Heat Pump Evaluation: Weighing Evolving Methods for an Evolving Technology

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ABSTRACT

Across several states and utility jurisdictions, heat pumps have become a critical component of greenhouse gas emissions reduction plans, due to their efficient offset of carbon-intensive fossil fuels. Evaluating space conditioning heat pump performance and impacts is challenging due to the broad array of displaced heating fuels, the possibility of partial displacement, and wide variation in usage patterns among customers. The authors of this paper are currently conducting a rigorous evaluation of a New York State Energy Research & Development Authority (NYSERDA) program that incentivized air-source and ground-source heat pump installations among primarily residential customers in 2018. The study has provided a unique opportunity to compare evaluation methods and results in two ways: 1) at the building level, through analysis of pre- and post-installation utility and delivered fuel data; and 2) at the equipment level, through yearlong measurement and verification using cloud-communicating devices.

The authors determined similar results between the two phases. Air-source heat pumps (ASHPs)—including both ductless mini-split and ducted air-source systems—saved approximately 60,000 MMBtu per year across all fuels including electricity (at site) among 4,043 participants (15 MMBtu per year per participant). Ground-source heat pumps saved 23,000 MMBtu per year across 470 participants (49 MMBtu per year per participant). The study demonstrated the reasonableness of preliminary, building-level impact estimation but showed its limitations in explaining why heat pump performance varied among sampled projects. Equipment-level M&V data allowed evaluators to pinpoint specific reasons for heating savings variation and to quantify fuel-specific impacts more granularly.

To achieve aggressive carbon reduction goals, administrators of heat pump programs are challenged with developing realistic heat pump savings estimates at immense scale. This paper examines evaluation methods and results, identifies best practices for scalable heat pump savings estimation, and provides a roadmap for evaluators to select the most appropriate methods possible.

Introduction

With their electrification benefits, modular design, and application versatility, heat pumps have increasingly become prominent decarbonization measures in utility programs. Program administrators see heat pumps as critical to achieving aggressive carbon emissions reduction goals. But heat pump usage patterns and subsequent impacts are difficult to predict, making goal setting and tracking, incentive calibration, and customer targeting even more nebulous.

The authors of this paper are conducting a two-phase impact evaluation of NYSERDA heat pump programs that have evolved significantly since the 2018 evaluation timeframe. The programs supported both residential and non-residential customers with the installation of ducted ASHPs, ductless mini-split heat pumps (DMSHPs), or ground-source heat pumps (GSHPs) to displace preexisting systems that

[1] Any opinions expressed, explicitly or implicitly, are those of the authors and do not necessarily represent those of the New York State Energy Research and Development Authority.

typically used fossil fuels or electric resistance for heating. All New York customers receiving electricity from an investor-owned utility in New York were eligible to participate in the programs. Program eligibility criteria did not require the preexisting heating or cooling equipment to be removed. 99% of program-sponsored ASHPs in 2018 were DMSHPs, the majority of which were classified as "cold climate."

While program outreach—and, in the case of ASHPs, savings claims—primarily focused on heating season savings, the two-stage evaluation assesses both heating and cooling season impacts. However, as of November 2021, the authors are concluding the cooling season analysis. Phase 1 of evaluation involved site-specific, building-level impact analysis of 235 heat pump installations throughout New York. To ensure sufficient post-installation data for building-level analysis using utility billing data, evaluators analyzed projects installed from program inception through 2018. Phase 2 involved equipment-level measurement and verification (M&V) at 137 sampled projects through deployment and continual analysis of data transmitted through remotely communicating devices. This paper therefore compares and contrasts the methods and results for Phase 1 (heating and cooling impacts) and Phase 2 (heating impacts only). Throughout much of this paper, we use total MMBtu savings across all fuels (including electricity, at site) as a simplified proxy for total energy savings and subsequent carbon emissions reduction across fuel types.

Phase 1 – Billing Analysis

Billing Analysis Methods

Evaluators initiated data collection with a Qualtrics-based mixed-mode survey[2] among prior program participants to collect data on installed heat pump characteristics and use patterns, customer demographics, and utility account information. The survey responses provided a more in-depth understanding of heat pump usage patterns, displacement of heating and cooling loads served by preexisting HVAC equipment, and any occupancy changes or other major non-routine events that occurred in the years since installation. Bolstered by a $15 incentive, the survey received 775 complete responses from a census attempt of 4,515 participating customers.

Phase 1 of the evaluation involved site-specific, weather-normalized analysis of pre- and post-installation consumption data among the 434 survey respondents who provided viable account information. Evaluators obtained consumption data from 8 utilities and 45 suppliers of delivered fuels. Delivered fuel data collection historically has been difficult. With 43% of the evaluation sample using heating oil or propane, delivered fuels represented an important segment for data collection. The evaluation team was able to achieve a 55% success rate in delivered fuel data collection by securing customer authorizations, calling before the heating season intensified, batching calls (one dealer call for all authorizing customers), and using experienced callers without automated systems.

Next, we further screened the electric consumption data to ensure sufficient pre- and post-installation data (34 removed) and absence of solar photovoltaic systems, which can skew the pre/post analysis of heat pump impacts (78 removed). Anticipating sensitivity in the correlation of electric consumption with degree-day data, the team next developed three analysis filtering scenarios to present a range of evaluated results. Each scenario incorporates increasing levels of strictness in regard to data cleanliness, statistical significance, and weather dependency. Table 1 presents the preliminary filtering criteria that were imposed on all sites to determine how each would be evaluated. Any sites that did not meet all post-installation electric criteria presented in the table below were not included in the final evaluation sample.

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[2] The evaluation team used Qualtrics as a secure customer engagement platform to facilitate the web-based survey. To mitigate bias, we mailed postcards with personalized survey links for customers without tracked email addresses.

