T_{inlet_air}) as the independent variable. This is equivalent to assuming the condenser temperature is randomly distributed and doesn't bias the results.[17] We ran regressions using data for days with exclusively heat pump

[16] A reminder to the reader that this report defines the "useful energy output" numerator term in COP as the energy added to the storage tank by the heat pump system, not the energy delivered in the hot water from the tank as used in some reports.

[17] Condenser temperature would track the temperature of water that's being heated in the lower part of the tank, so would generally lie between cold water inlet and hot water exit temperature.

operation. Figure 16 shows the result of regression for one site. See Appendix E for results from each site.

Table 8. Field COP values across sites.

Site	Manufacturer	Average Inlet Air Temperature (F)	Average Field COP
01	AO Smith	66	3.25
02	Bradford White	65	3.10
03[18]	Rheem	61	3.98
04	Bradford White	61	2.82
05	Bradford White	65	3.59
06	Bradford White	62	2.62
07	Rheem	62	3.68
08	Rheem	64	3.49
09	Bradford White	63	2.99
Avg	**-**	***63***	***3.28***

We use COP regression results to predict the performance of the heat pump under different assumed inlet air temperatures in our modeled performance section below.

[18] Because there were a limited number of days of operation exclusively in heat pump mode at this site, we don't have high confidence in the heat pump COP value, and did not use this value in performance modeling.

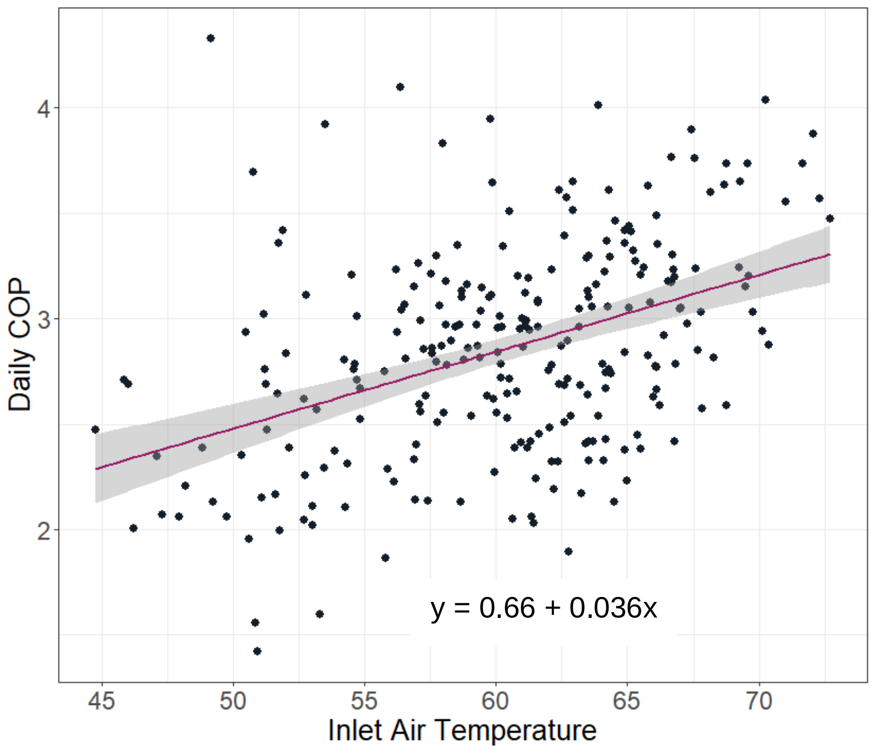

Figure 16. COP vs. inlet air temperature with regression line for site 04, calculated by day. The slope of 0.036 translates to a 1-unit increase in COP for a 28 °F increase in inlet air temperature.

FRACTION ELECTRIC RESISTANCE

For heat pump water heaters operating in hybrid mode, increased hot water load will in general lead to increased electric resistance use, in terms of both absolute energy use, and the relative contribution of resistance vs heat pump input. We capture this effect in the term $fe_{resistance}$, the fraction of total energy output that's reflected in resistance input. We once again used regression analysis of our field data to find a value for $fe_{resistance}$ for the systems studied. Manufacturer-specific algorithms trigger electric resistance backup heating in hybrid mode and differences in these algorithms impact performance. Figure 17 reflects the trend of increased proportion of electric resistance backup heating during days with higher hot water energy demand. We use the regression results in modeling to predict the fraction of output supplied by resistance heating.

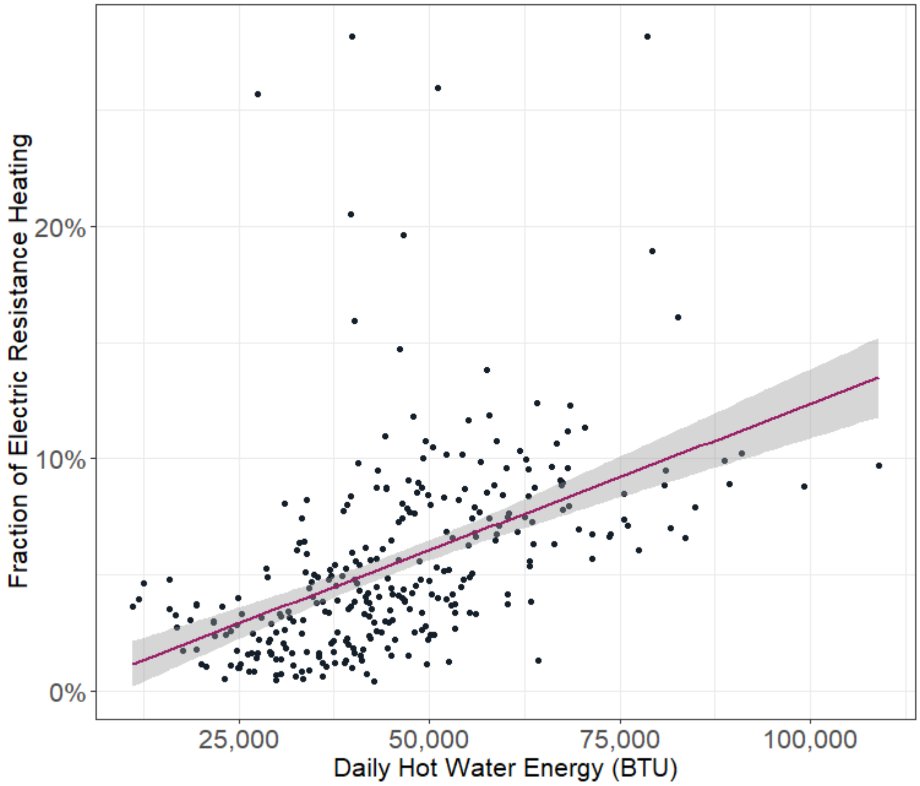

Figure 17. Fraction of electric resistance energy vs. daily hot water energy with regression line for site 03, calculated by day.

MODELED PERFORMANCE

To generalize the results of our field study, we've calculated the expected performance of HPWHs under hypothetical operating conditions (see Table 9). The 25 to 75 gal/day range of hot water use generally reflects the range we found in the field study. The range also recognizes limitations on the technology at low and high usage. Very low users will see less benefit from the more efficient but more expensive heat pump technology. High users (say above 75 gal/day) are likely to experience greater use of electric resistance operation that reduces savings. Larger storage tanks should generally increase overall capacity and reduce the need for electric resistance heating, so would benefit high users. Exploration of larger tank size is beyond the scope of our modeling.[19]

Following is a summary of our approach to modeling:

- Use assumed hot and cold water temperatures and hot water draw volume to calculate hot water energy delivered, Q_{hot_water}

[19] The control algorithms used by the manufacturer appear to have a significant influence on the use of electric resistance heat, so a larger tank size alone does not guarantee higher efficiency. Larger tanks will also generally have higher standby losses.

- Use standby loss regression results, assumed tank temperature, and assumed environmental temperature to calculate standby loss ($Q_{standby}$) and total output energy (Q_{hot_water} + $Q_{standby}$)
- (When modeling HPWHs in hybrid mode) Use the fraction resistance ($fe_{resistance}$) regression results and the total output energy (Q_{hot_water} + $Q_{standby}$) to estimate the fraction of the total load that will be supplied by electric resistance input, and calculate electric resistance energy input, $Qe_{resistance}$
- Calculate the remaining load that will be supplied by heat pump output, $Q_{refrigerant}$
- Use COP regression results and assumed inlet air temperature to estimate heat pump COP
- Use COP and $Q_{refrigerant}$ to calculate electric energy input required to the heat pump, $Qe_{heatpump}$
- Sum up the input electrical energy required, including controls energy, $Qe_{heatpump}$ + $Qe_{resistance}$ + $Qe_{controls}$
- Calculate the ratio of hot water energy output to electrical energy input—this is the modeled energy factor

Table 9. Assumed operating conditions used in performance modeling.

Modeled scenario	Cold water temperature (°F)	Hot water setpoint (°F)	Daily hot water use (gal)	Basement air temperature (°F)
DOE test conditions[20]	58	125	55	67.5
Low usage, low temperature lift	58	115	25	70
Medium usage, low temperature lift	58	115	50	70
High usage, low temperature lift	58	115	75	70
Low usage, high temperature lift	58	125	25	55
Medium usage, high temperature lift	58	125	50	55
High usage, high temperature lift	58	125	75	55

We grouped the water heaters represented in the field study according to manufacturer, and we used COP and $fe_{resistance}$ results combined across units within each group in our performance modeling. We considered both heat pump and hybrid controls settings in each case, though we didn't have sufficient data to include all cases. We once again point out that the sample size is

[20] Our modeling can only approximate DOE test conditions – it does not adjust for DOE-specified timing of each draw within the day, and test conditions assume a uniform environmental temperature which isn't typical of real basements.

small, and urge caution in drawing conclusions, especially as to differentiating performance by manufacturer (Table 10). Values for the Rheem system exclude site 03 due to the limited data available to estimate heat pump COP.

Average modelled energy factors across all manufacturers are 2.55 in heat pump mode and 2.15 in hybrid mode under the medium usage, high temperature lift scenario that is most representative of an average cold climate installation. All estimated energy factor values calculated under DOE test conditions are lower than manufacturer's rated values. We don't have a clear understanding of the cause, but can speculate that different draw rates in the field environment compared to the test protocol, and possibly non-uniform air temperatures in basements, contribute.

Table 10. Modeled EF in various scenarios by manufacturer and control setting.

Modeled scenario	**AO Smith n = 1**		**Bradford White n = 5**		**Rheem n = 2**	
	Heat Pump	*Hybrid*	*Heat Pump*	*Hybrid*	*Heat Pump*	*Hybrid*
DOE test conditions	2.85	-	2.94	2.08	3.30	2.93
Low usage, low temperature lift	2.47	-	2.71	1.88	2.95	2.71
Medium usage, low temperature lift	2.88	-	3.01	2.09	3.35	3.00
High usage, low temperature lift	3.05	-	3.12	2.18	3.51	3.06
Low usage, high temperature lift	1.99	-	2.21	1.67	2.42	2.33
Medium usage, high temperature lift	2.33	-	2.50	1.91	2.79	2.62
High usage, high temperature lift	2.48	-	2.62	2.02	2.94	2.69
Rated UEF from AHRI database[21]	3.45	-	3.39	-	3.55	-

[21] We have added the rated UEF values under the HP only column because we suspect that HPWHs generally do not trigger electric resistance backup during DOE testing procedures.

We don't see evidence of a decrease in energy factor when moving from medium to high hot water use in any of our scenarios. We expected to see this in at least some cases, since higher hot water demand triggers a greater fractional use of electric resistance use and eventually a decrease in energy factor (see again Figure 14). We suspect the linear regression used to develop the $fe_{resistance}$ factor doesn't fully capture the trend toward electric resistance use in the systems studied.

We also calculated blended energy factor values that use the performance of all the systems included in the field study and combines heat pump and hybrid operation in the proportions observed in data (Table 11). This information may be of value to program planners seeking typical performance values not specific to any manufacturer or model.

Table 11. Blended performance modeling results.

Modeled scenario	***Heat Pump EF***	***Hybrid EF***	***Weighted Average EF[22]***
DOE test conditions	3.02	2.37	2.92
Low usage, low temperature lift	2.74	2.16	2.68
Medium usage, low temperature lift	3.08	2.39	3.01
High usage, low temperature lift	3.21	2.47	3.13
Low usage, high temperature lift	2.23	1.89	2.19
Medium usage, high temperature lift	2.55	2.15	2.50
High usage, high temperature lift	2.68	2.24	2.62

We've extended our modeling to include energy savings and estimated operating cost for each HPWH product represented in the study. The average annual energy savings in the medium usage, high lift scenario range is 2435 kWh in heat pump mode and 2188 kWh in hybrid mode (a full table of estimated energy savings is located in Appendix F. Operating cost savings and simple payback periods are reported in Table 12.

Operating cost savings are also modelled under the medium usage, high lift scenario for propane and natural gas water heaters due to their prevalence in MECA service territories. Incremental costs are not provided for these replacement scenarios because it is outside the scope of this research. However, the operating cost savings for propane water heaters are

[22] This average uses the proportion of days in observed heat pump or hybrid mode for each site to calculate a weighted, modeled EF.

significant and could likely provide attractive payback periods for homeowners. The operating cost savings compared to natural gas water heaters are small or negative. This suggests that HPWH replacements of natural gas systems may not have economically attractive payback periods with current fuel prices.

Table 12. Estimated operating cost of HPWHs, and savings as compared to an electric resistance water heater in medium usage, high lift conditions.

