Residential Heat Pump Water Heater Performance in the Upper Midwest

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ABSTRACT

The newest generation of heat pump water heaters (HPWHs) are a promising measure for energy and carbon reduction programs, but there are lingering concerns about their field performance and applicability in cold climates. Our team investigates this issue through a detailed monitoring of 9 residential HPWHs installed in partially conditioned basements and a survey of 81 HPWH rebate recipients in Michigan's cold climate. Our analysis estimates the field performance and models cost and emissions impacts of the technology against baselines of electric resistance, propane, and natural gas storage tank water heaters. HPWH compressors have a cooling effect on the surrounding air, which is a concern in heating-dominate climates. We analyze the effect of HPWH operation on household heating loads to determine if they increase space heating energy use and review survey data to determine impacts on household comfort. Our research findings show field-derived efficiencies that are lower than the equipment's rated Uniform Energy Factor (UEF).[1] This can be largely explained by the low water usage, cold climate installation conditions reducing compressor efficiency and capacity, and the prevalence of electric resistance backup heating in the field. Despite the lower efficiency, the systems have significant operating cost advantages to electric resistance water heaters, high satisfaction among owners, and the space heating impacts did not bother customers or increase space heating loads.

Introduction

The new generation of residential HPWHs have rated UEFs well above three. Slipstream conducted a field monitoring project and customer survey to quantify the performance of HPWHs and gauge satisfaction for customers in the cold climate of Michigan.

The primary objectives of this project are to 1) characterize HPWH performance 2) calculate the cost and energy savings compared to an electric resistance water heater 3) estimate HPWH compressor operation's impact on basement temperature and space heating 4) conduct a survey on owner satisfaction.

This builds on cold climate HPWH performance research conducted by Ecotope and Steve Winter's Group in the Northwest and Northeast by assessing a newer generation HPWHs in the Midwest. The full version of the report is available and can be found on Slipstream's website.[2]

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[1] The field-derived efficiency represents the ratio of delivered hot water energy and input energy consumption from our monitored data. These values include efficiency reductions associated with standby loss.
[2] https://slipstreaminc.org/research/heat-pump-water-heaters-cold-climates

Project Overview

Study Design

Utility members of the Michigan Electric Cooperative Association (MECA) cover upper and lower Michigan and tend to serve rural, single family households with high prevalence of delivered fuels and electric heat. Slipstream recruited field study candidates by screening households that received HPWH rebates through the energy efficiency program and selected willing participants with the newest generation of HPWHs. Households that relied heavily on supplemental heating systems or heat their homes with air-source heat pumps were not included because we did not collect the needed data to estimate heating loads for these systems. Three different manufacturers are represented in the monitored HPWHs. In addition to the field monitoring, we conducted a survey of 81 households that had installed HPWHs to understand the user experience.

During the monitoring period that spanned from September 2020 until September 2021, data on air and water temperatures were recorded each second and power data each minute. The monitoring included accurate in-line water temperature measurements, volumetric hot water consumption, an array of air temperature sensors to account for basement temperature stratification, and a sensor on the furnace gas valve to estimate the house heating load. We requested that participants set their water heaters to electric resistance mode for 2 weeks in the winter and 2 weeks in the summer to quantify the rate of standby loss at each site.[3]

Monitored performance may not be representative of typical conditions. Slipstream extrapolated the field performance of each system under various temperature and hot water usage conditions to provide a more complete understanding of how the studied sites may perform under different applications.

Site conditions

All nine field study participants lived in single family homes with private wells and their HPWH installed in full, partially conditioned basements.[4] Michigan's cold climate conditions raise concerns for the performance of HPWHs due to lower groundwater temperature and colder ambient temperatures at the compressor air intake. Heat pump compressors transfer heat more efficiently in warm temperatures, so cooler ambient conditions could reduce efficiency compared to a warmer location, like a California garage. The daily ambient temperature near the water heater ranged from 50 to 74 and averaged 63ºF.