Table 1. Screening Criteria and Scenarios for Electric and Fossil Fuels Consumption Data

Fuel Type	Period	Scenario	Days of Data	Bill Reads	R^2	t-test
Electric	Pre	Strict	>180 days	<50% estimated	Any	>2
		Moderate	>180 days	<50% estimated	Any	Any
		Mild	>180 days	Any	Any	Any
	Post	Strict	>270 days	<50% estimated	>0.6	>2
		Moderate	>270 days	<50% estimated	>0.2	Any
		Mild	>270 days	Any	Any	Any
Fossil Fuels	Pre	Strict	>180 days	<50% estimated	Any	>2
		Moderate	>180 days	<50% estimated	Any	>2
		Mild	>180 days	Any	Any	Any
	Post	Strict	>180 days	<50% estimated	>0.6	>2
		Moderate	>180 days	<50% estimated	>0.6	>2
		Mild	>180 days	Any	Any	Any

The team used lower R^2 thresholds than are sometimes used for residential HVAC analysis for the moderate and mild scenarios. This is due to observed heat pump use patterns. Enough units were used in the fashion of appliances—with unit operation driven by occupant behavior almost as much as by outside air temperature—that excluding those without strong weather correlation would have likely biased the analysis.

The accounts passing the three screening scenarios were weighted to best represent the total population of program participants. We weighted results based on two stratification variables: equipment type (ASHP ducted, ASHP ductless, and GSHP) and the three climate zones in New York (ICC 2011). Phase 1 billing analysis concluded with the quantification of program-wide savings, differentiated by the stratification variables, and by other variables of interest from the survey or tracking database.

Billing Analysis Results

Figure 1 illustrates the achieved savings distinguished by the three screening thresholds described in Table 1. Using the moderate screening threshold, the billing analysis showed that ASHPs and GSHPs achieved per-project savings of approximately 15 and 46 MMBtu per year, respectively, across all fuels including electricity (at site).

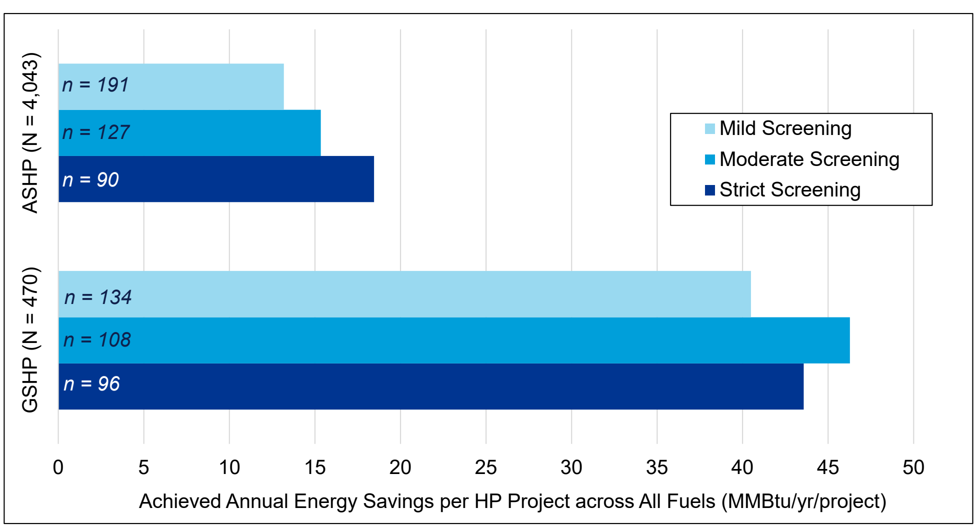

Figure 1. ASHP and GSHP Billing Analysis Results by Electric Screening Threshold

The authors also compared billing analysis results among different variables that could influence heat pump savings. Such variables were self-reported by participants in the Phase 1 survey or determined from program tracking databases. Figure 2 illustrates the per-site MMBtu savings variation for one such variable: customer-reported usage of preexisting heating systems. After reporting that their heat pump is used for at least some heating, respondents were asked how much their existing heating system is still used. In cases where the customers continue to use their existing heating system frequently, the resulting savings are significantly lower. Figure 2 illustrates that heat pumps used as the primary heating equipment are more likely to realize deep savings.

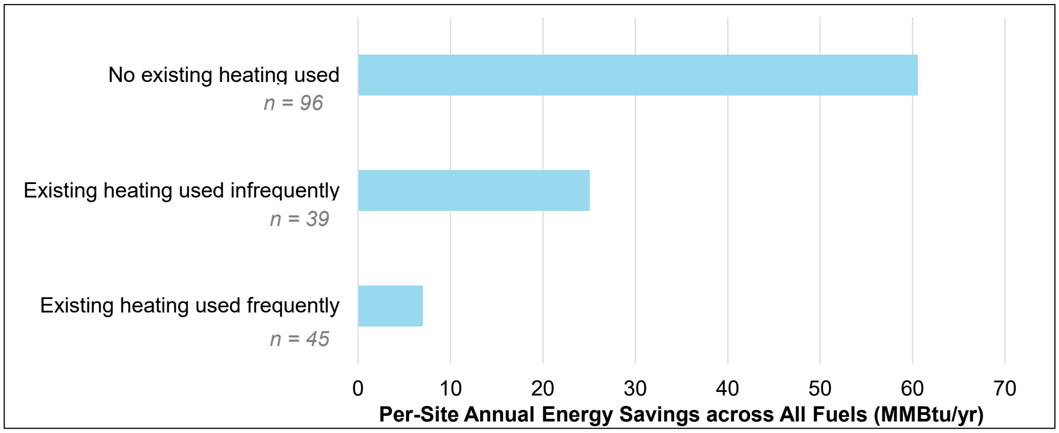

Figure 2. Billing Analysis Results as a Function of Preexisting Heating System Use (ASHPs and GSHPs Combined)

Evaluators identified two other notable trends that affected Phase 1 savings:

- Urban customers realized lower savings per project than rural customers. We hypothesized that: 1) urban customers were more likely to install DMSHPs that conditioned a limited portion of the property's square footage, and 2) DMSHPs were more likely in multifamily settings to be exclusively used for cooling as a replacement for window air conditioners.
- Installations at existing buildings outperformed those in newly constructed buildings. To define baseline consumption for new construction installations, we adjusted post-installation consumption data to reflect code-compliant systems self-reported by the customer as the preferred alternatives in the absence of the program. In some cases, heat pumps defined the baseline scenario, significantly reducing MMBtu savings as compared with fossil fuel alternatives.