Manufacturer	**ERWH Annual Operating Cost ($)**[23][24]	**Incremental Installation Cost of HPWH ($)**[25] **(2)**	**HPWH Operating Cost ($)**		**Operating Cost Savings ($)**		**Simple Payback (years)**	
			Heat Pump	*Hybrid*	*Heat Pump*	*Hybrid*	*Heat Pump*	*Hybrid*
AO Smith	452	860	160	-	292	-	2.9	-
Bradford White	452	860	150	196	302	255	2.8	3.4
Rheem	452	860	134	142	317	309	2.7	2.8

Table 13. Cost impacts with natural gas and propane baselines in the medium usage, high lift scenario.

Manufacturer	**Operating cost savings with propane water heater ($)**[26][27]		**Operating cost savings with natural gas water heater ($)**[28]	
	Heat Pump	*Hybrid*	*Heat Pump*	*Hybrid*
AO Smith	196	-	4	-
Bradford White	211	165	17	-29
Rheem	225	216	31	23

[23] UEF of 0.95 is per MEMD workpaper FES-H2A
[24] Based on Great Lakes Energy residential electric rate of $0.125 per kWh
[25] ERWH costs are estimated from the NREL database. HPWH equipment and labor costs are averaged across field study participants' rebate invoices. The invoices are from 2018-2019, which does not reflect cost increases for HPWHs due to supply chain constraints in 2020-2021.
[26] A UEF of 0.64 is the assumed efficiency for both the propane and natural gas water heaters. This is the minimum UEF for a medium draw EnergyStar gas storage water heater in the MEMD workpaper FES-C9.
[27] Assumes Michigan's 5 year average propane price from 2016-2021 of $1.92/gallon from EIA.
[28] Assumes Michigan's 5 year average natural gas price from 2016-2021 of $9.70/MMBtu from EIA

All the performance modeling and cost savings results discussed above may be useful in exploring general trends but should not be taken as quantitative estimates of performance or operating cost for specific HPWH products under specific operating conditions.

SPACE HEATING AND BASEMENT TEMPERATURE IMPACTS

Heat pump water heaters have a space cooling impact on the immediate environment and quantifying the impact of this cooling on whole-house space heating load was one objective of the project. All nine of the homes in the field study used fuel-fired central heating systems (all of them propane-fired with one exception, an oil furnace which was paired with an air-source heat pump), and all had the main equipment installed in the basement (Table 14). The propane (or oil) was unmetered in every case. We quantified space heating provided from the primary systems by monitoring the gas valve status and multiplying burner run time by manufacturer's nameplate rated output.[29]

Table 14. Basement construction and heating systems.

Site	Floor area (ft^2)	Volume (ft^3)	Wall construction	HPWH in separate room?	Walk-out door to grade?	Primary heating system	Primary system rated output (BTU/hr)
01	1,176	8,285	Concrete block	No	No	Furnace	78660
02	1,468	10,643	Concrete block	No	No	Boiler	102,000
03	1,161 155	11,610 1,555	Concrete walls with insulation, drywall	Yes	Yes	Furnace	67,000
04	1,440 20(mech room)	13,389 186(mech room)	Concrete walls partially finished	Yes	Yes	Furnace	64,400
05	1,041	8,328	Concrete block	No	Yes	Oil furnace + ASHP	Furnace: 85,000 Heat pump: 42,000(47F) 26,200 (17F)
06	613	3,678	Field Stone walls	No	No	Furnace	44,200
07	448	3,584	Field Stone walls	No	No	Furnace	58,995
08	243	1,651	Field Stone walls	No	No	Furnace	55,500
09	1,431	11,349	Poured Concrete walls	No	Yes	Furnace	66,400

[29] Heating output was calculated separately for first and second stage operation for furnaces with 2-stage gas valves.

We consider all the basements to be “partially conditioned” in having primary heating equipment and (except in one case with a hydronic system) ductwork with one or more supply registers in the basement, but with no separate heating zone control.

The use of auxiliary heating systems is a common means of reducing the cost of heating with propane in MECA service areas, and four of the nine field study households reported frequent use of auxiliary heat during heating seasons prior to the start of the study (Table 15). As mentioned earlier, each of these participants agreed to avoid use of the auxiliary system for about two weeks of each month during the study period. We also placed temperature recording devices near the auxiliary sources to confirm use or non-use of these heat sources. Our evaluation of the data suggests that two of the four households (sites 04 and 05) followed the suggested schedule for the use of auxiliary heat, and we limited space heating analysis to these periods. The other two households (03 and 06) showed apparent irregular use of auxiliary heating systems, and we developed algorithms using temperature data to estimate the number of hours of auxiliary heating each day for those sites. We didn’t try to directly quantify the output of auxiliary systems or their effect on space heating loads, but assume each has a constant output when operating, and added operating time as an independent variable in analysis.

Table 15. Auxiliary heating systems used in field study homes.

Site	Aux system(s)	Historic usage pattern	Usage during study
03	LP Fireplace and LP Direct Vent Stove	Daily- thermostat controlled	Irregular
04	Pellet Stove	Daily- manual control kept running 24 hours a day in heating season	No use on first 14 days of each month
05	Central Air Source Heat Pump	Daily- manual control of switchover typically around 25 degrees	No use on first 14 days of each month
06	Pellet Stove	Daily evening use only then irregular use after failure in December	Irregular

We used linear regression of daily values of primary space heating energy against average indoor-outdoor temperature difference to characterize heating energy use in each home, with the energy extracted by the HPWH as a separate independent variable. We assume that Q_{air} and $Q_{standby}$ contribute equally but in opposite directions to space heating and calculate the net heat extracted by the HPWH from the environment as $Q_{air} – Q_{standby}$, or Q_{space}. For the two sites with irregular auxiliary heating use, we added a third independent variable reflecting hours of auxiliary heat operation. The regression solves for the proportional impact of Q_{space} on the total space heating load: a coefficient of zero means no impact, and a coefficient of 1.0 means that space heating increases to exactly make up for the heat taken up by the HPWH. We have no reason to expect coefficients to fall below zero or above 1.0. Additional discussion of space heating analysis, including auxiliary heating issues specific to each site, can be found can be found in Appendix B.

Space Heating Analysis Results

Figure 18 shows a scatter plot of space heating against indoor-outdoor temperature difference for one site. Heat extracted by the HPWH is represented by a gradation in the color of each point. A significant effect of HPWH operation on space heating should show up as a tendency for the lighter colored points to lie near the upper side of the grouping, but no such effect is visible. Similar scatter plots for all sites can be found can be found in Appendix G.

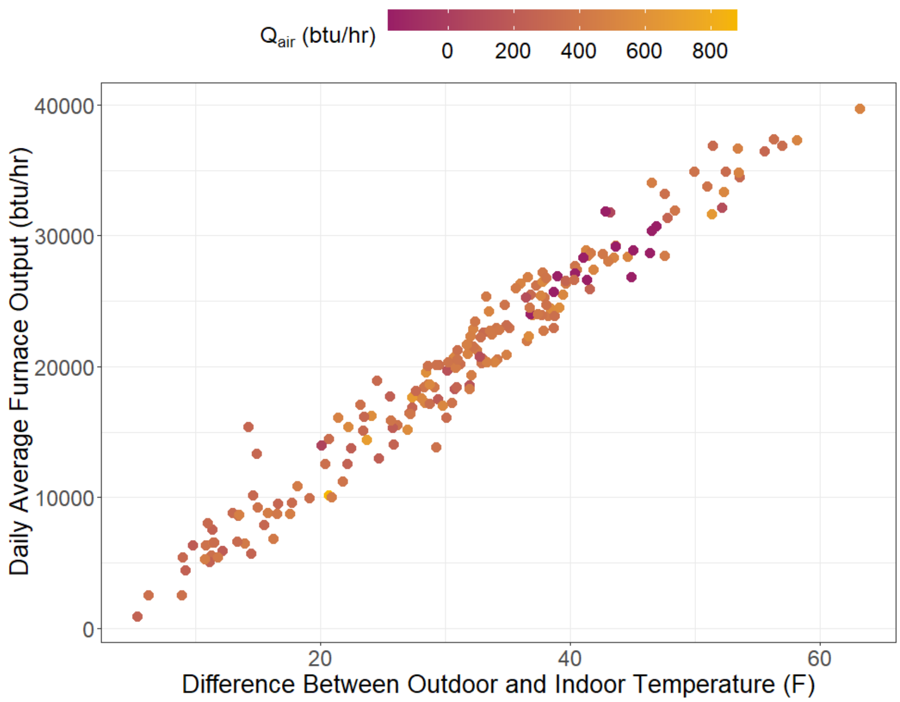

Figure 18. Site 8 daily furnace energy by the average temperature difference. The color gradient shows the amount of Q_{air} energy extracted from the house on that day.

Regression results for each home are included in Table 16. The temperature difference coefficient is the regression prediction of the additional BTU/hr required per additional degree of indoor-outdoor temperature difference. The Q_{space} coefficient is the predicted furnace output in BTU/hr for each additional BTU/hr of net energy uptake by the water heater. A Q_{space} coefficient of 1.0 would indicate that 100% of the water heater energy uptake was offset by added furnace operation.

The widely ranging values of Q_{space} simply don't provide evidence of a systematic impact of HPWH operation on space heating across the homes in this study. The variability in the regression results, the inconsistent sign, and the large magnitudes in the extreme cases all suggest that there may be a site-specific correlation of some other factor or factors that affect space heating with HPWH operation.

Table 16. Space heating regression results.

Site	Intercept	Temperature Difference Coefficient	Q_{space} Coefficient	Auxiliary Heat Coefficient
01	-3340**	801**	-0.67	-
02	260	387**	0.56	-
03	883	294**	0.60	-25953**
04	427	549**	-1.54	-
05	-2909**	389**	-0.16	-
06	16	525**	-1.17**	-35930**
07	-2883**	555**	-1.88**	-
08	-1329**	693**	-0.45	-
09	-1158*	539**	2.14*	-

Significance codes: 1% = **, 5% = *

The lack of a noticeable space heating effect may be partly explained by the relative magnitude of space heating and HPWH energy exchange with the space (Q_{space}). Table 17 shows that Q_{space} is less than 5% of the average space heating load in all the study homes. If, say, half of Q_{space} translated to increased space heating load, the maximum effect would be less than 2.5%, which is in the noise level for space heating regression analysis. The Q_{space} fraction in several of the homes is almost certainly too small to be detectable. Ultimately, we must conclude that it's possible some fraction of Q_{space} is reflected by increased furnace output, but that the fraction is probably small and difficult to quantify.

Table 17. Average space and water heating energy loads. Furnace output is averaged over all days during which the furnace ran.

Site	Average Furnace Output (btu/hr)	Average Delivered Hot Water Energy (btu/hr)	Average Q_{space} (btu/hr)	Q_{space}'s percent of furnace energy
01	25,540	935	594	2.3%
02	13,251	629	335	2.5%
03	18,280	1,761	880	4.8%
04	22,106	468	237	1.1%
05	10,099	817	453	4.5%
06	9,005	765	169	1.9%
07	14,519	1,054	609	4.2%
08	20,418	633	337	1.7%
09	17,827	321	153	0.9%

Basement Temperature Impacts

A decrease in temperature of the immediate environment is another expected outcome of operating a HPWH. To explore this, we isolated heat pump operating cycles in the data, and evaluated the temperature trends during and after each cycle. We used an array of temperature sensors located five to ten feet from the HPWH in each case. Each array consisted of four sensors placed 8, 32, and 64 inches above the floor, and one just below the ceiling joists (which varied in height). The array was out of the direct line of air exiting the water heater and the positioning was intended to be representative of the general environment around the water heater, but not the entire basement. Operation of the furnace created noticeable cycling of basement temperatures in most of the study homes. The effect was strongest at the ceiling level sensor, and least at the lowest sensor. In two homes, the HPWH is located in a utility or mechanical room; in both cases the door was typically left open, but the partially enclosed space may amplify the temperature droop when the heat pump system operates. Figure 19 shows air temperature at the array sensors during heat pump cycling; the effect of furnace cycling is also clearly visible.

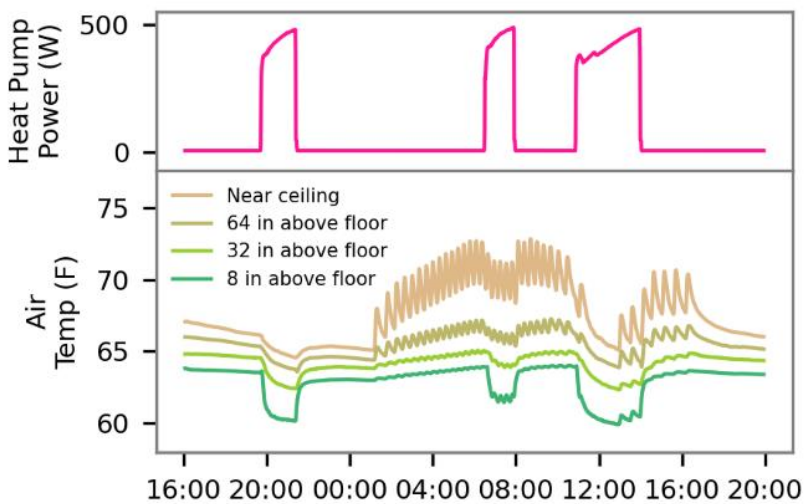

Figure 19. Basement temperature trends during heat pump and furnace cycling.

We evaluated temperature trends associated with each heat pump cycle as follows:

- Establish the average space temperature at the start of each cycle. To mitigate the effects of furnace cycling on this temperature, we applied an averaging period of one median-length furnace operating cycle, with the averaging period ending immediately before the start of heat pump operation.
- Calculate the temperature difference from the cycle-start temperature (i.e., the temperature droop) every minute from the start of the cycle to a maximum of 300 minutes. A drop in temperature is presented as a negative number.
- Establish an end-of-cycle temperature, again using a time period average to reduce the effect of furnace cycling. The end of the cycle is defined as the end of a continuous period of heat pump operation, regardless of duration (including cycles lasting more than 300 minutes). The difference between ending and starting temperature is the temperature drop for the cycle (a temperature reduction appears as a negative value).