Lower groundwater temperatures put more strain on water heaters recovering from hot water draw episodes, which could trigger the inefficient electric resistance backup heating. Figure 1 shows trends in groundwater temperature across the monitoring period, showing the lowest temperatures of around 55ºF during March. The average temperature of delivered hot water ranged from 108 to 127ºF and averaged 117ºF. We could not continuously measure hot

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[3] During periods of exclusively electric resistance heating, we can assume that the input energy required to deliver hot water is equal to the hot water energy delivered because the theoretical electric resistance coil efficiency of 100%. From this, we can calculate standby losses by subtracting the input energy used to deliver hot water (and controls power) from the total energy delivered to the tank. On the other hand, compressor COP varies which complicates this calculation.

[4] Partially conditioned space in this case means that heating and cooling equipment are installed in the basement, but basement air temperature is not actively controlled.

water setpoints, but the average setpoint temperature at the beginning of the study was 127 ºF with one water heater at 140 ºF.

The monitored sites had lower hot water use than is typical in single family homes. On average, our sites use 33 gallons of water per day which is lower than the DOE test procedure's medium use assumption of 55 gallons per day. Low water usage reduces the energy savings compared to an electric resistance water heater and decreases the equipment's field-derived efficiency.

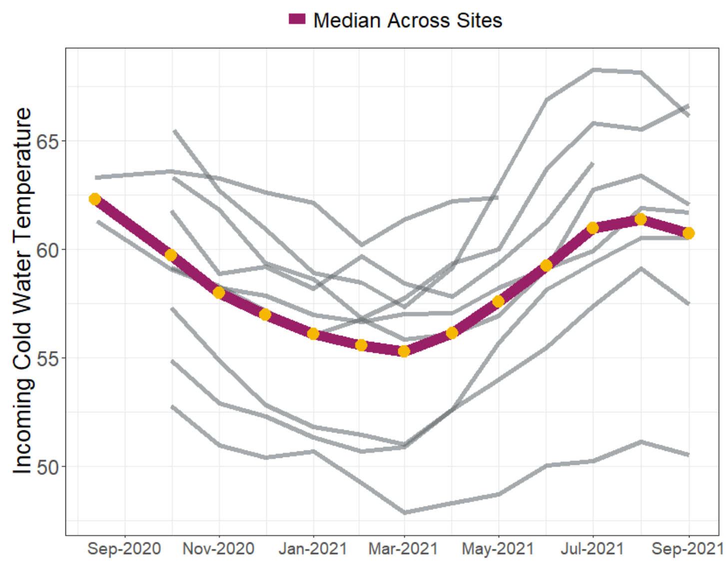

Figure 1. Average groundwater temperature across monitoring period.

Characterizing Energy Use

Figure 2 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 $Qe_{controls}$, (electric power for resistance heat, heat pump compressor operation, and controls operation) while outputs include hot water energy (Q_{hot_water}) and standby heat loss ($Q_{standby}$). By definition, the sum of inputs balances total outputs.[5] 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 2, 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 fraction of input energy from electric resistance is determined to a large degree by the equipment's control settings. The water heater at Site 01, for example, was kept in the heat pump only setting for most of the study period according to the field data and a participant

[5] We assume controls power does not contribute to heating water, so $Qe_{controls}$ appears as an excess quantity on the input side.

survey. It shows very little electric resistance usage. Site 06 was primarily in hybrid mode, which allows for electric resistance heating when the system is strained for capacity. Its heavy reliance on electric resistance backup could be due to the manufacturer's algorithm controlling coil use and household draw patterns depleting the tank quickly. Indeed, Site 06 did have peaky usage behavior and consumed 40% of its hot water between 5 PM and 8 PM. This is higher than the study's average of 31% during that period.