Phase 2: Measurement and Verification

Evaluation Phase 2 involved M&V at a sub-sample of the 588 survey respondents that expressed interest in hosting a site visit at their home or business. Evaluators visited 137 representative sites throughout New York to confirm survey response information, physically inspect the installed heat pumps, and deploy a combination of communicating and non-communicating meters. On-site data collection procedures varied depending on the installed HVAC equipment types and the selected level of metering rigor as described in the two paragraphs below.

Core M&V Methods

Field evaluators executed core M&V procedures at 125 of the 137 sites in the evaluation sample. The core procedures represent industry-standard approaches for heat pump evaluation with the addition of advanced communicating devices, which operated using a data platform provided by a software-as-a-service (SaaS) contractor. The remote monitoring technology is designed to continuously transmit metered data to a secure, cloud-based repository via cellular network. Remotely monitored points included: compressor circuit amperage, outdoor fan circuit amperage, groundwater pump circuit amperage (for GSHPs), and supply air stream temperature and relative humidity. Field engineers supplemented the communicating meters with non-communicating meters on supply/return groundwater loop piping (for GSHPs) and various spot measurements of voltage, amperage, and real power at different heat pump operating modes and speeds.

Intensive M&V Methods

For 12 sites evaluators conducted higher-rigor M&V with the objective of collecting real-world performance data to inform the 125 core sites and to reveal potential areas of focus in future studies. The intensive metering sites were selected to represent at least one of each major type of heat pump (e.g., ducted ASHP, DMSHP, GSHP) in each of New York's climate zones. The intensive approach supplemented the core protocol with long-term metering of true RMS power on each of the relevant power circuits identified above, long-term metering of temperatures and relative humidities before and after the heat pumps' coils, and spot measurements of delivered airflow at different modes/speeds using a balometer or flow hood. The supplementary intensive meters were non-communicating devices. Intensive site data allowed evaluators to compare at each metering interval the installed heat pump system's power draw with its delivered heating Btu. As heating performance increases with milder outside air temperatures, evaluators created curves that characterize the weather-dependence of each high-rigor site's heat pump performance.

Site-Specific Analysis Methods

Figure 3 illustrates the methodology for impact analysis of M&V data. Analysts processed metered data to characterize the heat pump's heating/cooling loads and operational patterns. Heat pump operation data was correlated with outside air temperatures over the metering period to determine the weather effects on heat pump operation. These correlations were extrapolated over a full year using typical weather data for the most proximate weather station. To quantify baseline energy usage, in the absence of non-routine events such as changes in occupancy, we assigned the heat pump's annualized heating output to the preexisting, code-compliant, or other alternative system. The evaluation team quantified annual energy impacts for each metered heat pump system by comparing the heating loads and performance efficiencies between baseline and as-built conditions. Final, site-specific impact results include savings or penalties by fuel: electricity, natural gas, and delivered fuels, as applicable. To develop program-wide savings, site-specific results were expanded to the population of participants using the M&V sampling weights defined by equipment type and climate zone strata.

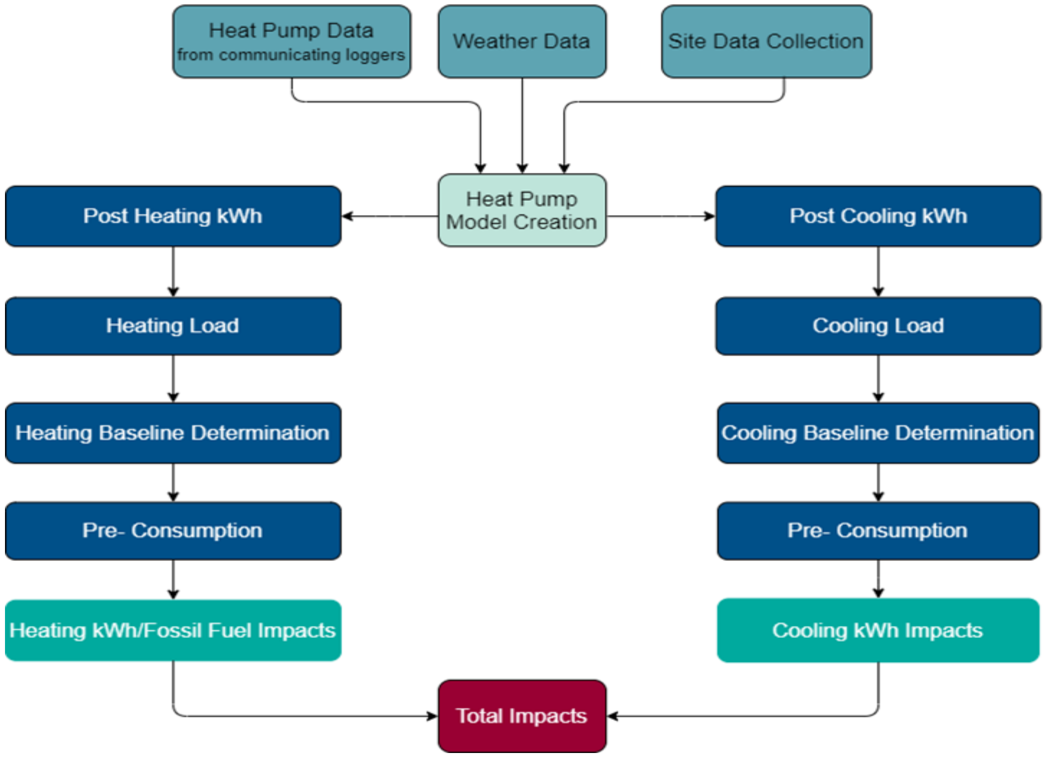

Figure 3. Impact Analysis Methodology for Phase 2 M&V Data

M&V Results

Comparison with Billing Analysis

Figure 4 compares M&V results with billing analysis results (moderate screening).