- Calculate the temperature change from the end-of-cycle temperature for every minute after the end of each heat pump cycle, for up to 240 minutes or until the start of a subsequent heat pump cycle, whichever is less. The typical post-cycle trend is an increasing temperature.

Average air temperature changes during and after heat pump cycles are shown in Table 18. A negative value indicates a temperature lower than the start temperature. The HPWH location at site 03 is a utility room, and at site 04 is a mechanical room. On average, basement space temperature is clearly depressed, though only moderately, during heat pump operation, and temperatures recover to a level that is generally near the pre-cycle value within a few hours. Uninsulated stone, concrete, and concrete block basement walls have substantial thermal mass, and heat transfer between walls and air leaving the HPWH may be a factor in mitigating air temperature droop during cycles and in the "recovery" after each cycle. This mass effect is likely greatest at four of the nine sites where outlet air from the HPWH impinges directly on an uninsulated foundation wall, and at a fifth site where outlet air is directed onto a partition wall within 18 inches of the foundation wall (Table 19).[30]

Table 18. Basement temperature changes with heat pump operation.

Site	Number of heat pump cycles in data	Average length of cycle (minutes)	Average basement temperature at start of heat pump cycle (°F)	Average temperature change over heat pump cycle (°F)	Average temperature change from before cycle to end of post-cycle period (°F)
01	962	122.8	65.4	-1.6	-0.1
02	762	89.8	64.3	-1.9	-0.0
03	1425	104.8	62.1	-2.6	1.4
04	590	152.7	63.3	-3.4	-0.3
05	793	114.4	64.9	-1.4	-0.5
06	508	106.8	61.9	-2.5	-0.1
07	965	114.2	62.4	-2.7	0.2
08	569	129.0	63.2	-2.7	-0.8
09	555	95.7	63.2	-1.5	-0.1
Avg	**-**	**-**	***63.4***	***-2.3***	***-0.1***

[30] This impingement of air on an adjacent wall may also lead to mixing of outlet air with inlet air, reducing the average temperature of inlet air and leading to decreased performance.

Table 19. Orientation of HPWH outlet air with respect to foundation wall.

Site	Distance of outlet air port from basement wall	Direction of airflow relative to exterior foundation wall
01	15 feet	Away from wall
02	6 inches	Directly toward wall
03	24 inches	Away from wall
04	18 inches	Directly toward partition wall, adjacent to main foundation wall
05	6 inches	Directly toward wall
06	6 inches	Directly toward wall
07	24 inches	Away from wall
08	24 inches	Away from wall
09	3 inches	Directly toward wall

Another factor limiting temperature droop is the continuous heat loss from basements to the exterior environment in cold climates throughout the heating season. Any net reduction in basement air temperature will directly reduce this heat loss, providing a feedback mechanism that partially offsets the reduction.

We suspect the average increase in temperature at site 03 is due to the association of hot water use with laundry cycles. The washer and dryer share a utility room with the furnace and water heater, and we observed a temperature rise in the room when the dryer was operated. Washer use, water heater cycling, and dryer use may well be correlated in time.

This analysis considers the dynamics of temperature drop and recovery over individual heat pump cycles. We can't estimate the long-term average reduction in basement air temperature resulting from HPWH operation from the data gathered. However, the apparent modest size of at least the transient basement temperature depression seems to be consistent with our survey findings (discussed below), in which the majority of respondents expressed neither a positive nor negative reaction to wintertime temperature/humidity changes.

SURVEY RESULTS

The nine field study participants and 72 other member/customers of MECA utilities completed a survey on their experience owning a HPWH. All survey respondents received a rebate on their HPWH through the residential HVAC program from their MECA utility. The survey explored member/customers experience owning a HPWH, with a particular interest in the performance, comfort impacts, and general satisfaction.

BACKGROUND

All survey respondents live in Michigan and tend to be in rural areas with a high prevalence of delivered fuels and electric water heating fuel types. Indeed, 64 respondents (80%) replaced an electric water heater with a HPWH, while 11 and 5 respondents replaced propane and natural gas water heaters respectively. Household occupancy ranged from 1-7 for surveyed households, with an average of 2.8 occupants. The reported water heater setpoints ranged from 115 °F to 145 °F, with the median setpoint temperature at 125 °F.

Figure 20 shows that most survey respondents had HPWHs installed in or after 2019. The dotted line denotes when MECA utilities HPWH rebate incentives increased from $300 to $700, which led to a sharp increase in HPWH rebates in 2019 and beyond. Figure 21 shows the number of survey responses by HPWH manufacturer. Interestingly, 32 respondents (40%) reported not using a professional installer.

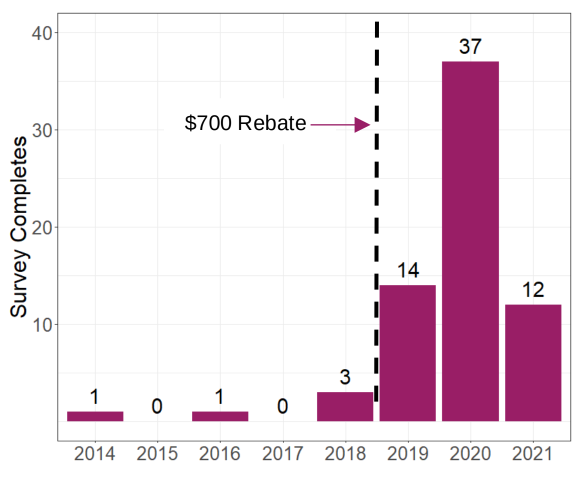

Figure 20. Installation Year for Survey Participants

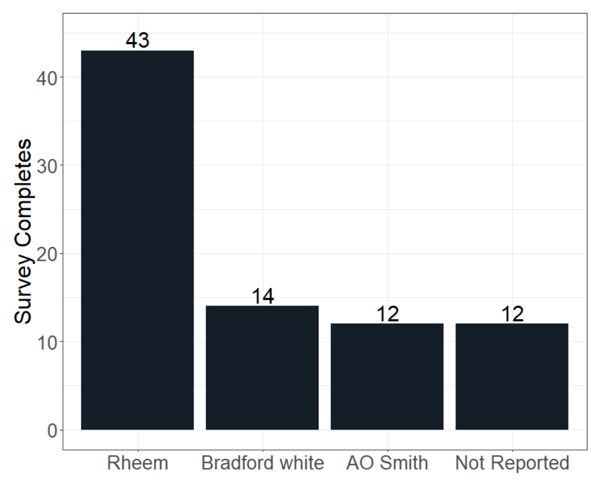

Figure 21. Manufacturer of Survey Participants' HPWHs

SATISFACTION

Survey respondents were overwhelmingly satisfied with their heat pump water heaters. Figure 22 shows that almost all respondents reported high satisfaction with their HPWH. These encouraging results suggest that HPWHs are well-received by homeowners in MECA member utilities' service territories.

> "Very happy with cost savings and how quiet it is. The rebate was a big plus."
> – Cloverland member

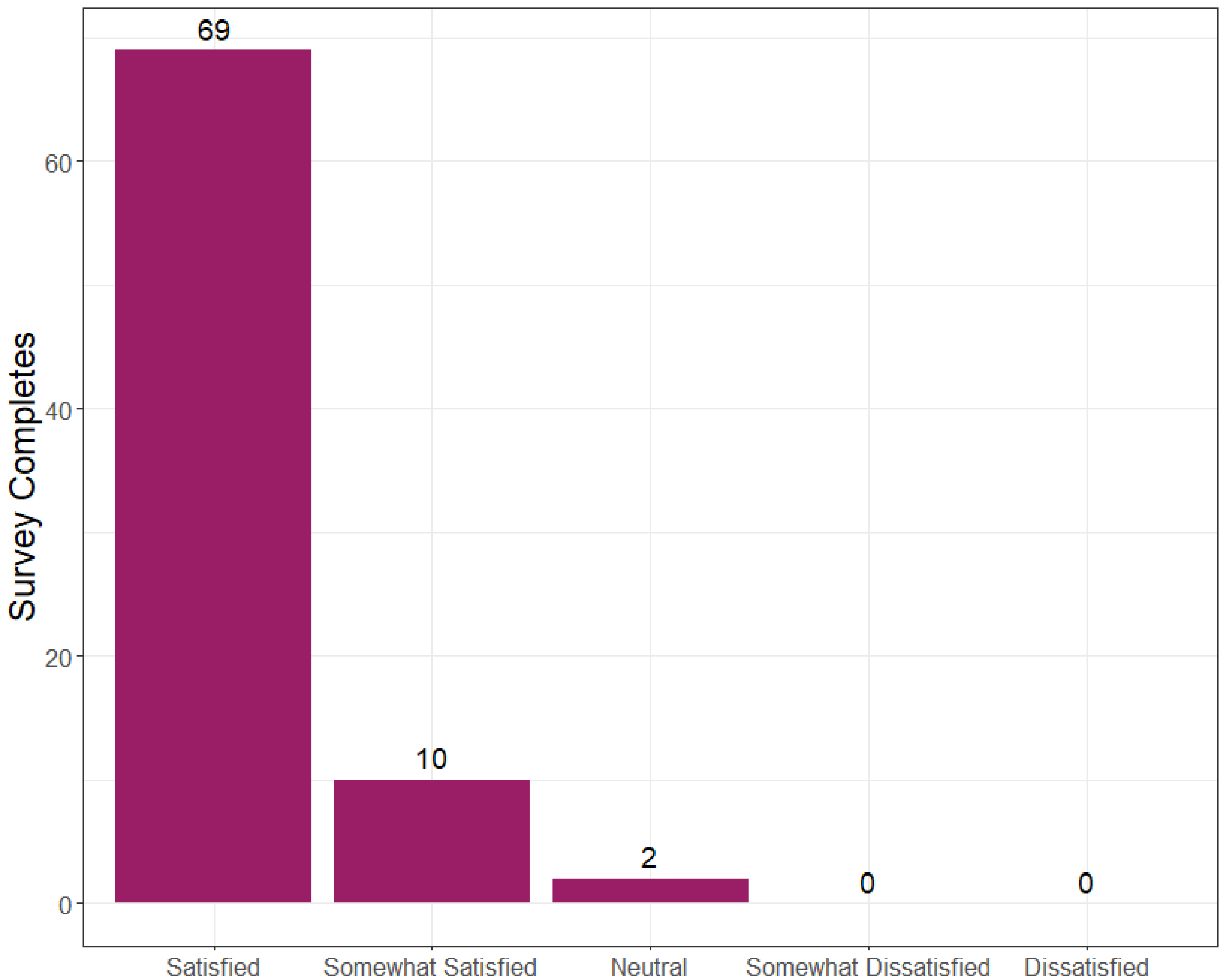

Figure 22. Satisfaction with HPWH

PERFORMANCE

Most survey respondents did not experience increases in hot water shortages after switching to a HPWH. Figure 23 shows that only seven survey respondents (9%) run out of hot water more with their HPWH compared to their previous water heater. Common reasons for hot water shortages revolved around usage patterns, such as hosting visitors or using many hot water end uses simultaneously.

"Wish I would have gotten the 80 gallon size instead of 50. This would help with the slow recovery when in heat pump only mode." – GLE member

The most common control setting is hybrid, which utilizes electric resistance coils during periods of high demand for faster recovery. Households using the heat pump control setting are more likely to experience hot water shortages during large draws. Of the seven respondents that experienced increases in hot water shortages, four used the heat pump control setting. The number of hot water shortages could be reduced by educating households on control settings and how they are impacted by different water usage behaviors. Multiple survey respondents enjoyed utilizing the vacation control setting, which temporarily reduces the hot water setpoint during long unoccupied periods.

“I love the option to put it on "vacation mode" for a set period! Simple and easy to do, works well, and it's nice to not be using that energy while I'm away.”
– GLE member

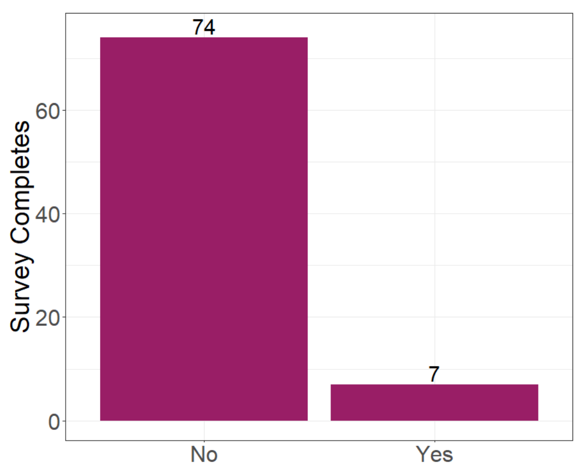

Figure 23. Do you experience more hot water shortages with your HPWH?

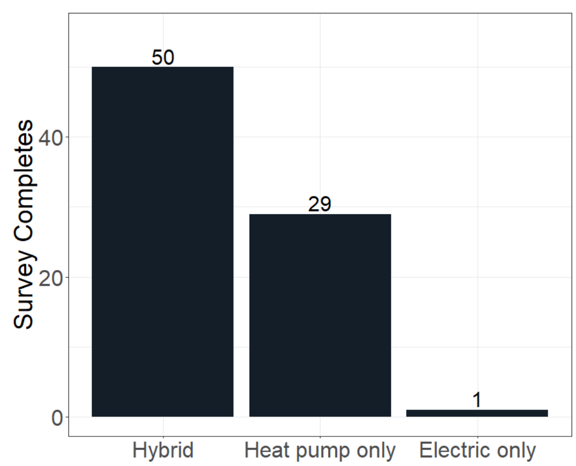

Figure 24. Most common control setting

COMFORT AND NOISE

During compressor cycles, a heat pump water heater cools and dehumidifies the surrounding air. While this could be a welcome impact during hot and humid weather, the cooling effect is a concern for homeowners in heating dominant climates. The cooling effect impacts the air near the HPWH, so residents that frequently occupy the space surrounding their water heater are most likely to be impacted. In our survey, 69 respondents (86%) had their HPWHs installed in the basement, which is generally a partially conditioned and low occupancy part of a single-family home. The comfort and noise impacts may be more significant in smaller residential buildings, such as multifamily or manufactured homes, due to heavier occupation of the space near the HPWH.