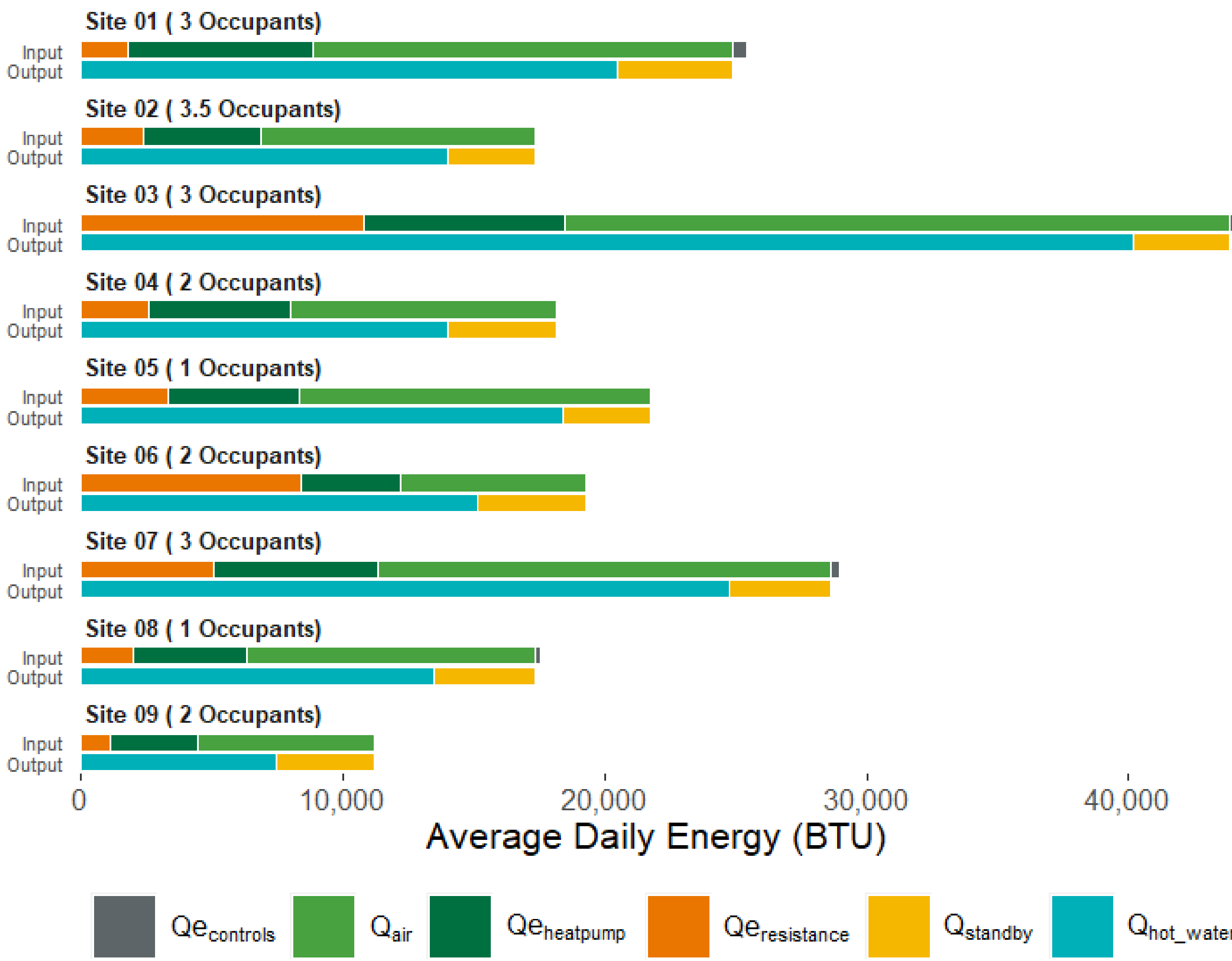

Figure 2. Characterized energy use across sites.

Performance

Efficiency

The energy efficiency performance is an important consideration when considering the technologies potential in cold climates. In Table 1, we report the average field-derived efficiency, the rated uniform energy factor, and the modeled efficiency in various scenarios. The field-derived efficiency is the average daily hot water energy output divided by total electrical energy input as measured at the studied sites. Because our sites may not represent an average household, we extrapolated system dynamics from the field data to estimate performance under more representative conditions. Our site-specific models utilized linear regression approaches to predict the standby loss, compressor efficiency, and the fraction of electric resistance backup from collected data. We defined days that did not use electric resistance backup as heat pump only mode and days with any supplemental backup as hybrid mode. It is possible that some days in our hybrid mode are misclassified as heat pump only mode because the hot water demand didn't trigger electric resistance backup. The rated UEF is the efficiency reported in the product specifications and is based on testing conditions defined by the DOE.