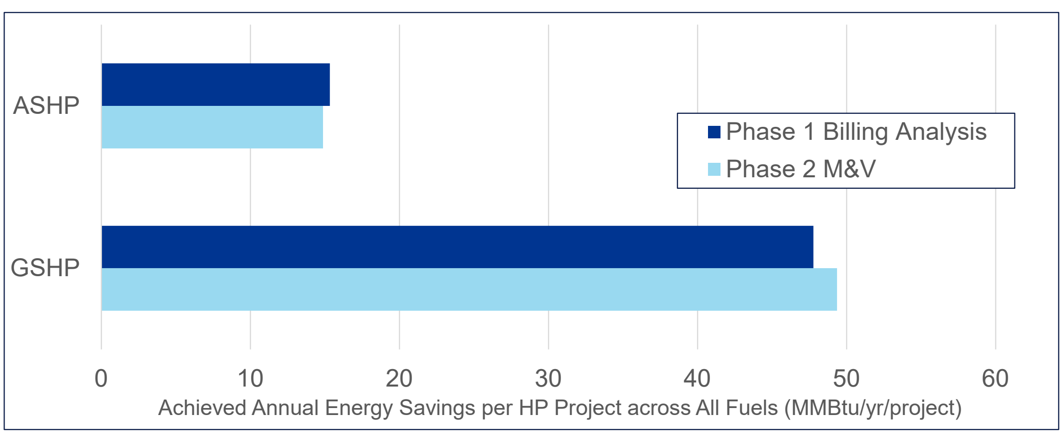

Figure 4. Comparison of Phase 1 and Phase 2 Savings for ASHPs and GSHPs

Phase 2 per-project savings closely resembled that of Phase 1. It is important to note that Phase 1 savings include impacts during heating and cooling seasons, while at the time of this writing, Phase 2 includes only heating impacts. We are currently analyzing the M&V impacts during the cooling season and expect that Phase 2 savings will slightly increase as a result. Nonetheless, Phase 2 results demonstrate the reasonableness of Phase 1's preliminary at-the-meter analysis.

The evaluation team investigated results by variables of interest to explore opportunities for customer targeting and savings optimization. Figure 5 illustrates Phase 2 per-project results as a function of customer-reported responses to the question "Do you still use your preexisting heating system(s) to supplement the heat pumps?" Customers categorized under "no" include those who decommissioned the preexisting fossil-fuel heating equipment as well as electric heat customers that fully transitioned from the preexisting resistance system to heat pumps.

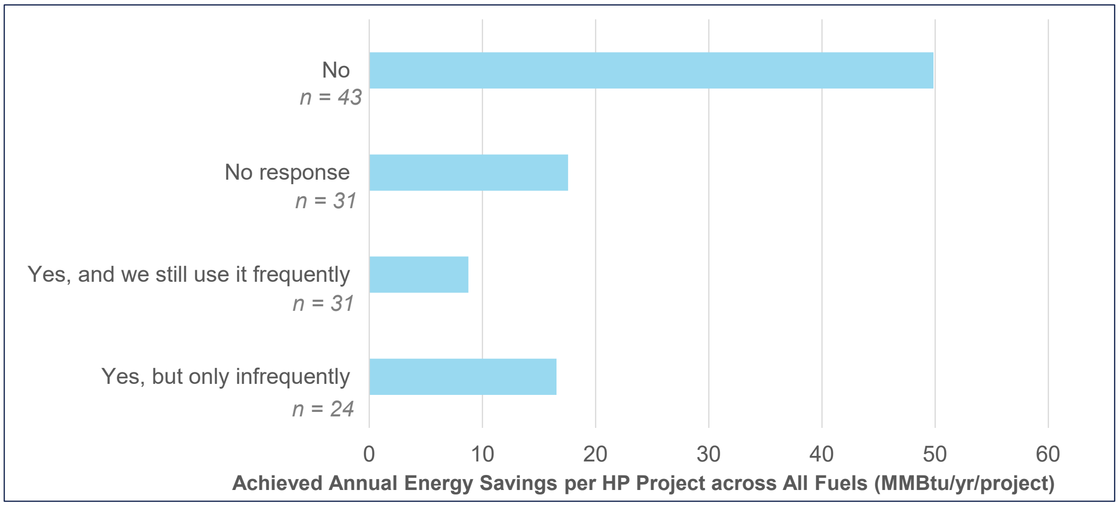

Figure 5. Phase 2 Results by Customer-Reported Use of Preexisting Heating System(s)

Phase 2 showed similar variation as Phase 1, demonstrating that exclusively-used heat pumps outperformed those used in conjunction with other heating systems. Figure 6 illustrates the variation of per-project savings by preexisting heating fuel.