> "One added benefit: I do not have to run my dehumidifier in the basement anymore." – GLE member

Figure 25 shows that more homeowners found the comfort impacts from HPWHs to be a benefit, rather than an inconvenience. Many survey respondents touted the dehumidification benefits of HPWHs, which eliminated the need to use a dehumidifier in some cases. Noise impacts may be a larger homeowner experience issue than comfort impacts for members/customers. Twenty-four respondents (30%) claimed that the noise from their HPWH was noticeable. The noise disruption likely comes from compressor operation and disruption could be somewhat mitigated by opting for the hybrid control setting, which uses the compressor less. Similar to comfort impacts, noise disruption can be reduced when the HPWH is installed in a low occupancy area.

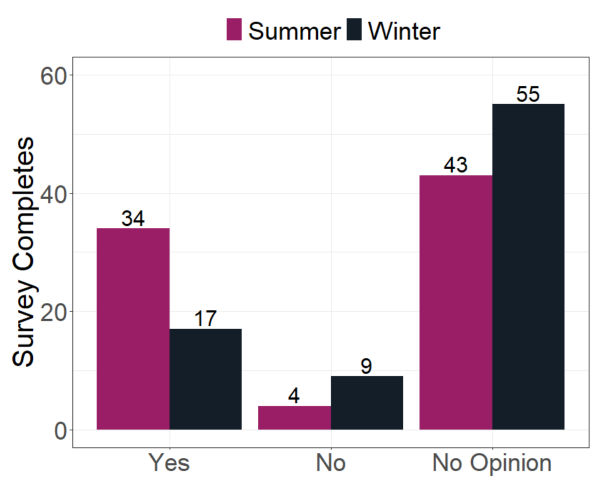

Figure 25. Do you like the changes to temperature and humidity?

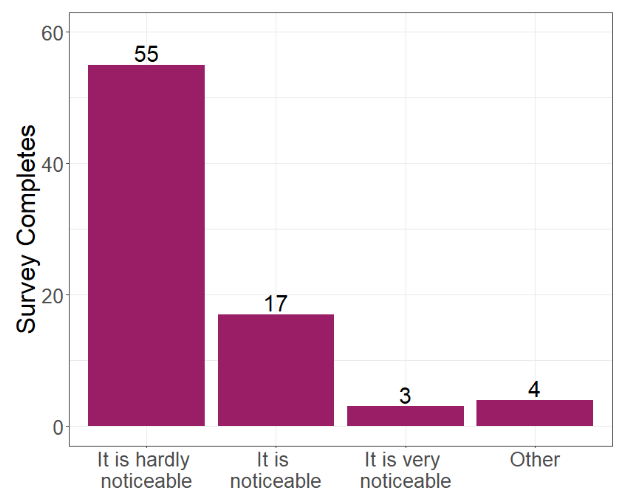

Figure 26. How do you feel about the noise from your HPWH?

MEMBER EXPERIENCE

Table 20 shows that the rebate program was the most significant factor motivating MECA member/customers to purchase their HPWHs. This is evidence that the increased incentive for HPWHs starting in the 2019 program year has led to increased measure adoption. Interestingly, contractor recommendations had an insignificant impact on survey respondent's decision to purchase a HPWH. Because contractors are typically a trusted advisor for residential HVAC decisions, there may be opportunities to increase HPWH adoption through contractor trainings and incentives for promoting HPWHs to homes that would benefit.

Table 20. Number of survey respondents reporting impact of various decision factors on HPWH purchase.

Decision factor	Very Significant	Significant	Neither	Somewhat Insignificant	Insignificant	No Response
Rebate Program	57	20	2	-	1	1
Energy or Cost Savings	51	23	3	-	1	3
Existing Water Heater Age	25	28	10	2	14	2
Information from Utility	20	28	19	3	7	4
Contractor Recommendation	5	10	14	1	46	5
Health and Safety	4	12	25	-	37	3

For those that did have a professional installation, Figure 27 shows that not all respondents received the same level of information. Although most were provided with the manual, only around half had training that explained each operating mode. The configured operating mode can have a big impact on energy savings and customer satisfaction, so ensuring that homeowners have these discussions at time of sale or during installation could help improve the homeowners' experience.

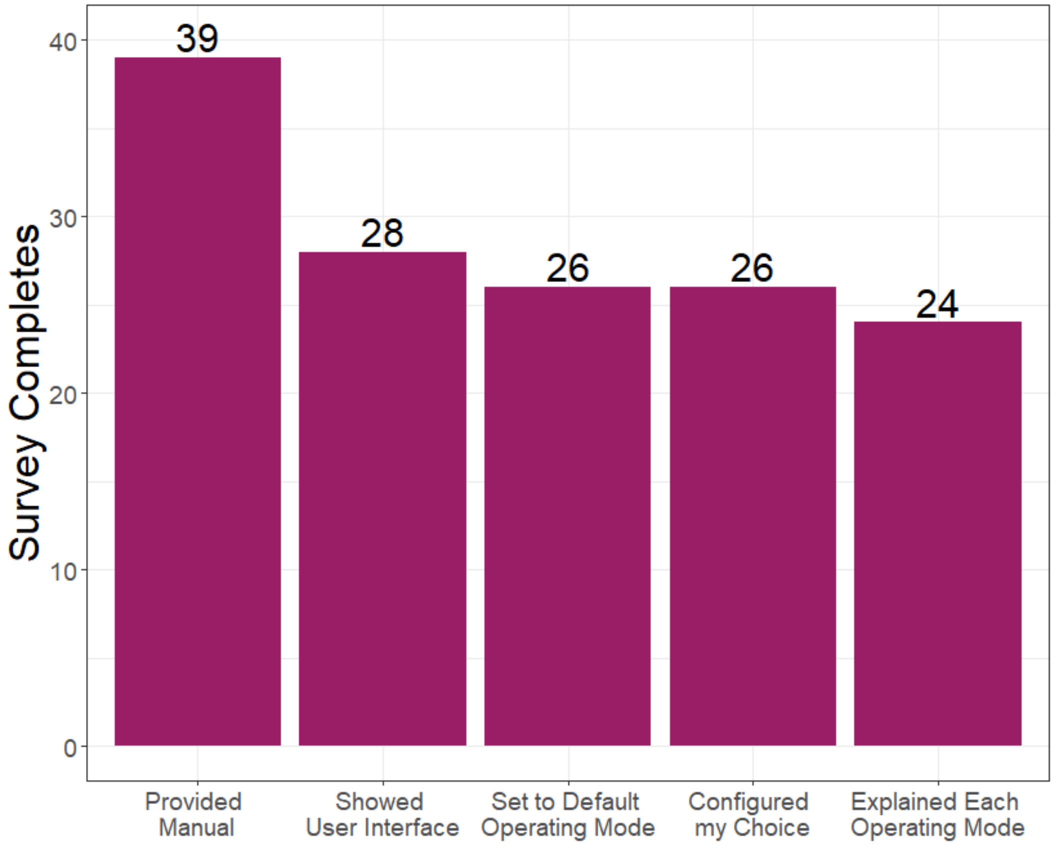

Figure 27. Information received from contractor.

Three survey respondents complained of bad smells coming from their water heater, with the reported issue being that the wrong anode rod was installed for their area. Utilities offering incentives for electric water heaters have an opportunity to add value and ensure customer satisfaction by providing recommendations on anode rod selection tailored to local water conditions.

"[We] had terrible sulfur tastes and smell[s]. I changed out the anode [rod] and added one that removed the sulfur taste and smell." – Cloverland member

LOAD PROFILES AND CARBON IMPACTS

LOAD PROFILES

Heat pump water heaters generally do not reheat during hot water draw episodes and instead have delay time before reheating the tank. The hourly power load profiles in Figure 28 show the highest peak between 8-10 PM and a second peak between 9-11 AM. These peaks are consistent with the water heater's reheat energy being delayed a couple hours from typical household water usage events occurring in the morning and early evening. The median load profile shows that the MEMD's peak period does not coincide with either of the HPWHs morning or evening recovery event.

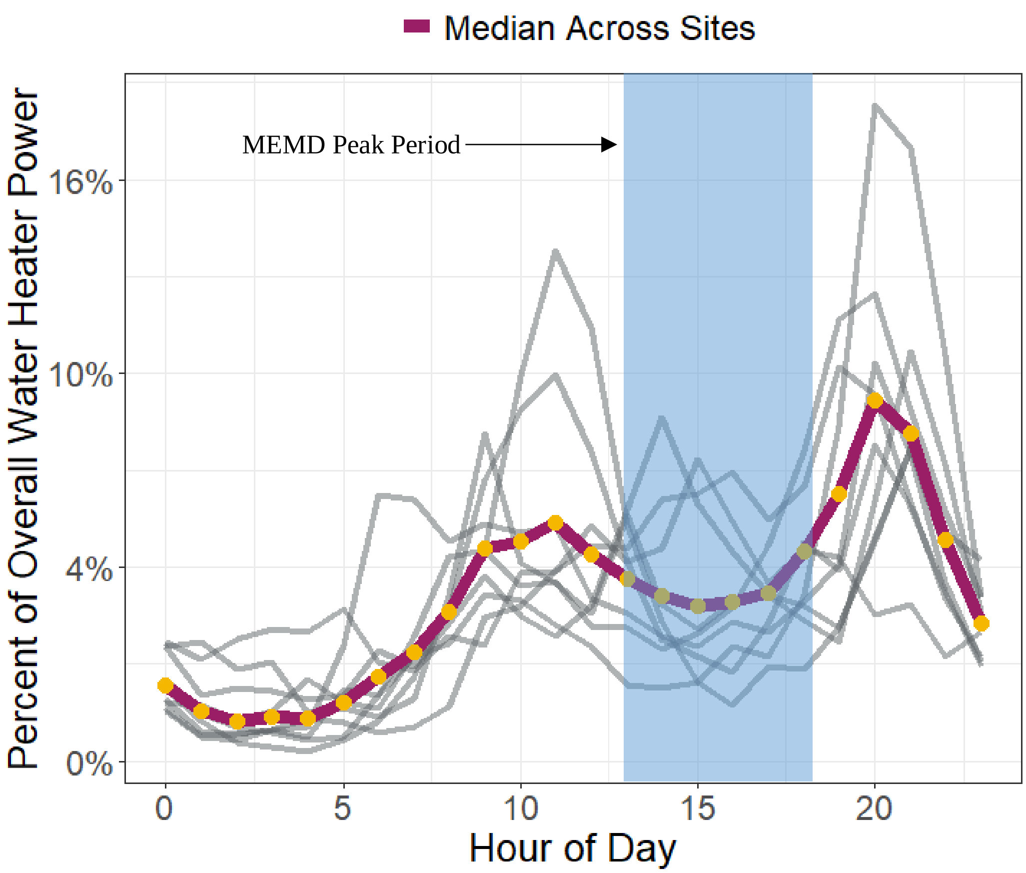

Figure 28. Hourly loads by site (in grey) and median across sites. Shading shows the MEMD-defined coincident peak period.[31]

CARBON

Heat pump water heaters generate significantly less carbon than electric resistance, natural gas, and propane-fired water heaters (Table 21). Natural gas and propane water heater

[31] The peak period is defined as 1-6 PM per the Michigan Energy Measure Database.

emissions are directly released outside the house where combustion occurs. Although both natural gas and propane emit less carbon per BTU than electric sources, they consume much more energy than HPWHs, resulting in higher emissions.

HPWHs generate much less emissions than ERWHs because they consume approximately three times less electric energy, causing a substantial reduction in environmental impacts. This analysis does not account for time-of-use, which is ideally considered when comparing carbon impacts of electric technologies because the carbon intensity of the electric grid varies across hours, days, and seasons. Instead, the average carbon intensity[32] is estimated based on Great Lakes Energy's 2020 fuel mix[33] and applied to all electricity consumed by both HPWHs and ERWHs.

Table 21. HPWH carbon impacts compared to modelled baseline technologies.

Site	Annual Carbon Emissions (lbs)			
	Heat Pump Water Heater	**Electric Resistance Water Heater**	**NG Water Heater[34]**	**Propane Water Heater**
01	628	1738	1557	1849
02	464	1212	1085	1290
03	1245	3065	2745	3262
04	537	1271	1138	1352
05	558	1522	1363	1620
06	812	1348	1207	1435
07	773	2004	1794	2132
08	436	1211	1085	1289
09	301	784	702	834
Avg	***639***	***1573***	***1409***	***1674***

UNDERSTANDING FINDINGS IN CONTEXT

Ratings and Other Field Research

Over the past decade, numerous studies across the country have assessed field performance of HPWHs. Below is a summary of a few focused on HPWHs installed in other cold climates.[35]

32 The carbon intensity of Michigan's electricity generators is a weighted averaged from EIA plant-level carbon emissions data for Michigan.
33 Great Lakes Energy fuel mix can be found here: https://www.gtlakes.com/fuel-mix-report-2/
34 Carbon intensity of natural gas and propane are from EIA
35 Note that other studies typically use term "average COP (aCOP)" for what we call field energy factor (EF_{field})

In 2012 Steven Winter Associates field monitored fourteen HPWHs in Massachusetts and Rhode Island for over a year.[36] These HPWHs were produced by three different manufacturers and had storage tanks that ranged from 50-80 gallons. The water heaters were installed in unconditioned basements with cold water inlet temperatures and average air temperatures comparable to basements in the Midwest. The average rated energy factor was 2.4 and water heaters achieved an average field energy factor that was 1.88 (or 79%) of the rated energy factor.