The results show field-derived energy factors are significantly lower than the rated UEF. This is partly due to the lower hot water usage from our monitored sites. After normalizing water usage to match the DOE test procedures, the efficiencies increase but is still lower than the rated UEF. One explanation for this discrepancy is that our modeling approach is based on field draw patterns instead of the draw patterns implemented in DOE testing. Field draw patterns may be irregular and can trigger more electric resistance backup, which negatively impacts performance.

Our results show comparable efficiency to other research conducted on older equipment with lower rated UEFs. In the Northeast, a 2012 Steve Winter Group study showed field efficiencies between 1.0-2.6 with results varying greatly with usage (Steve Winter Associates 2012). Ecotope estimates similar performance in their 2015 study with water heater efficiency ranging from 1.6-2.4 (Ecotope 2015).

These efficiency results show that factors such as low water usage and irregular usage patterns can have a big impact on performance. Modelers and program planners could consider derating the rated UEFs of HPWHs when predicting actual field performance of newer generation HPWHs.

Table 1. Equipment Efficiency

Scenario	Heat Pump Mode	Hybrid Mode	Weighted Avg[6]
Field-derived	2.56	1.60	2.17
Cold climate scenario[7]	2.55	2.15	2.50
DOE test scenario[8]	3.02	2.37	2.92
Uniform Energy Factor	-	-	3.45

Figure 3 compares trends in daily field-derived efficiency between two sites. In Site 03, we see a continuous pattern of points, with efficiency peaking at around 50 to 70 gallons per day

[6] This is weighted based on the average proportion of energy consumption in each operating mode.
[7] Cold climate scenario details: 50 gallons per day, 58F groundwater temp, 125F setpoint temp, 55F basement temp.
[8] DOE test condition details: 55 gallons per day, 58F groundwater temp, 125F setpoint temp, 67.5F basement temp.

and decreasing with higher usage as the fraction of electric resistance heating increases. Site 03 is manufactured by Rheem. This HPWH was efficient in hybrid mode and allowed for significant contributions from the heat pump compressor.

Site 06 shows a less expected trend with two distinct clouds of points. The purple grouping shows field-derived efficiency increasing with hot water usage, which is driven by the constant effect of standby loss becoming less impactful as the delivered hot water energy increases. The electric resistance backup elements do not operate for these days, suggesting that the system is in a heat pump only mode. There is another distinct group of mostly yellow dots hovering between energy factors of 1 and 1.5, which is likely under the hybrid control setting. This Bradford White water heater seems to trigger electric resistance more in hybrid mode, which has a negative impact on performance.

Ideally, installed HPWHs will use heat pump only mode to generate the most energy savings, but this may not be feasible for all households. If a hybrid mode is selected, it should be noted that not all the manufacturer-defined control settings are programmed the same; and this can have a substantial impact on system performance.