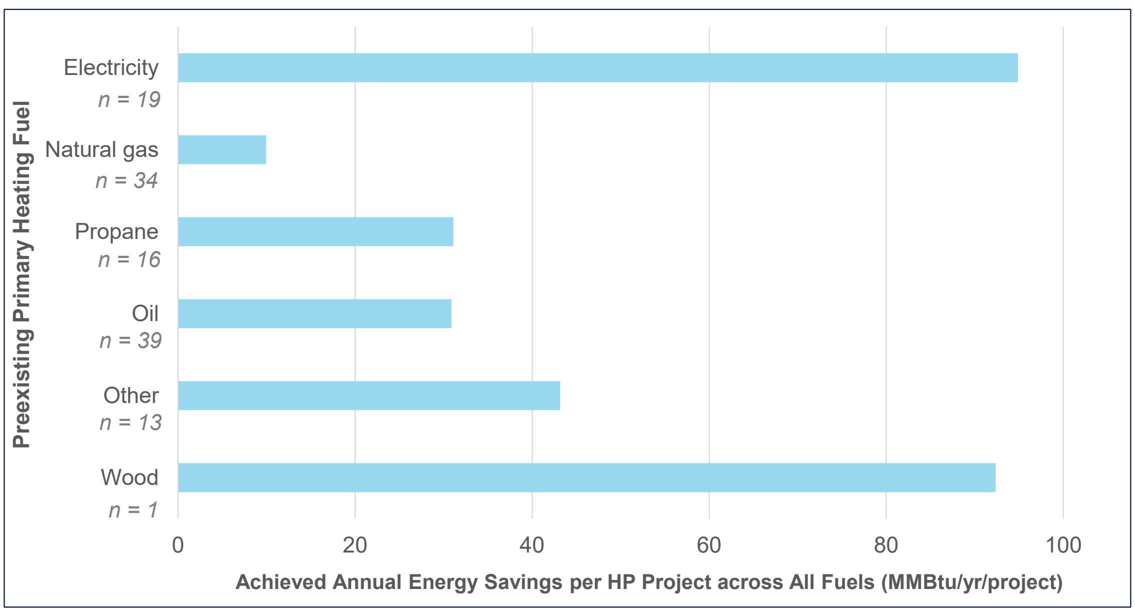

Figure 6. Phase 2 Evaluated Heating Savings by Preexisting Heating Fuel (ASHP and GSHP Combined)

We observed notable differences in performance among delivered fuels, natural gas, and electricity. Systems displacing delivered fuels (oil, propane) outperformed systems displacing natural gas

We hypothesize that gas-fired systems were more likely to remain online and in use than oil- or propane-fired systems, primarily due to the relative affordability and stability of natural gas in New York. Heat pumps displacing preexisting electric systems performed best, indicating higher likelihood of complete removal of electric resistance heating systems.

Impacts by Fuel

Heat pumps have garnered significant interest due to their ability to efficiently offset carbon-intensive fossil fuels. Quantification of fuel-specific impacts is therefore crucial to measuring the success of heat pump installations. Figure 7 illustrates the fuel-specific impacts, including beneficial electrification, for ASHPs within the evaluation sample of 97 ASHP projects. Beneficial electrification, as illustrated by the orange bar, indicates the new site-level electric heating load introduced by the rebated ASHPs as a result of displacing fossil fuels.

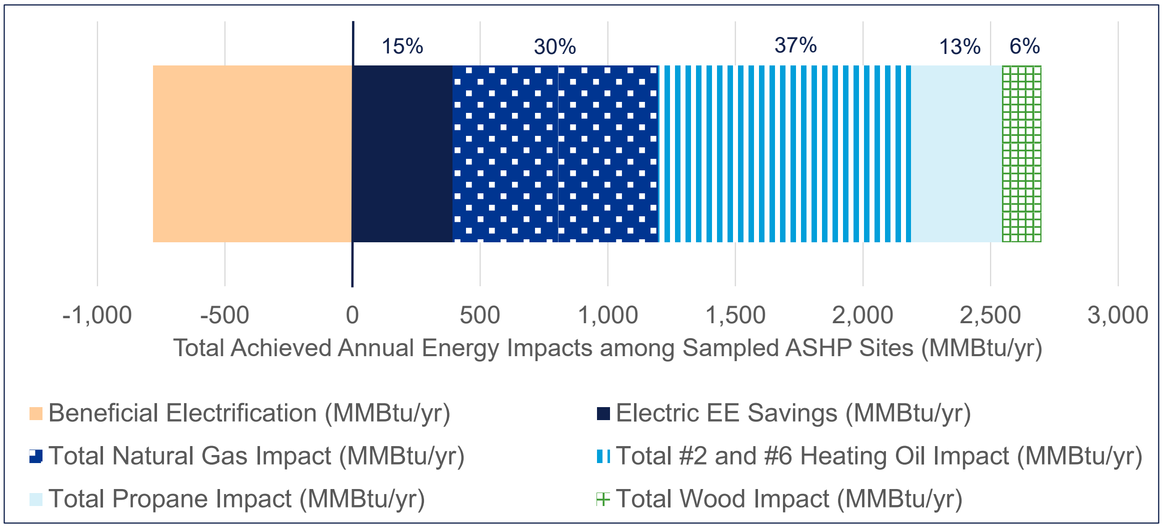

Figure 7. Phase 2 Achieved ASHP Heating Impacts by Fuel among Sampled Projects, Converted to Site MMBtu

Figure 8 similarly presents fuel-specific GSHP impacts. Due to more comprehensive tracking data for GSHP projects, we were able to expand this analysis to the full population of 470 GSHP projects.

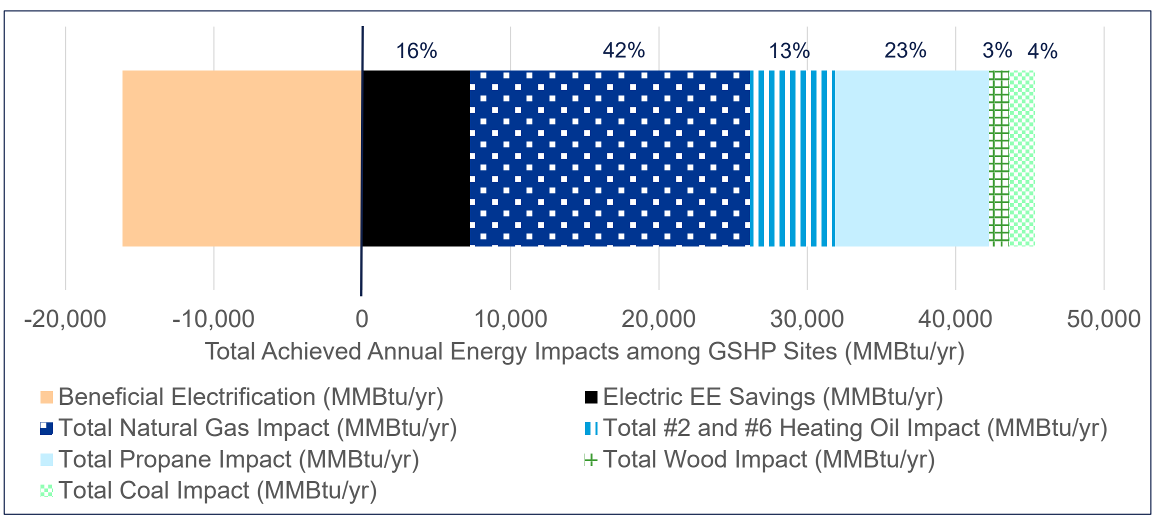

Figure 8. Phase 2 Achieved GSHP Heating Impacts by Fuel among Full GSHP Population, Converted to Site MMBtu