The Northwest Energy Efficiency Alliance (NEEA) funded a 2012-2015 model validation study to inform a field-calibrated engineering model of energy savings estimates for HPWHs installed in the Northwest.[37] This study drew from two previously completed field studies and added additional sites for field monitoring to arrive at a total of well over 100 sites spanning the diversity of installation configurations that might be seen in the Northwest. There were 8 water heaters in the coldest climate zone and installed in basements with an average field EF of 2.2.

A more recent study from 2018 conducted by Energy350 in British Columbia field monitored both "split system" HPWHs with compressors located outside the home as well as the latest generation of high-efficiency integrated HPWHs with rated UEFs above 3.[38] Most integrated HPWHs were ducted to the exterior except for one 80-gallon model that drew air from an interior space conditioned by a wood-pellet stove. For this unit, the inlet water temperature was 51F and the ambient room temperature averaged 69F. The average daily hot water use was 46 gallons and field measured energy factor was 2.08 which was similar performance to the HPWHs in our study.

According to the few studies referenced above and results from our study, the field performance has not increased correspondingly with the latest increase in the UEF rating of the newest generation of HPWHs. Lower field performance may be attributed to several different factors. As one example, the DOE test standard uses 55 gallons of daily hot water use. The daily hot water use for the HPWHs referenced in the studies above was 42-46 gallons which compares to our study's average daily hot water use of 33 gallons.[39] As discussed above, low performance of HPWHs compared to rated performance in this study can be at least partially attributed to lower daily hot water use than what is used in test conditions. Overall, results of HPWH performance in this study match findings from other studies in the field albeit there are not too many measurements for the newest generation of HPWHs.

Comparing Results to the Michigan Energy Measures Database (MEMD)

The HPWH is a longstanding measure in the MEMD which has evolved over time. According to the way the measure is constructed, there appears to be a general consensus that most HPWHs are located in basements, and this is supported by our survey results. One notable

[36] Steven Winter Associates (2012). Heat Pump Water Heaters: Evaluation of Field Installed Performance. Sponsored by National Grid and NStar.
[37] Ecotope (2015). Heat Pump Water Heater Model Validation Study. Prepared for NEEA.
[38] Energy350 (2018). CO2 & Integrated Heat Pump Water Heater Performance Report. Submitted to Fortis BC.
[39] In Ecotope (2015) study 42 gallons was modeled hot water usage for HPWHs expecting to serve 2.7 occupants.

recent change to the MEMD was in 2019 when a distinction was made between "semi-conditioned" and "conditioned" installation locations. The MEMD assumes semi-conditioned spaces are 54F whereas conditioned spaces are assumed to be 70F. While cooling savings are counted for conditioned spaces, no space heating penalty is accounted for in the energy savings algorithm. Estimated savings are quite a bit higher for installations in conditioned spaces. All HPWHs in this study are installed in semi-conditioned spaces.

Table 22 compares MEMD assumptions to those used in our cold climate modeling scenario and averages from the monitoring data. The largest discrepancy between the MEMD and our results is energy factor. The MEMD assumes the rated EF, which is higher than EF_{field} and the EF modeled from field data due to hot water usage patterns and other suboptimal conditions experienced in the field. Despite lower field efficiencies, the modelled savings is comparable to the MEMD's value. The absence of a substantial reduction in savings can be partially attributed to small differences in hot water usage but is most likely due to additional complexities modeled in our scenarios that are not considered in the MEMD[40].

Table 22. Comparison of MEMD assumptions for the HPWH measure and field study results

Variable	Field Study Averages	Cold Climate Model Scenario[41]	MEMD Assumption
Ambient air temperature	63F	55F	54F[42]
Cold inlet water temperature	58F	58F	54F
Hot water temperature	117F	125F	125F
Hot water use	33 gallons	50 gallons	45 gallons
Energy Factor	2.17	2.50	3.5[43]
Nominal tank capacity	50 gallons	50 gallons	50 gallons
People per household	2.67	-	2.57
Percent of heating hours using electric resistance	2.57%[44]	-	3%
Annual electricity savings	-	2,386 kWh	2,225 kWh

[40] Notably, our model includes standby loss, COP, and the fraction of electric resistance heating as functions of the temperature difference between the tank and environment, the ambient basement temperature, and delivered energy use, respectfully.
[41] This is referred to as the "Medium Usage, High Temperature Lift Scenario" in other sections of the report.
[42] Assumes "semi-conditioned" measure since all sites in our study were installed in "semi-conditioned" basements.
[43] The value here is the rated UEF. MEMD does produce savings estimates for HPWHs with lower UEFs than 3.5
[44] Sites ranged from .22% to 8.97%.

As shown in the table above, modeled annual electricity savings from our study are similar to the savings value in the MEMD for a HPWH with a comparable UEF. A more detailed examination of how results from the survey and field measurement from this study compare to the HPWH MEMD measure and whether any adjustments to the measure are warranted would be helpful. Further investigation into the differences of 65 and 80-gallon HPWH field performance in Michigan and what a measure might look like for those tank sizes would also be beneficial given their popularity in the market.

APPENDIX A MONITORING SYSTEM

Specific sensors and devices used the monitoring system are listed in Table 23.

Table 23. Monitoring system components.

Measured variable	Measurement sensor or device
HPWH electric power	Egauge power meter with appropriate current transformers
HPWH current draw	Current sensor
Volumetric hot water consumption	Badger meter with pulse output
Hot and cold water temperatures	Omega 44008 thermistor temperature sensors (immersion sensors in piping)
Air temperature and humidity at HPWH inlet	E+E model EE08 temperature/humidity sensor
Air temperatures of HPWH environment (typically 6 to 12 ft from water heater)	Three thermistor temperature sensors and one E+E model EE08 temperature/humidity sensor (placed at 32 inches above floor)
Current draw of furnace gas valve	Current sensor
Air temperature in return air duct	Thermistor
External cold water pipe temperature near entry to home	Thermistor
External hot water pipe temperature downstream of water heater	Thermistor
Space temperature at main house thermostat	Hobo UX100-003
Space temperatures at other locations in home	Hobo U10-003 or UX120-006
Outdoor air temperature	Hobo MX2302

For measurement of water volume, we selected standard utility-style water meters with digital pulse output modules providing about 200 pulses per gallon of water drawn. The meters came from the factory with individual 3-point calibration curves, and we ran additional calibration checks to verify their accuracy and made small adjustments based on the calibration test results.

For measuring the temperature of cold water entering and hot water leaving the water heater, we selected thermistor sensors in integral, low-mass wells designed for direct immersion in the water stream. Immersion sensors allow for better accuracy than external pipe temperature sensors – this is particularly important where plastic pipe is in use – and faster response to temperature changes. We checked the absolute accuracy of all the water temperature sensors before installation.

Each monitoring system included five air temperature sensors. Four of these were suspended in a vertical array to sense air temperature at various heights from floor to ceiling [previous experience had shown us that basement air temperature is often highly stratified]. We positioned the vertical array at each site about 5 to 10 feet from the HPWH and out of the direct path of the exhaust airflow, intended to capture the general environmental temperature. The fifth air temperature sensor was positioned to capture intake air temperature. Two sensors, the vertical array sensor 32 inches above floor level and the intake air sensor, measured humidity as well as temperature. The others were simple thermistor temperature sensors.

We placed additional temperature sensors on the cold water pipe upstream and hot water pipe downstream of the water heater, and in the central heating system return air duct – these sensors don't play a role in our analysis.

Other sensors connected to our primary data collection system included a current sensor placed directly at the HPWH and a current sensor at the primary heating system gas valve (or oil burner in one case).

All these sensors at each site were connected to a Campbell Scientific CR1000X data acquisition system in an enclosure suspended or mounted on a wall near the HPWH. Hot water energy delivery from a water heater is calculated as water flow multiplied by the temperature difference of hot water and cold water. Since these temperatures can change quickly, the measurements must be made over relatively short time intervals. We programmed the Campbell system to record all measured values at 1 second intervals, allowing precise, high resolution calculation of delivered hot water energy, as well as providing high-resolution current measurements that were important in identifying exact periods of heat pump and electric resistance operation.

Separate from the Campbell-based system, we measured electric power at each site using a digital power meter with compatible current transducers. Power measurement included the HPWH, the primary heating system, and whole-house mains power. Electric power data was recorded at one-minute intervals.

We set up remote communications with the data collection system at each site, using either the household internet connection, or Slipstream cell modems. Data was downloaded several times each day through an automated system – this system also ran initial screening for outliers in data that might signal measurement hardware problems. Data was saved on company servers where it could be accessed for further analysis.

APPENDIX B ANALYSIS THEORY AND METHODS

The energy flows to and from self-contained storage water heaters can be characterized as shown in Figure 29, where the following terms apply:

Q_{hot_water} is the useful energy delivered from the water heater to fixtures in the building.
$Qe_{heatpump}$ is the electrical energy used to operate the heat pump compressor and fan.
$Qe_{resistance}$ is the electrical energy delivered to electric resistance coils to heat water directly.
$Qe_{controls}$ (not shown in the figure) is the electrical energy delivered to the controls circuitry in each water heater.
Q_{air} is the heat extracted from air surrounding the water heater during compressor operation, primarily heat absorbed by the evaporator, offset to some degree by heat loss from the compressor motor and from the condenser coils back to the surrounding environment.
$Q_{standby}$ is the continuous loss of heat from the tank to the surrounding environment.
Q_{stored} is the energy stored in the tank in the form of hot water.

Each of these values is treated as positive when energy is flowing in the usual direction (as shown by the arrows), and with the exception of Q_{stored}, typically represent a daily total flow of energy.

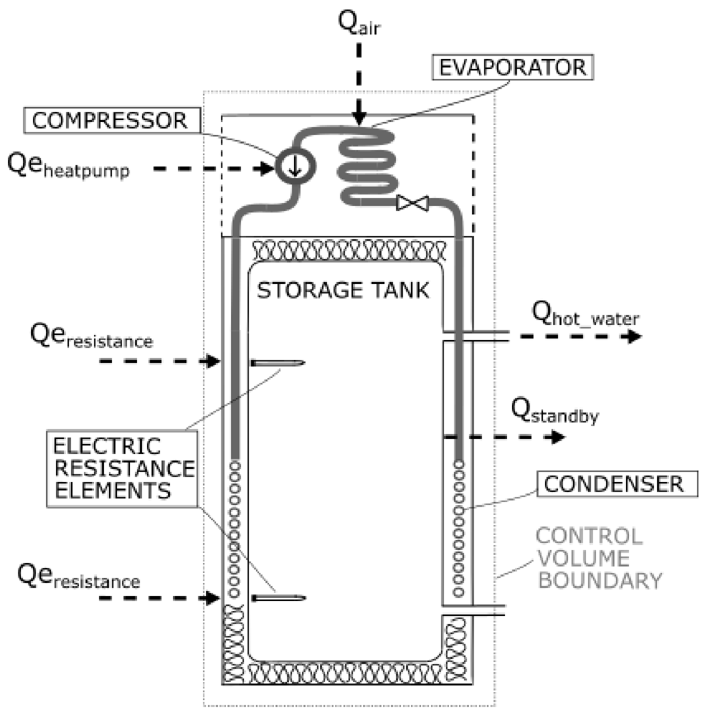

Figure 29. Energy entering and leaving a heat pump water heater, with control volume.

In addition to power delivered to the heat pump (compressor and fan) and the electric resistance elements, some power goes to system controls, and the total electric energy consumed can be expressed as:

$$Qe_{total} = Qe_{heatpump} + Qe_{resistance} + Qe_{controls}$$

We assume controls energy stays outside the control volume shown and doesn't contribute to the energy balance across the boundary. Based on this, we can ignore controls energy in calculations that balance input and output energy. We do add controls energy back in when considering overall Energy Factor, operating energy, and operating cost.

Our measurement system recorded the total electric energy delivered to each HPWH, from which we disaggregated power used for heat pump operation (including compressor and fan operation), electric resistance heating, and controls.

Applying the principle of conservation of energy, overall energy flows across the control volume boundary around the tank are subject to

$$Q_{in} = Q_{out} + \Delta Q_{stored}$$

Where Qin and Qout represent total energy flows over a time period, and ΔQstored is the net change in energy stored within the control volume (or water storage tank) over the same time period. The time period used in analysis will usually be a day.

Where Qin and Qout represent total energy flows over a time period, and ΔQstored is the net change in energy stored within the control volume (or water storage tank) over the same time period. We assume the hot water stored in the tank reaches a fixed average temperature at the end of any reheating cycle, and thus assume there is no change in net stored energy for analysis periods that span a number of cycles (with accounting for any hot water drawn after a reheat cycle). A typical time period used in analysis is a day.

Assuming the amount of stored energy has a constant value at the end of each analysis period, the ΔQstored factor drops out. Expanding Qin and Qout to their components:

$$Q_{in} = Q_{out}$$

or

$$Qe_{heatpump} + Qe_{resistance} + Q_{air} = Q_{hot\_water} + Q_{standby}$$

Our study included measurement of water temperatures at the entrance to and exit from the tank, and water flow volume, allowing direct calculation of Qhot_water from data:

$$Q_{hot\_water} = Vol_{hot\_water} * density * specific\ heat * (T_{hot} - T_{cold})$$

This fundamental equation for thermal energy carried in a fluid also allows us to model water heating loads under any assumed conditions of volumetric use and temperatures.

The Energy Factor (EF) of a water heater is the ratio of the useful energy output to the purchased energy input as measured under specific test conditions, and is the most commonly used metric for overall efficiency. While our study could not duplicate the test conditions needed to formally derive EF, we used the ratio of useful energy output to electric energy input in our data to calculate a "Field Energy Factor" (EFfield)[45].

$$EF_{field} = \frac{Useful\ output}{Electric\ input} = \frac{Q_{hot\_water}}{Qe_{heatpump} + Qe_{resistance} + Qe_{controls}}$$

[45] Some reports on HPWHs use the term "COP" to describe the value we call EFfield – we've retained the more conventional engineering definition of COP.