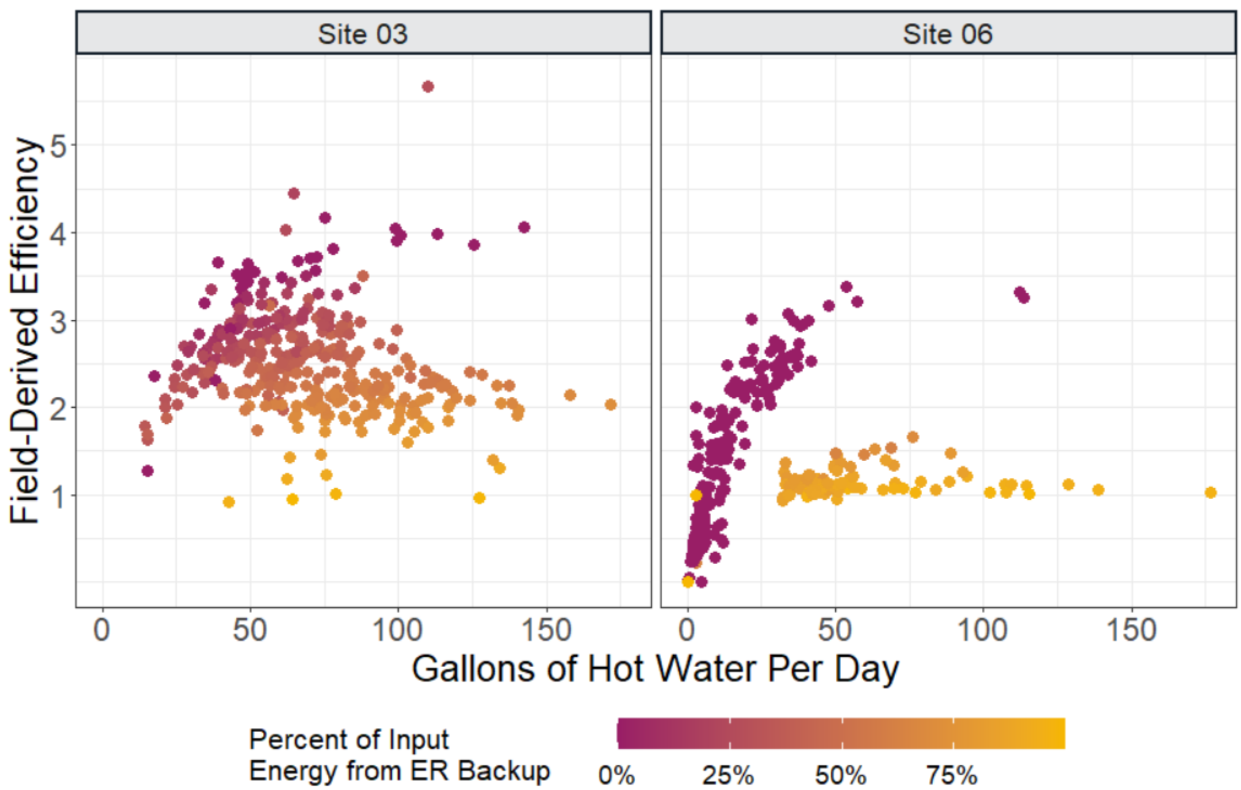

Figure 3. Comparison of daily energy factor and hot water use.

Energy Impacts

Table 2 shows the annual impacts from HPWHs in the cold climate scenario. The results show significant savings for HPWHs when replacing an electric resistance water heater. The incremental costs of HPWHs fluctuate across localities, global economic trends, and utility rebates. Despite these uncertainties, the $300 annual operating cost savings make a compelling case for replacing electric resistance water heaters. It could also be a good option for replacing a propane- or fuel oil-fired water heater, but these fuel switching replacements may not be supported by all utility programs and homeowners could face additional costs for electrical upgrades to support the intervention.

The carbon savings show that replacing any of the baseline water heaters with a HPWH will reduce carbon. These results are largely driven by the carbon intensity of electricity on the grid. In this case, we used the average emissions factor from Great Lakes Energy's fuel mix because we could not measure the time-of-use for the baseline electric resistance water heaters. The carbon savings can vary drastically across localities, time, and between marginal and average emission factors.

Table 2. Cold climate annual energy, cost, and carbon impacts.

Baseline system	Energy Savings (kWh)	Cost Savings	Carbon Savings (lbs)
Electric Resistance[9]	2401	$300[10]	934[11]
Propane-fired[12]	3809	$209[13]	1035
Natural Gas-fired[9]	3809	$15[14]	770

Space Heating Impacts

Heat pump water heaters have a space cooling impact on the immediate environment and to objectives of this study were to quantify its impact on basement temperature and whole-house space heating load.

Basement temperature effect

A decrease in temperature of the immediate environment is another expected outcome of operating a HPWH. To explore the impact of HPWH compressor cycles on the basement temperature, we isolated heat pump operating cycles in the data and evaluated the temperature trends at the beginning and end of each compressor cycle. We accounted for the effect of furnace operation by averaging temperatures over the average length of a heating cycle.