For both ASHPs and GSHPs, evaluators determined significant savings shares for natural gas, fuel oils, and propane. Comparison of beneficial electrification (penalty in orange) and fuel-by-fuel savings illustrates the compelling case for heat pumps—for every MMBtu of new electric load, the installed heat pumps saved approximately 3 MMBtu across all fuel sources.

Improving Heat Pump Savings Claims

Phase 1 billing analysis provided an initial assessment of at-the-grid impacts but limited the evaluators' ability to pinpoint reasons for unexpected heat pump performance. As explored in this section, equipment-level M&V allowed evaluators to investigate heat pump operation more deeply and identify opportunities to right-size heat pump savings claims moving forward. The authors have identified three best practices for program administrators estimating heat pump savings.

Estimating Heat Pump Output

Phase 1 and Phase 2 illustrated that ASHPs generally did not operate as whole-home heating systems. With the prevalence of DMSHPs rebated in 2018, this finding was expected. Evaluators compared the annual heating output of all 97 sampled ASHPs (vertical bars) with an average, whole-home, annual heating load value referenced from a Northeast Energy Efficiency Partnerships study on heat pump study (NEEP 2015).

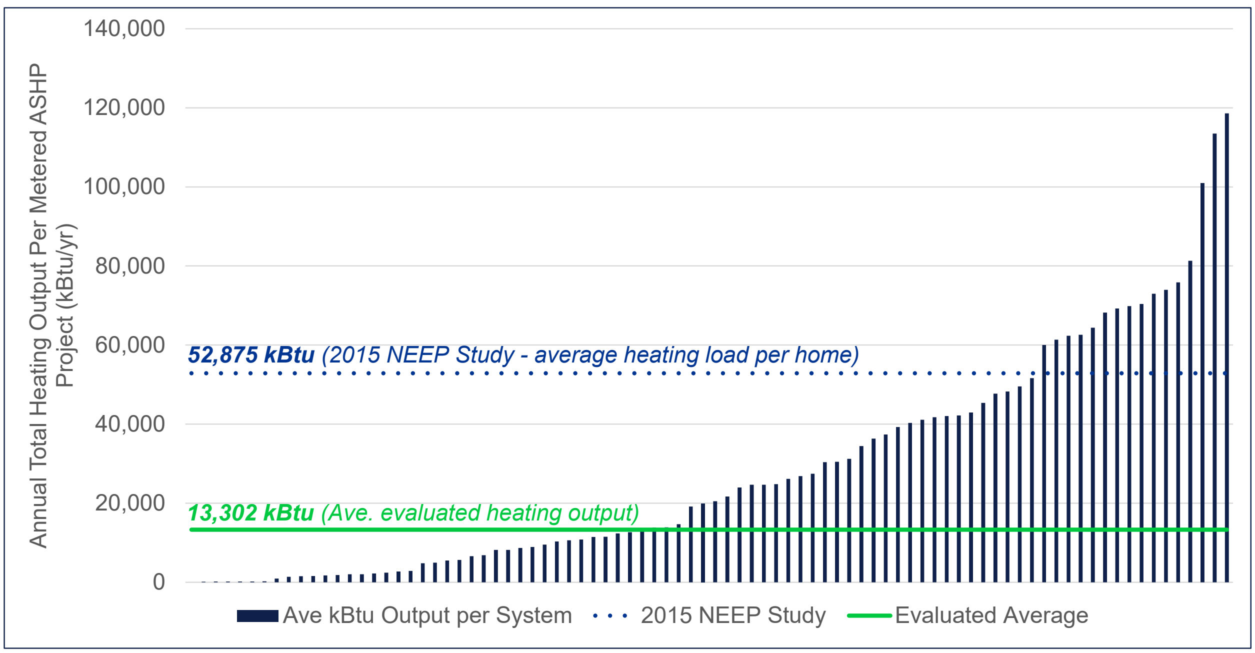

Figure 9. Comparison of Evaluated and Whole-Home Heating Output among Sampled ASHPs

On average, evaluated ASHPs delivered about a quarter of a typical home's annualized heating load. After comparing equipment-level heating outputs with rated heating capacities, we determined an average equivalent full-load heating hours (EFLHH) value of 549 for ASHPs. As seen in the leftmost part of the figure, some evaluated ASHPs provided negligible heat over the course of a year. As is currently being confirmed in our analysis of cooling impacts, some units were purchased primarily for cooling. Less frequent operation led to reduced opportunity for savings as compared with more carbon-intensive systems. While the body of heat pump evaluation research is rapidly growing, other DMSHP studies in the Northeast have shown similar findings of approximately 450 EFLHH (MA/RI 2016). Figure 9 illustrates opportunities for right-sizing program savings assumptions. For DMSHPs, total installed capacity provides a more realistic starting point for "best case" savings, rather than a whole-home heating output value.

GSHPs operated more frequently in heating mode but also exhibited a wide range of operation, as illustrated by Figure 10's analysis of EFLHH. We quantified EFLHH in two ways, using the annualized heating output divided by either the rated GSHP capacity (blue line) or contractor-estimated Manual J heating load (green line) as required by the program and included in tracking data.