We further isolated periods of operation using the compressor alone, both compressor and electric resistance, and electric resistance alone to quantify performance under these control settings.

Standby heat loss as used in this report means heat loss from the stored hot water to the surrounding environment[46]. Quantification of standby loss is an important step in modeling the performance of water heaters under varying conditions. Our test setup does not include a way to measure standby loss directly, but we can use the basic input output energy balance to derive an estimate from measurements during periods of exclusively electric resistance operation:

$$Qe_{resistance} = Q_{hot\_water} + Q_{standby}$$

This equation allows calculation of standby loss for any period of purely electric resistance heating. And working on the usual assumption that the rate of heat loss from a water heater storage tank is proportional to the temperature difference between the stored hot water and the surrounding environment, regression of standby loss against the tank-to-environment temperature difference provides an estimated loss coefficient that can be used in modeling performance under arbitrary conditions.

The next important concept needed for modeling is Coefficient of Performance, characterizing the compressor and refrigerant system in isolation from the rest of the water heater. To explain the concept, we change the control volume boundary so the compressor and evaporator are outside the boundary, and identify the term Qrefrigerant as representing the intermediate flow of refrigerant energy to the water tank (Figure 30).

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[46] The term "standby" is used in some contexts to mean periods when no hot water draws occur, or heat loss occurring during those periods.

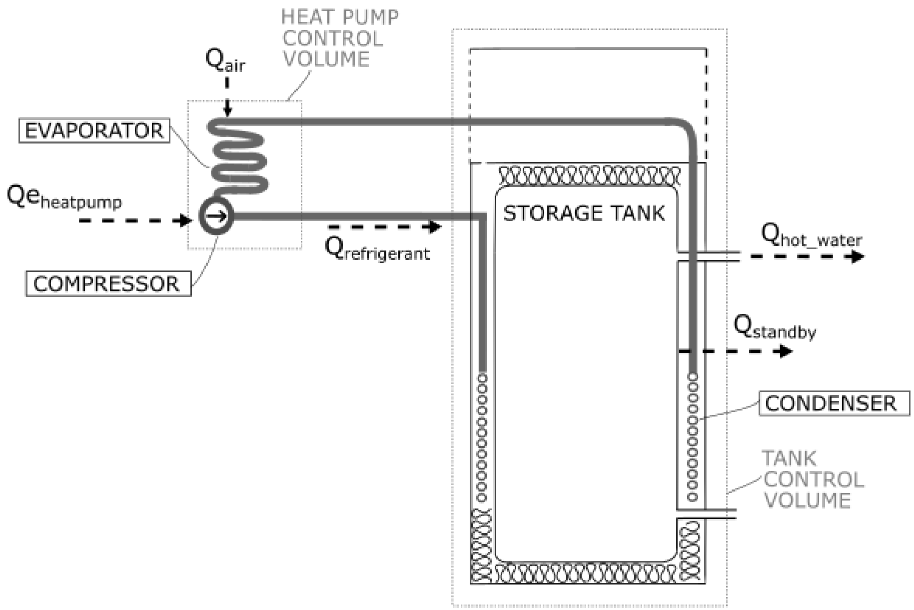


Figure 30. Alternate control volumes used in analysis.

Coefficient of Performance (COP) as applied to heat pumps is generally defined as the ratio of useful heating or cooling energy output to electrical energy input. Applied to a HPWH, COP is the ratio of energy delivered from the compressor-driven refrigerant system to the water storage tank divided by the electrical energy input for heat pump operation[47]:

$$COP = \frac{Q_{refrigerant}}{Q_{e\_heatpump}}$$

We have no means to directly measure the energy delivered from the refrigerant system to the water tank, but can apply the basic the input – output energy balance to the tank control volume as shown in Figzzz (and once again assuming no net change in stored energy over the analysis interval):

$$Q_{in} = Q_{out}$$

Which can be written as:

[47] This definition of COP aligns with the common engineering definition of the term, and should not be confused with Energy Factor (EF).

$$Q_{refrigerant} = Q_{hot\_water} + Q_{standby}$$

(This analysis of energy input and output at the tank-only control volume can make use of data over periods of hybrid operation that include some portion of electric resistance heating. In this case, the electric resistance contribution, $Qe_{resistance}$, must be removed from both sides of the energy balance equation.)

And COP, is calculated as:

$$COP = \frac{Q_{hot\_water} + Q_{standby}}{Qe_{heatpump}}$$

COP is expected to vary with the temperature difference between the evaporator and the condenser of a heat pump system (the "temperature lift"), but with no direct measurement of the condenser-side temperature, we settled on using T_{inlet_air} as the sole determinant of COP in each system. We characterize the COP for the systems studied using linear regression of calculated COP against T_{inlet_air}, and use the resulting coefficient, β_{cop}, in modeling (discussed below)[48].

We can also use the energy balance around the heat pump control volume to solve for Qair, which isn't needed for our performance calculations or modeling, but will be of interest when considering space heating impact. Using the solution for Qrefrigerant presented above, and values of $Qe_{heatpump}$ extracted from data, we can solve directly for Qair:

$$Q_{air} = Q_{refrigerant} - Qe_{heatpump}$$

For periods when both heat pump and electric resistance heating are in use, we can use our disaggregation of the total electric input to characterize the relative contribution of each. We use the fraction of total output met by resistance heating as a useful way to capture the relative contribution of resistance and heat pump operation:

$$fe_{resistance} = \frac{Qe_{resistance}}{Q_{out}} = \frac{Qe_{resistance}}{Q_{hot\_water} + Q_{standby}}$$

We obtain $fe_{resistance}$ by regression.

Modeling of hybrid and heat pump control settings limited by availability of data.

[48] Other variables that affect performance include airflow rate and condensation at the evaporator. We assume the airflow rate is nearly constant, and assume condensation to be a second-order factor that can be ignored.

Total electric energy use of a HPWH (excluding controls) can be broken down into the energy used to power the electric resistance elements and that used for heat pump (compressor) operation. We identify these fractions for each daily period

Finally, we can calculate the heat removed from the water heater environment. To do this, we consider yet another control volume that includes the compressor and evaporator coil (and the fan), with inputs comprising electrical energy to the compressor and thermal energy in the air passing over the evaporator, and refrigerant energy delivered to the tank as the only output, with the energy balance as:

$$Qe_{heatpump} + Q_{air} = Q_{refrigerant}$$

PERFORMANCE MODELING

Combining elements from above, we can estimate the performance of a HPWH under arbitrary conditions. All modeling is done on a daily basis.

Model variable	Calculate from
Qhot_water	Volumetric hot water use Hot water temperature Cold water temperature
Qstandby	Hot water temperature Environmental (basement) temperature Regression slope derived from data
Total load	Qhot_water + Qstandby
COP	Energy balance calculation of COP from data Regression to obtain relationship of COP to T_{inlet_air} using data
Fe_resistance	(for modeling of hybrid operation) Total load (hot water + standby) Relationship of Fe_r to total load derived from data
$Qe_{resistance}$	Total load (hot water + standby) Fe_r
$Qe_{heatpump}$	Total load (hot water + standby) (1-Fe_r) COP
Qe_{total}	$Qe_{resistance} + Qe_{heatpump} + Qe_{controls}$
Qair	(not used in performance modeling)

<u>Hot water energy output</u>

Hot water energy can be modeled for any combination of volumetric use and temperatures (cold water and hot water) using the equation for heat carried in a fluid [ref to page 13].

Standby heat loss

To estimate standby heat loss under arbitrary conditions, we use the characteristic standby heat loss coefficient derived from regression of our field data for periods of electric-resistance-only operation to the assumed hot water and water heater environmental temperatures assumed in the model:

$$Q_{standby} = \beta_{standby} * (T_{hot} - T_{environment})$$

Total required input

The total energy leaving the tank is the sum of the hot water energy output and standby loss, and using the input – output equality, this also represents the required input energy. Repeating the energy balance around the water tank as shown above:

$$Q_{refrigerant} + Qe_{resistance} = Q_{hot\_water} + Q_{standby}$$

Fraction electric resistance

The fraction of the load supplied by electric resistance heating falls into one of three groups. In two of these groups (heat pump only and resistance only), the fraction of input energy provided by electric resistance is fully determined. In the third group, representing hybrid operation, the manufacturer's sensors (sensing water temperature at several heights of the tank) and control algorithms determine when the heat pump and/or resistance elements are activated. Since we can't directly observe the manufacturers' control signals, we rely on data to find trends in the use of heat pump and resistance heating as a function of hot water consumption (and standby loss, which is a factor especially when hot water use is low).

Operating mode	**F_{er}, Fraction of total tank input energy provided by electric resistance**
Electric resistance operation	1.0
Heat pump operation	0.0
Hybrid operation	Derived from data, varies with controls setting (hybrid, high performance) and hot water consumption

And it follows that for the first condition, with the load met entirely by electric resistance heating:

$$Qe_{resistance} = Q_{hot\_water} + Q_{standby}$$

For the second condition, in which the load is met entirely by heat pump operation:

$$Q_{refrigerant} = Q_{hot\_water} + Q_{standby}$$

To solve for $Qe_{heatpump}$, the input that's of real interest, we can rearrange the relationship between COP, Qrefrigerant, and $Qe_{heatpump}$:

$$Qe_{heatpump} = \frac{Q_{refrigerant}}{COP}$$

For modeling purposes, COP will be the value predicted from our regression of measured COP vs temperature lift.

$$COP = \alpha_{cop} + \beta_{cop} * \left(T_{hot\_water} - T_{inlet\_air}\right)$$

Combining expressions, we can solve for the electrical energy required to maintain tank temperature using the heat pump alone:

$$Qe_{heatpump} = \frac{Q_{hot\_water} + Q_{standby}}{COP}$$

For the third condition, combining the two heating modes, we rely on the fraction of electric energy used for resistance heating that we derived from data

$$Qe_{resistance} = fe_{resistance} * (Q_{hot\_water} + Q_{standby})$$

With the remainder of input energy delivered via refrigerant:

$$Q_{refrigerant} = (1 - fe_{resistance}) * (Q_{hot\_water} + Q_{standby})$$

Which can again be solved for the electric energy required for heat pump operation:

$$Qe_{heatpump} = \frac{(1 - fe_{resistance}) * (Q_{hot\_water} + Q_{standby})}{COP}$$

And finally:

$$Qe_{total} = Qe_{heatpump} + Qe_{resistance} + Qe_{controls}$$

Energy factor can be calculated for modeling conditions just as done using field data.

SPACE HEATING IMPACTS

Detection of any impact of HPWH use on home space heating needs, and quantification of that impact, was a project objective. [Heating only, we don't consider cooling or dehumidification]

HPWHs extract heat from the air passing over the evaporator coil, and exhaust cooler air back to the surrounding environment [footnote on reduced humidity?]. In the context of HPWHs installed in basements and without ducting to external areas, this heat removal can be viewed as interacting with the thermal environment of the house in two ways – reduced basement air temperature, and potentially increased overall space heating energy use. Two extreme cases demonstrate these effects.

One extreme is a basement environment that has a fixed heat input from an external source and is thermally decoupled from the main living level of the home (no air leakage or conductive heat flow). In this case, operation of the HPWH will reduce the basement temperature but have no effect on the space heating energy use of the home. We would expect basement temperature to drop to some level at which the fixed heat input is in balance on average with the heat extracted by the HPWH plus heat loss through exterior walls and floors, and through air leakage. The other extreme would be a basement that comprises a separate, thermostatically controlled heating zone within the home, with well-mixed air (hence a thermal connection between HPWH and thermostat). In this case, we would expect the thermostat to activate the heating system to maintain the set temperature, with the net increase in output equal to the amount of heat extracted by the water heater. This scenario is expected to apply in a general sense to HPWHs installed in the main living space of a home (if the assumed coupling of HPWH to thermostat exists)[49]. We expect our real-world basements to fall between these extremes, combining some net temperature droop with some increase in overall space heating load.

There are several mechanisms that provide some thermal coupling between basements and fully conditioned main living space in typical real homes, and because of these, we expect HPWH operation should increase net space heating loads to some degree. Figure 31 and provide a guide to the most significant of these mechanisms. The direct thermal interaction of the HPWH with basement air is represented by Q_{air} and $Q_{standby}$. Assuming the majority of water heating is provided by heat pump operation (rather than electric resistance), $Q_{standby}$ will partially but never fully offset Q_{air}, and Q_{air}-$Q_{standby}$ is the driver of reduced air temperature.

[49] There are scenarios that go beyond the second, fully-coupled case. Cool air from a hpwh placed near the thermostat may trigger excess heating that raises the temperature in other parts of the home above setpoint, leading to a heating penalty even greater than the net energy taken up by the hpwh.