From conducting this analysis, we found that typical compressor cycles last 90-120 minutes and the temperature near the HPWH decreased an average of 2.3ºF in our study's open basement installations. However, temperatures typically return to pre-cycle conditions within a

[9] A UEF of 0.95 is assumed for the electric resistance water heater efficiency per MEMD workpaper FES-H2A.
[10] Based on Great Lakes Energy residential electric rate of $0.125 per kWh.
[11] The carbon intensity of Michigan's electricity generators is a weighted average from 2020 EIA plant-level carbon emissions data for Michigan and we assumed Great Lakes Energy fuel mix.
[12] A UEF of 0.64 is assumed combustion efficiency for both propane and natural gas fired water heaters based on MEMD workpaper FES-C9.
[13] Assumes Michigan's 5 year average propane price from 2016-2021 of $1.92/gallon from EIA.
[14] Assumes Michigan's 5 year average natural gas price from 2016-2021 of $9.70/MMBtu from EIA.

few hours of the compressor cycle. The substantial thermal mass of uninsulated stone or concrete may mitigate the effect of compressor cycles on the basement temperature. Temperature impacts would be exaggerated if installed in unvented closets or other small spaces and this could have significant impacts on compressor performance. Ecotope observed 6-7 ºF reductions in small installation locations (Ecotope 2015). Although we did not notice significant temperature depressions, there may be season-long effect on basement temperature that were unobserved in this study.

Impact on space heating load

Slipstream also analyzed the potential impact of a HPWH's cooling effect on the home's heating load to determine if installing HPWHs in basements of cold climates increases space heating energy consumption. To do this, we used a linear regression of daily primary space heating energy against average indoor-outdoor temperature difference to characterize heating energy use in each home and included an additional independent variable called Q_{space}, which represents the HPWH's net impact on basement temperature considering both the compressor's cooling effect and heat released by the hot water tank from standby loss.

From the regression results, we could not detect a systemic impact of HPWH operation on space heating across the homes in this study. Figure 4 shows the daily space heating load across in indoor and outdoor temperature difference. The colors of the points don't show a discernible trend in the amount of Q_{air} and the home's heating load. The lack of a noticeable space heating effect may be partly explained by the proximity of water heater to the thermostat and the relative magnitude of Q_{space} and the home's heating load. Across sites, the Q_{space} is less than 5% of the average space heating load for homes, which generally fits into the acceptable noise level of the regression. Ultimately, we must conclude that it's possible that some fraction of Q_{space} is likely reflected in the furnace output, but the magnitude is too small and difficult to quantify in this study. These results align with an Oak Ridge National Lab study that reported small impacts of HPWH operation on space heating and cooling (Baxter 2016) and PNNL's research that shows smaller impacts when the water heater is not in close proximity to the thermostat (Widder 2017).