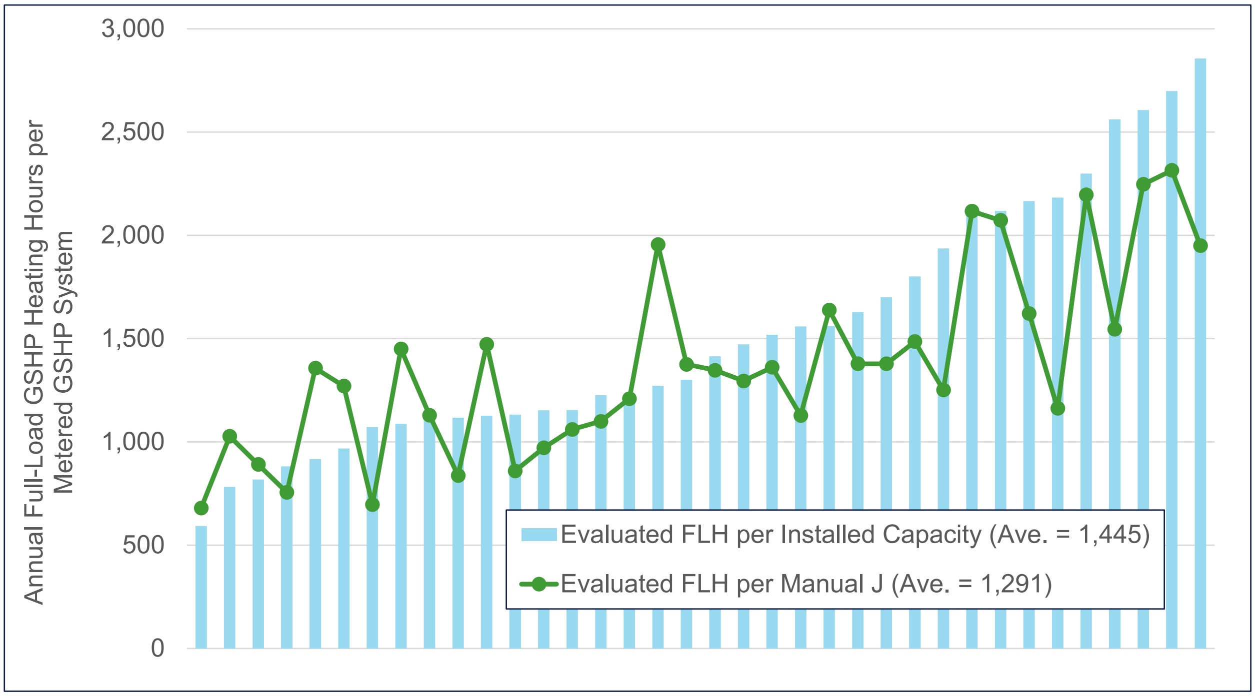

Figure 10. Comparison of Evaluated and Program-Assumed EFLHH among Sampled GSHPs

For GSHPs, our comparison of capacity- and Manual J-based EFLHHs showed that contractors generally right-sized the systems to estimated heating load. On average, GSHP operation resembled TRM-recommended full-load heating hours values in the Northeast region (CT 2021, MA 2020, NY 2020).

Eligibility Screening and Tiered Incentives

Figures 2 and 5 illustrate the impact of the preexisting heating system use on achieved heat pump savings. Program administrators should train participating contractors to collect and track credible information on the status of preexisting heating systems. This information will be crucial for differentiating between whole-home and partial ASHPs as discussed above. Program designs that target full displacement or that creates full and partial displacement "tiers" will be better aligned.

Customized Baselines

For heat pump installations in new construction or end-of-life scenarios, savings should be informed by the customers' preferred alternative systems and fuel choices in the absence of the program. Program tracking databases should intake these variables and triangulate the most appropriate baseline against which new construction or end-of-life performance is measured. Accurately tracking displaced fuel type is particularly critical for programs with electrification and carbon reduction goals.

When and How to Use Heat Pump Evaluation Methods

The evaluation upon which this paper is based used multiple evaluation methods within a single study, providing an opportunity for methodological comparisons. As demonstrated, multiple provide useful results. This section addresses how to choose the right method for a particular evaluation.

In impact evaluation, residential HVAC system performance is most often evaluated using one of four methods (EVO 2012). Listed in order of typically increasing cost, they are:

1. Program-wide analysis of premise-level energy consumption of all participating homes using utility billing data alone,
2. Site-specific analysis of premise-level energy consumption using utility billing data with survey or on-site observed data (IPMVP Option C),
3. Site-specific building simulation models calibrated using utility billing data with survey and on-site observed data (IPMVP Option D),
4. Site-specific analysis based on equipment level metering, interview, and observational data (IPMVP Options A or B, depending on metering rigor).

While there is no single best approach, answers to a series of questions regarding budget, schedule, and technical objectives can help to make an informed choice. All of this discussion presumes the program collects sufficient information to identify and contact residents that received the heat pumps; this presumption may not be true for upstream or midstream programs. Figure 11 summarizes the advantages and disadvantages of each method.