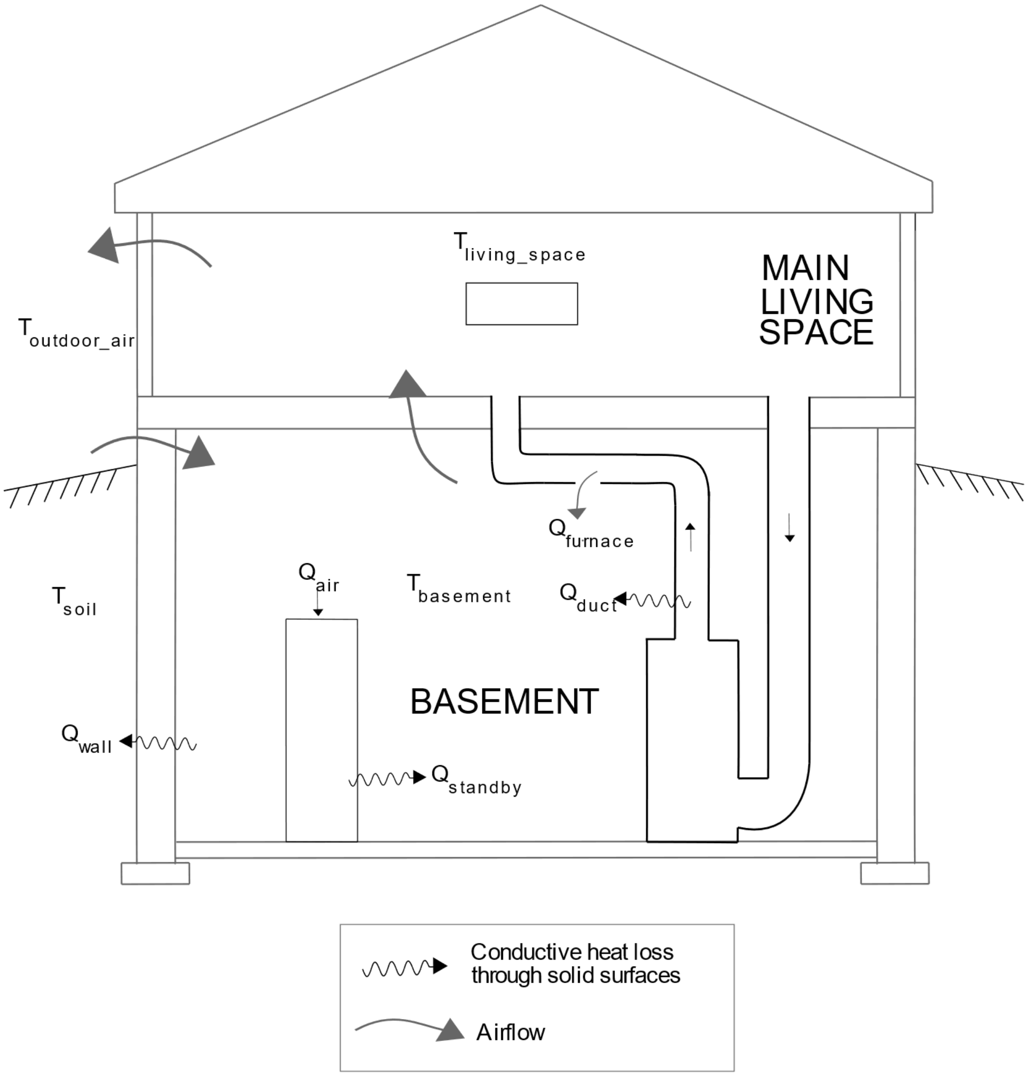


Figure 31. Major mechanisms influencing basement temperature and coupling with main living space.

Table 24. Effects of basement temperature reduction on space heating.

Name	Description	Effect of basement temperature reduction	How basement temperature reduction couples to thermostat	Expected impact on overall space heating
Qduct	Heat loss from warm air ducts to basement	Increase	Amount of heat reaching living space is decreased	Increase

Name	Description	Effect of basement temperature reduction	How basement temperature reduction couples to thermostat	Expected impact on overall space heating
Qfloor	Heat transfer from living space to basement	Increase	Direct heat loss from living space	Increase
Qfurnace	Direct forced air heat to basement	Assuming no change in supply air flow, no effect	No coupling	None
Airflow, basement to Main Living Space	Cooler air from basement generally rises to main levels during winter(1)	Decreases air temperature	Cools air entering living space	Increase
Qwall	Heat loss from basement to environment (above and below grade)	Reduces heat loss	No coupling	None

Notes: (1) In wintertime, temperature-driven ("stack effect") infiltration air typically enters the basement and lower levels of any building, moves upward, and exits from upper levels. Wind and mechanical ventilation may change this pattern to some degree.

Our exploration of space heating impacts of HPWH operation was based on the common method of regression of heating energy against the indoor-outdoor temperature difference. This analysis Specific steps included

- Identifying and excluding from analysis periods of significant auxiliary heating use
- Estimation of space heating provided by the primary heating system
- Regression of primary space heating against indoor-outdoor temperature difference and HPWH heat pump (compressor) operation

The basic regression describing the heating load for a specific home is:

$$H_{site} = \beta_{UA} * (T_{thermostat} - T_{outdoors}) + \beta_{HPWH} * Qair$$

Or, where auxiliary heating input is considered:

$$H_{site} = \beta_{UA} * (T_{thermostat} - T_{outdoors}) + \beta_{aux} * Aux + \beta_{HPWH} * Qair$$

Where the following terms apply:

Q_{hot_water} is the useful energy delivered from the water heater to fixtures in the building.
$Qe_{heatpump}$ is the electrical energy used to operate the heat pump compressor and fan.
$Qe_{resistance}$ is the electrical energy delivered to electric resistance coils to heat water directly.

H_{site} is the predicted space heating requirement in BTU/hr
β_{UA} is the slope of space heating vs temperature difference BTU/hr °F)
$T_{thermostat}$ is the temperature in the house main living space
$T_{outdoors}$ is the outdoor temperature space
β_{aux} is the slope of space heating vs auxiliary heating runtime (BTU/hr / hr runtime)
Aux is the runtime of the auxiliary heating system(s)
β_{HPWH} is the slope of space heating vs HPWH net energy uptake (BTU/hr / BTU/hr)
Q_{air} is the net energy uptake of the HPWH (BTU/hr)

The regression of space heating load against temperature difference ignores the variable effects of factors including solar gains, other internal heat gains from cooking and miscellaneous electric loads, and infiltration/ventilation airflow, as well as seasonal trends in heat loss through basement walls and floors. We don't believe any of these are likely to be correlated with HPWH operation, so may add noise to our regression results but are not likely to bias the results.

Several issues related to auxiliary heat and other factors at specific sites affected our approach to space heating analysis:

- Site 03 had two propane auxiliary heating devices. For purposes of analysis, we assume they have similar effective heat output, and we simply add the operating time of the two to create a single auxiliary heat variable. Site 03, also suffered a failure of the central furnace in March, 2021, and used auxiliary heat exclusively after March 15. We excluded that late winter period from space heating analysis.
- Site 04 had two ducted furnaces, one serving the first floor and basement, one serving the second floor. We were not able to set up monitoring of the second-floor furnace, and for purposes of analysis, we have little choice but to proceed using output of the first-floor furnace as the independent variable tracking space heating load. This is equivalent to assuming that either a) the second floor adds a proportional heating load to the first floor furnace, or b) that the second floor adds a random effect to the load on the first-floor system.
- Site 05 has a dual-fuel primary heating system that combines an air-source heat pump with an oil furnace. We excluded 121 days on which the heat pump was used from space heating analysis.
- Site 06 Auxiliary heat temperature data for shows some signs of being affected by solar gains to the space, and our approach to identifying auxiliary heat operation (based on the rate of temperature rise and/or maintaining an elevated temperature) may be less than perfect.
- Variation in actual output as compared to nameplate values could affect our results.

APPENDIX C SURVEY INSTRUMENTS

Heat Pump Water Heater Study: Field Study Participants

Help us learn about your experience with your heat pump water heater. By completing this survey, you'll help your utility and the Energy Optimization program improve their customer programs.

This survey will take less than 10 minutes to complete and your answers will remain confidential.

1. What operating mode is your heat pump water heater set on most of the time?

- Hybrid (default setting)
- Heat pump only
- Electric only
- Other, please describe:

2. Why did you select this operating mode?

3. What fuel did your last water heater use? (If the heat pump water heater was part of a new home, think back to the water heater you had in your previous home)

- Electricity
- Natural gas
- Propane
- Don't know
- Other

Our next questions are about your experience with your heat pump water heater.

4. Did you change how you use hot water after installing the heat pump water heater? This might include using less hot water for your laundry or spacing out activities that use hot water.

- Yes
- No

5. Please describe how you changed your hot water use.

6. Thinking about the operating mode you most commonly used on your heat pump water heater over the past year, did you ever run short of hot water?

- Yes
- No

7. How many times have you run short of hot water over the last year?

8. When you ran short of hot water, what, typically, was the cause?

9. Do you run short of hot water more frequently with your heat pump water heater than you have with previous water heaters?

- Yes
- No

10. Now, thinking back to when your heat pump water heater was in **heat pump only** operating mode last winter, did you run short of hot water at any time?

- Yes
- No
- Does not apply to me, my water heater is always in heat pump only operating mode

11. How many times did you run short of hot water while the water heater was in heat pump only mode?

- More than 10 times
- 4 to 10 times
- 1 to three times
- Never

12. Did you change the way you use hot water when in **heat pump only** mode?

- Yes
- No

13. What changes did you make?

14. Please share any other comments you have about your experience with your heat pump water heater in **heat pump only** operating mode.

15. Please describe your experience with your heat pump water heater while it was in **electric only** operating mode during the winter.

Our next questions are about the space where your heat pump water heater is located.

16. Has your household changed the way it uses the basement since the heat pump water heater was installed?

No	Yes	If yes, describe:
○	○	

17. Has the temperature and humidity changed in your basement in the summertime or the wintertime?

	No	Yes	No opinion
In the **wintertime**	○	○	☐
In the **summertime**	○	○	☐

18. How has the temperature and humidity changed?

	Cooler	Cooler and Dryer	Hotter	No change
In the **wintertime**	○	○	○	☐
In the **summertime**	○	○	○	☐

19. Do you like the temperature and humidity changes?

	No	Yes	No opinion
Wintertime temperature and humidity changes	○	○	☐
Summertime temperature and humidity changes	○	○	☐

20. Do you have any other comments on temperature or humidity changes with the heat pump water heater?

21. Which of the following statements best describes how you feel about the noise from your heat pump water heater. Pick one.

- It is very noticeable
- It is noticeable
- It is hardly noticeable
- Other, please describe:

Now we have some more general questions about your household and heat pump water heater.

22. Over the last year, on average, how many people have been living in your home?

23. How satisfied are you with your heat pump water heater?

- Dissatisfied
- Somewhat Dissatisfied
- Neutral
- Somewhat Satisfied
- Satisfied

24. How significant were the following factors in your decision to buy a heat pump water heater?

	Insignificant	Somewhat insignificant	Neither insignificant nor significant	Significant	Very significant
Recommendation from a contractor	○	○	○	○	☐
Age of existing water heater	○	○	○	○	☐
Health or safety	○	○	○	○	☐
Environment, energy savings, cost savings, technology	○	○	○	○	☐
Information from the utility	○	○	○	○	☐
Rebate program	○	○	○	○	☐

25. Was your heat pump water heater installed by a professional?

○ Yes

○ No

26. What information did the contractor give you about the operating modes? Check all that apply.

☐ Set the water heater to the default operating mode

☐ Explained the different operating modes

☐ Provided the manual

☐ Showed how to set the operating mode on the user screen on the water heater

☐ Set the operating mode to my choice

27. What operating mode was your heat pump water heater set to when it was first installed?

- Hybrid (default setting)
- Heat pump only
- Electric only
- Other

28. What maintenance tasks do you do on the water heater? Please describe.

29. How much do you think it costs to operate your heat pump water heater annually? Your best guess is fine.

Cost to operate:

30. How much money do you think you save in a year with your heat pump water heater? Your best guess is fine.

Amount saved annually:

31. Do you have any other comments about your heat pump water heater that you'd like to share?

32. Finally, please provide your contact information.

First name

Last name

Email address

Phone number

Heat Pump Water Heater Study: Rebate Program Participants

Help us learn about your experience with your heat pump water heater. By completing this survey, you'll help your utility and the Energy Optimization program improve their customer programs.

This survey will take less than 10 minutes to complete and your answers will remain confidential.

1. Do you have a heat pump water heater?

- Yes
- No

2. Do you know the make (brand name) and model of your heat pump water heater?

No	Yes	What make and model is it?	
○	○	○	

3. When was the heat pump water heater installed? (Year and month if you know.)

Year

Month

4. Is your heat pump water heater ducted to the outside?

No	Don't know	Yes	If yes, please describe:
○	○	○	

5. What operating mode is your heat pump water heater set on most of the time?

- Hybrid (default setting)
- Heat pump only
- Electric only
- Don't know
- Other

6. Why did you select this operating mode?

7. Do you know what temperature your heat pump water heater is set to now?

- Yes
- No

8. What temperature is it set to?

9. What fuel did your last water heater use? (If the heat pump water heater was part of a new home, think back to the water heater you had in your previous home)

- Electricity
- Natural gas
- Propane
- Don't know
- Other

Our next questions are about your experience with your heat pump water heater.

10. Did you change how you use hot water after installing the heat pump water heater? This might include using less hot water for your laundry or spacing out activities that use hot water.

- Yes
- No

11. Please describe how you changed your hot water use.

12. Thinking about the operating mode you most commonly used on your heat pump water heater over the past year, did you ever run short of hot water?

- Yes
- No

13. How many times have you run short of hot water over the last year?

14. When you ran short of hot water, what, typically, was the cause?

15. Do you run short of hot water more frequently with your heat pump water heater than you have with previous water heaters?

- Yes
- No

16. Have you experimented with different operating modes on your heat pump water heater?

- Yes
- No

17. Which operating modes **did not** work well for you? (Select all that apply)

- Hybrid
- Electric only
- Heat pump only
- High demand
- Energysaver

Our next questions are about the space where your heat pump water heater is located.

18. Where in your home is your heat pump water heater installed?

- Unfinished or partially finished basement
- Mechanical room in the basement
- Main living area
- Other

19. Briefly describe how you use your basement (for example, bedroom, office space, laundry, etc).

20. Has your household changed the way it uses your basement since the heat pump water heater was installed?

No	Yes	If yes, please describe:
○	○	

21. Has the temperature and humidity changed in the area where your heat pump water heater is installed in the summertime or the wintertime?