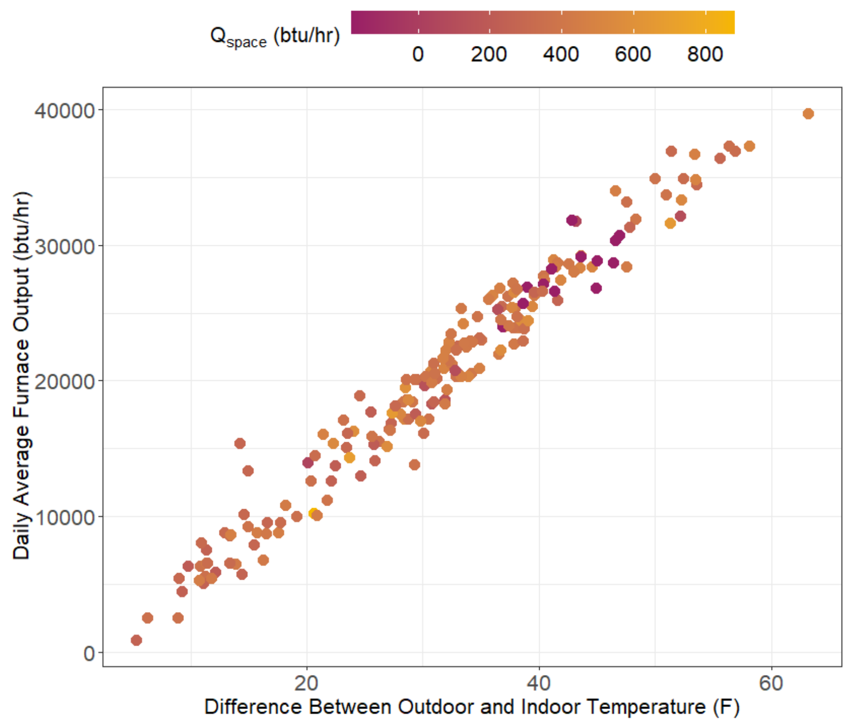

Figure 4. House space heating load with Q_{air}, or the heat extracted from the HPWH.

Survey

Background

To learn about the customer experience and satisfaction with HPWHs in Michigan, we supplemented the field research with a survey with the nine field study participants and 72 other households that installed HPWHs in MECA utility territories. Survey respondents live in rural Michigan with limited access to natural gas. Of the 81 respondents, 80% replaced an electric water heater, while 13% and 6% replaced propane and natural gas water heaters respectively. Survey respondents installed their HPWHs between 2013 and 2021, with 93% of installations occurring between 2019 and early 2021.

Households reported water heater setpoints ranging from 115 °F to 145 °F, with the median setpoint temperature at 125 °F. The most common control setting for participants is a hybrid mode, which allows for compressor and electric resistance heating. 50 study participants (62%) used a hybrid control setting most frequently, while 29 respondents (37%) reported heat pump only as their most common control setting. The major manufacturers represented in this survey are Rheem, Bradford White, and AO Smith. Interestingly, 32 respondents (40%) did not use a professional installer.

Equipment performance

The survey respondents expressed high satisfaction with their decision to purchase a HPWH, which is illustrated in Figure 5. In additional to general satisfaction, only seven respondents (9%) reported increases in hot water shortages compared to their previous water heater. HPWHs can have slower recovery than electric resistance or combustion based water heaters, so it is encouraging that only a small portion of the sample had increased shortages. 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, raising setpoints, or installing larger tanks.

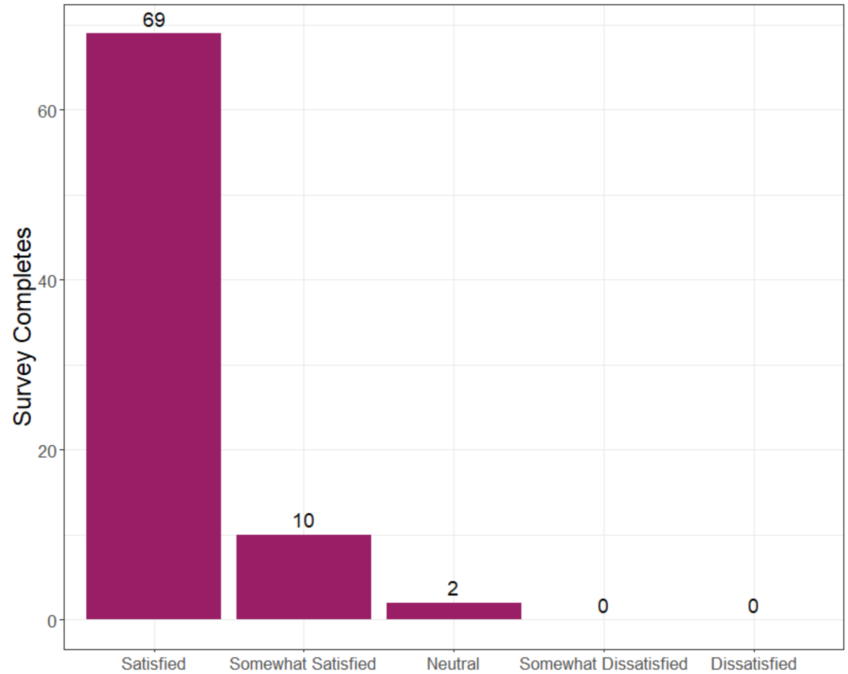

Figure 5. Household satisfaction with their HPWH.