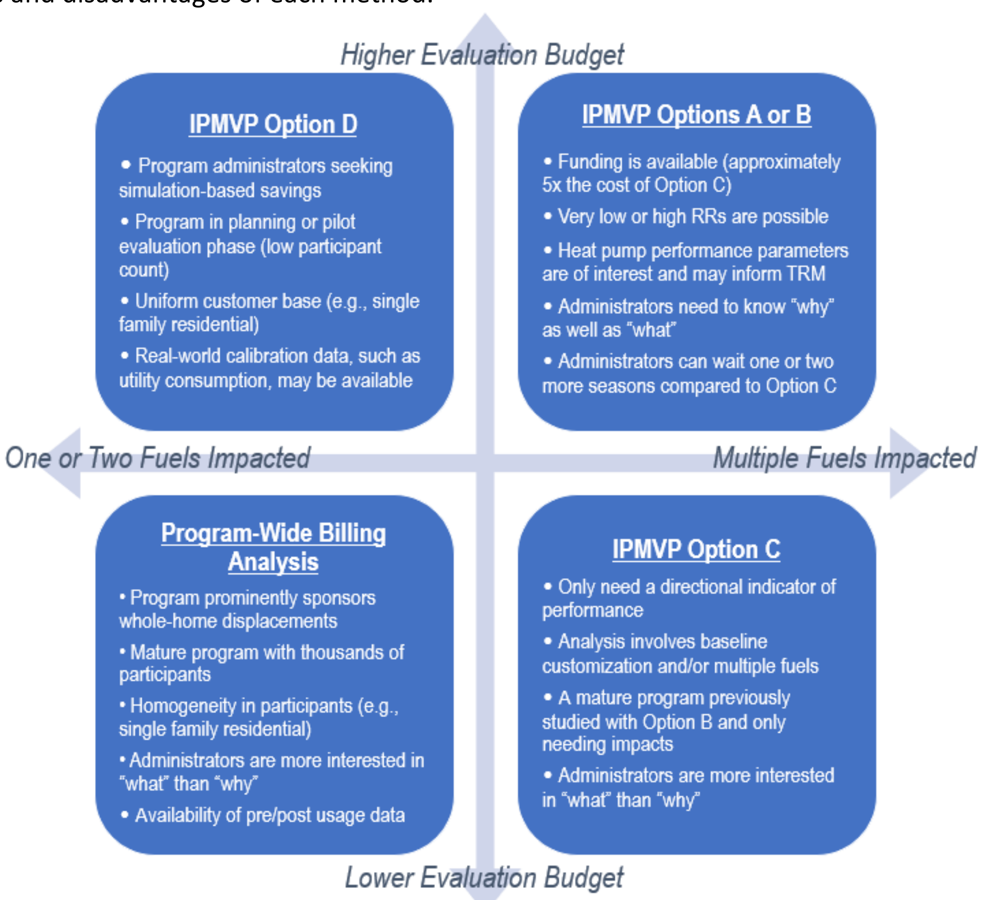

Figure 11. Quadrant of Most Appropriate Evaluation Methods by Evaluation Budget and Complexity of Fuels

Based on the evaluation team's experience, the first method above, **program-wide, premise-level consumption-based analysis** of every participant's home without paired interview or on-site data, is likely to be effective for heat pumps in uncommon and narrowly constrained circumstances—e.g., the program specifically targets a single displaced heating energy, electricity, in a known event type (retrofit, new construction/expansion, or replace on failure). The analysis shows that the volatility introduced by varying baseline fuels is too much for premise-level analysis to overcome without site-specific information, especially in a jurisdiction like the one studied, when the alternate fuels for the home are a broad combination of regulated and unregulated fuels.

The third listed method, **building simulation modeling**, can be a powerful tool for program design using prototypes and for pilot program testing where high investment per home is practical. It is especially valuable in projecting the impact of deep savings programs with multiple efficiency measures per home. It is less attractive for residential HVAC program evaluation that require many sample points. As Figures 9 and 10 illustrate, we found dramatic variation in EFLHH per customer, and customer-reported description of use is only moderately indicative of that variance. Uncertainty of use is less related to home construction than behavior. When this is the case, simulation is a less attractive option.

The fourth method, **equipment-level metering**, is the most accurate method for individual site estimation. It has more explanatory power than other methods. This is particularly important when the evaluated savings vary dramatically, as it did in the subject evaluation. Metering heat pumps directly shows not only how many full load hours they operate (though, sometimes premise-level analysis can do this as well) but also how frequently the heat pumps run, how loaded they are when they do operate, and—when other heating sources are also metered simultaneously—how often the heat pumps are primary or secondary heat sources. When other proxy variables such as supply air temperatures are metered, analysts can learn more about heat pumps' ability to meet comfort expectations and in-field efficiency. Regarding calendar time to results, they may require somewhat more time than premise-level metering-based analysis because the typical year of post-installation data collection cannot start immediately upon unit installation. The availability of near-real-time data collection reduces but does not eliminate this drawback compared to using utility data.

The second method, **site-specific analysis of premise-level energy consumption** with interview-based data, was expected to provide reasonable, preliminary savings results, particularly for whole-home heating systems, and did so, even with fuel switching. It was not presumed in advance to be as effective for partial displacement heating conditions— a common scenario for DMSHPs. Premise-level consumption analysis required intensive surveying, a relatively large sample, and collecting and cleaning consumption data for all relevant fuels. But as evidenced by similar Phase 1 and Phase 2 savings for ASHPs, even with the prevalence of partial-displacements DMSHPs in the sample, premise-level analysis proved to be a viable option for such installations.

Conclusion

This NYSERDA heat pump study demonstrated the benefits and shortcomings of two evaluation approaches. Phase 1 analysis of building-level utility consumption data provided preliminary ASHP and GSHP savings estimates of 15 and 46 MMBtu savings, respectively, per year per project across all fuels, including electricity at site. Phase 2 M&V results closely resembled Phase 1—15 and 49 MMBtu savings per year per project for ASHPs and GSHPs, respectively—despite the high share of partial-displacement DMSHPs in the participant population. While significantly less expensive than Phase 2, Phase 1 was limited in its ability to pinpoint why evaluated savings deviated from expectations. Phase 2 equipment-level M&V data allowed evaluators to comprehensively examine this variation and recommend best practices for estimating scalable, accurate savings for heat pump installations in New York that are expected to grow by orders of magnitude in the next decade. Such best practices include: collection and tracking of credible site-specific data on preexisting systems and alternative choices, application of customized baselines established by that information, and use of rated equipment capacities to determine reasonable savings values in partial displacement scenarios. Phase 2, however, required significant budget and time commitments, though remote-communicating capability allowed the team to continuously analyze the data among different seasons. To assist evaluators planning future heat pump research efforts, the authors have summarized the advantages and disadvantages of each method depending on program complexity, evaluation budget, data availability, and time constraints. While these best practices are presented in the context of a heat pump evaluation, their principles apply to any impact evaluations that warrant mixed-rigor approaches to programs with varying levels of data availability.

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