	No	Yes	No opinion
In the **wintertime**	○	○	☐
In the **summertime**	○	○	☐

22. How has the temperature and humidity changed?

	Cooler	Cooler and Dryer	Hotter	No change
In the **wintertime**	○	○	○	☐
In the **summertime**	○	○	○	☐

23. Do you like the temperature and humidity changes?

	No	Yes	No opinion
Wintertime temperature and humidity changes	○	○	☐
Summertime temperature and humidity changes	○	○	☐

24. Do you have any comments on temperature or humidity changes with the heat pump water heater?

25. Which of the following statements best describes how you feel about the noise from your heat pump water heater? Pick one.

- ○ It is very noticeable
- ○ It is noticeable
- ○ It is hardly noticeable
- ○ Other, please describe:

Now we have some more general questions about your household and heat pump water heater.

26. Over the last year, on average, how many people have been living in your home?

27. How satisfied are you with your heat pump water heater?

- Dissatisfied
- Somewhat Dissatisfied
- Neutral
- Somewhat Satisfied
- Satisfied

28. How significant were the following factors in your decision to buy a heat pump water heater?

	Insignificant	Somewhat insignificant	Neither insignificant nor significant	Significant	Very significant
Recommendation from a contractor	○	○	○	○	☐
Age of existing water heater	○	○	○	○	☐
Health or safety	○	○	○	○	☐
Environment, energy savings, cost savings, technology	○	○	○	○	☐
Information from the utility	○	○	○	○	☐
Rebate program	○	○	○	○	☐

29. Was your heat pump water heater installed by a professional?

○ Yes

○ No

30. What information did the contractor give you about the operating modes? Check all that apply.

☐ Set the water heater to the default operating mode

☐ Explained the different operating modes

☐ Provided the manual

☐ Showed how to set the operating mode on the user screen on the water heater

☐ Set the operating mode to my choice

31. What operating mode was the water heater set to when first installed?

32. What maintenance tasks, if any, do you do on the water heater? Please describe.

33. Do you think it costs less to operate your heat pump water heater than it did to operate your most recent conventional (non heat pump) water heater?

- Yes
- No
- Don't know

34. How much do you think it costs to operate your heat pump water heater annually? Your best guess is fine.

Cost to operate:

35. How much money do you think you save in a year with your heat pump water heater? Your best guess is fine.

Amount saved annually:

36. Do you have any other comments about your heat pump water heater that you'd like to share?

37. Finally, please provide your contact information.

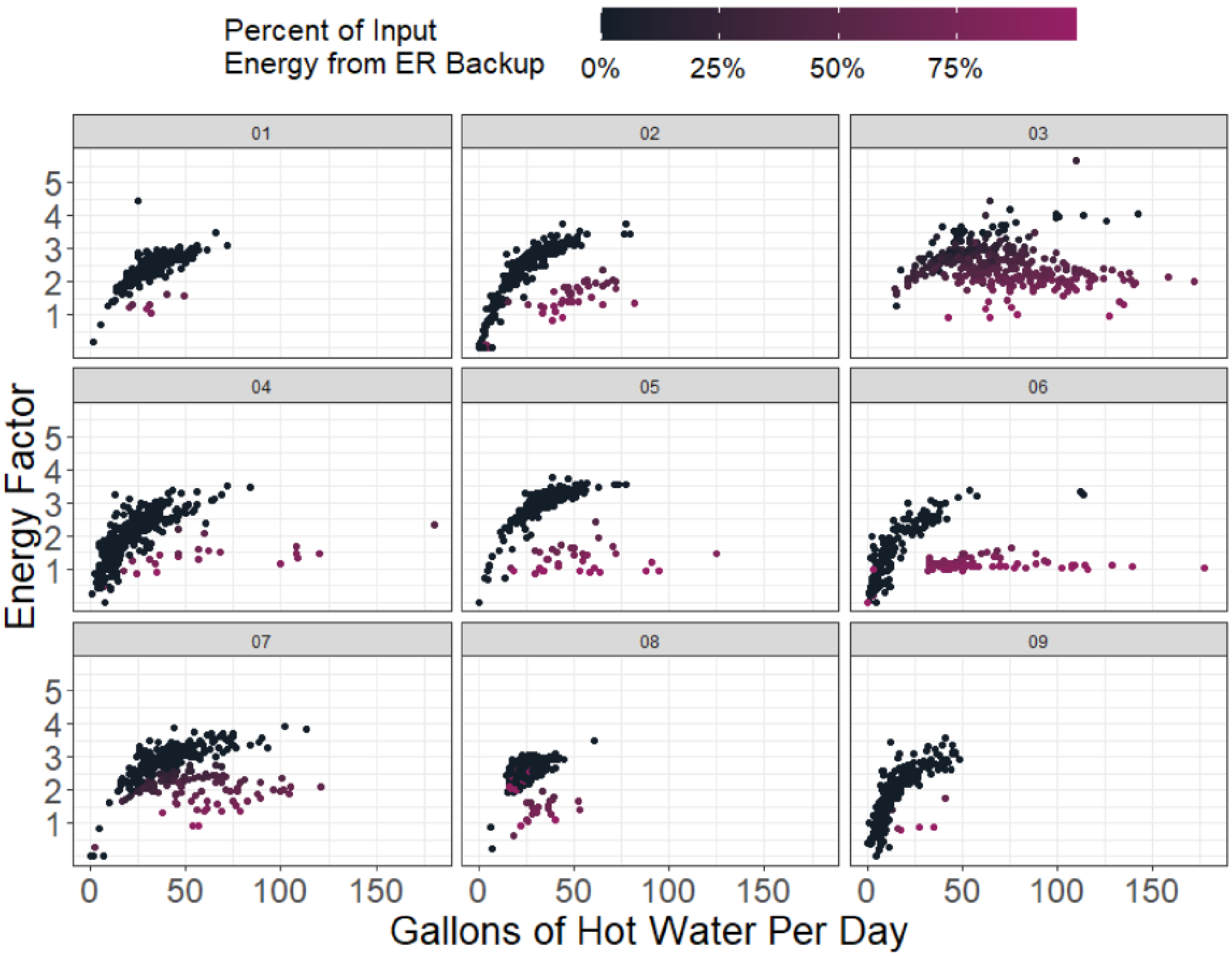
First name

Last name

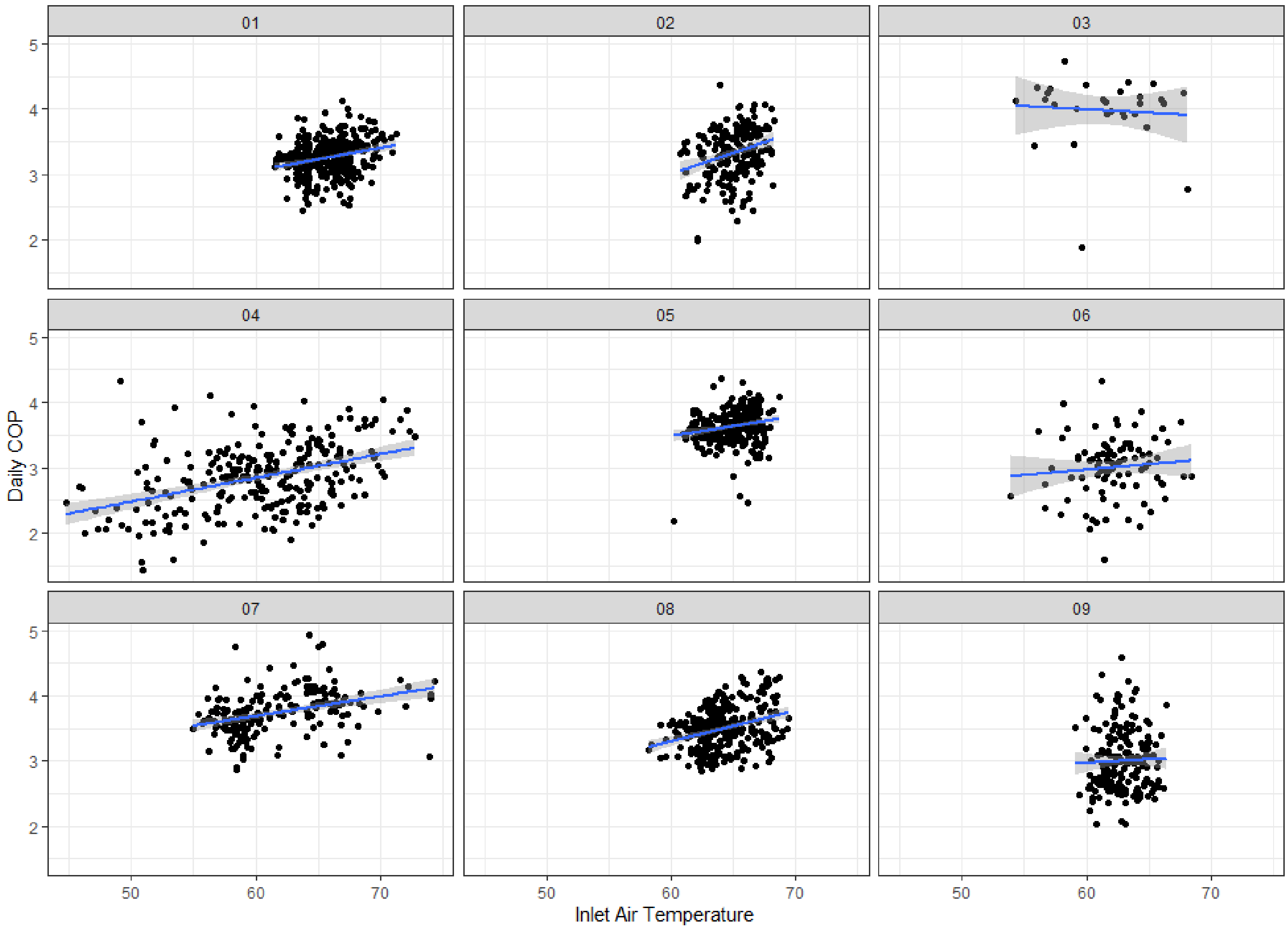
Email address

Phone number

APPENDIX D FIELD ENERGY FACTOR PLOTS



APPENDIX E COP REGRESSION PLOTS



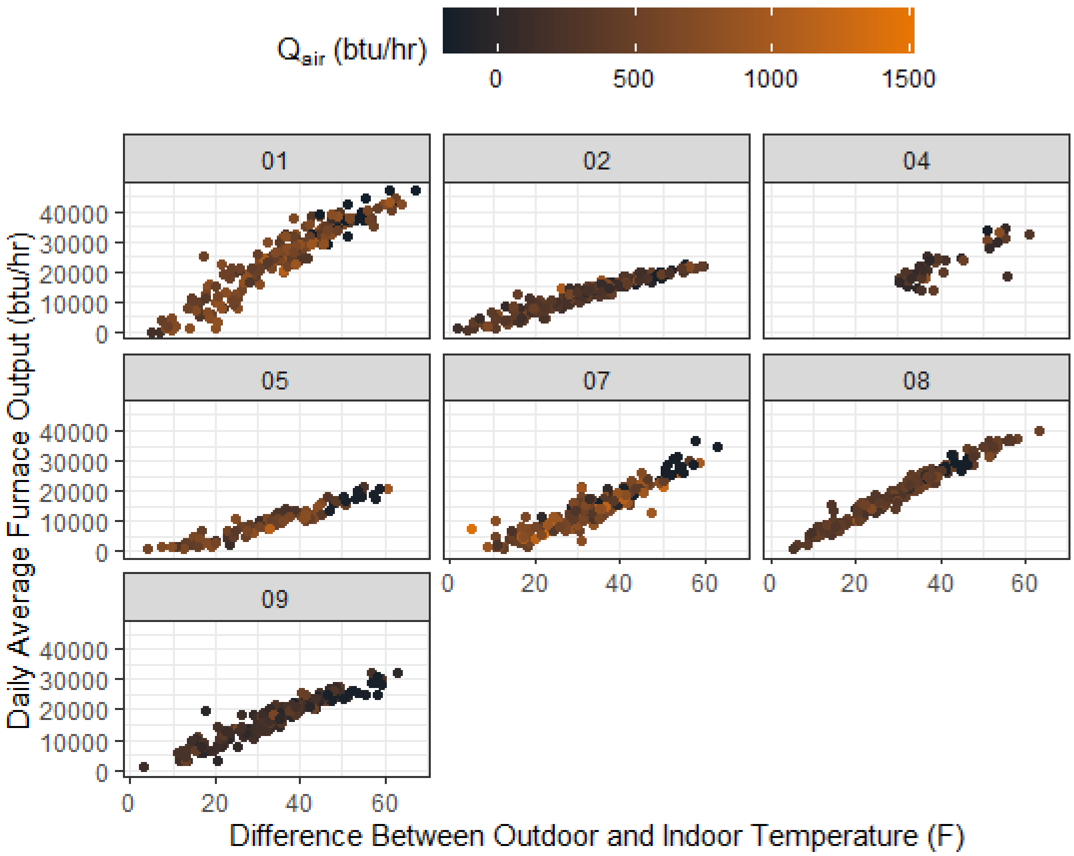
APPENDIX F PERFORMANCE MODELLING KWH ESTIMATES

Table 25. Electric energy savings in the medium usage, high lift scenario.

Manufacturer	ERWH Annual Energy Consumption (kWh)	HPWH Annual Energy Consumption (kWh)		Annual Energy Savings (kWh)	
		HP Only	Hybrid	HP Only	Hybrid
AO Smith	3614	1279	-	2335	-
Bradford White	3614	1200	1570	2414	2044
Rheem	3614	1074	1139	2540	2475

APPENDIX G SPACE HEATING SCATTER PLOTS

SCATTER PLOTS OF SPACE HEATING FOR SEVEN SITES WITH NO AUXILIARY HEATING, OR WITH AUXILIARY HEATING EXCLUDED



SCATTER PLOTS OF SPACE HEATING FOR TWO SITES WITH UNCONTROLLED AUXILIARY HEATING OPERATION