Comfort

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.

Figure 6 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, saving additional energy. 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. Like comfort impacts, noise disruption can be reduced when the HPWH is installed in a low occupancy area.

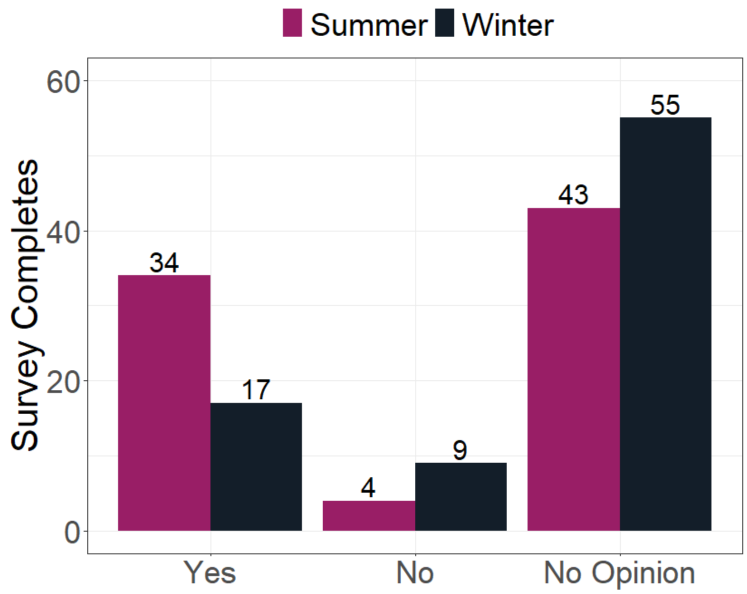

Figure 6. Do survey respondents like the changes to temperature and humidity after installing their HPWH?

Conclusion

The results from this study are generally positive, but signal that there are opportunities to improve field deployment of this technology. On a positive note, the monitored sites show significant energy savings and survey respondents report very high satisfaction with the technology. Additionally, the study results suggest that the HPWH's cooling effect may not be a significant concern in this cold climate application. We couldn't detect increased space heating due to the HPWH's cooling effect and our survey results show that most participants either didn't notice or preferred the cooling and dehumidification from the HPWH. These results are enough to confidently suggest replacing an electric resistance water heater with a HPWH in Michigan's cold climate to a household with a moderate hot water demand.

Despite these positive results, some of the results from the field study raise concern. The field efficiency levels are much lower than the rated UEF. Planners relying on rated equipment efficiencies could consider derating UEFs to reflect the 75% realized efficiency from this study. However, planners should be aware of factors like hot water demand, equipment type, climate, and control settings before adjusting efficiency assumptions.

A significant factor driving lower field efficiency is hot water usage. Our field study participants had significantly lower hot water usage than test conditions. This reduces the efficiency and energy savings. HPWHs are most beneficial in an application with a sustained, moderate water demand for the lifetime of the equipment. The expected hot water demand should be a consideration in contractor trainings or product marketing.

Another factor impacting performance is the control setting. The field data showed that some manufacturer algorithms for hybrid control make more liberal use of electric resistance backup heating than others. HPWHs are most efficient when they are in heat pump only mode, which avoids electric resistance backup entirely. We will improve field performance if HPWHs are kept at heat pump only mode immediately after installation. If the owner has hot water shortages, they can increase the tank's setpoint for more capacity. If the problem persists, they can change to hybrid mode. This could help households understand their water heating limits and determine if they really need the system to be in hybrid mode.

For future research, it will be important to test heat pump water heating technologies in other commercial and residential applications. It would be particularly interesting to test the comfort and energy impacts of HPWHs installed in smaller living spaces, like manufactured homes or multifamily residences. Additionally, other emerging technologies like 120V HPWHs present a promising solution to enable cost-effective fuel switching retrofits. Determining the best applications of these, and other 240V options, will help the industry optimize HPWH deployment to ensure that the products are well-received and save on costs.

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