Results May Vary: Are Variable-Speed Heat Pumps Always Better?

Chelsea Liddell, DNV
Cynthia Austin, SMUD
Amrita Chakraborty, SMUD

ABSTRACT

Sacramento Municipal Utility District (SMUD) has committed to eliminate greenhouse gas emissions from its generation by 2030, while maintaining reliability and low rates. It has programs to help its customers electrify their homes, reducing emissions while increasing the amount of electricity it sells, thus allowing continued low rates.

It is important for SMUD to understand the impact of electrification - both additional kWh load that generates revenue and additional peak kW load that could require infrastructure upgrades and more peak-hour generation. DNV analyzed data from homes that participated in SMUD's Advanced Homes Solutions rebate program to measure these impacts.

Specifically, DNV compared usage data from homes that installed either a dual-speed or variable-speed heat pump. SMUD expected that variable-speed heat pumps would be more efficient than dual-speed heat pumps.

DNV's analysis of whole-home electricity usage before and after heat pumps were installed included statistical methods designed to correct for:

- pre/post installation differences in usage caused by weather
- pre/post installation differences caused by societal changes
- differences between households with different heat pump types, including pre-installation differences in space conditioning demand.

DNV did not find statistically significant differences between heat pump types in either:

1. analysis of raw electricity usage data or
2. analysis using statistical methods to adjust raw data as described above.

Additional analysis of site-specific data did not yield insights into the reasons for this surprising result. Further research is needed to understand how the expected efficiency gains of variable speed heat pumps can be realized in installed settings.

Introduction

Heat pumps are one of the central technologies involved in the effort to electrify energy consumption. Many heat pumps replace fossil-fuel burning heating units, which result in carbon dioxide emissions. The fuel for many of these units is methane, which is itself a potent greenhouse gas, and a significant fraction leaks into the atmosphere before it reaches the heating unit (Chen et al. 2022). Finally, the gases emitted by these units have also been associated with negative health effects for home inhabitants (Michanowicz 2022). Heat pumps may also replace electric resistance heating, which heats much less efficiently.

Heat pumps' efficiency derives from the fact that, instead of burning fossil fuels or using electric resistance to create heat, that is, converting one type of energy to another, they rely on compressors to warm a refrigerant above the indoor air temperature[1], such that heat then transfers to the air in a home as it is passed over a heat exchanger. That refrigerant is then allowed to expand to a much cooler temperature outside, such that it is below the outdoor ambient temperature, and absorbs heat. The process then repeats. Because heat pumps do not simply convert energy between types, they can be much more efficient. For example, electric resistance heating is about 100% efficient (US DOE 2026a) but heat pumps are usually around 250-350% efficient (Teener 2023). Efficiency of fossil fuel heating systems is lower than either electric option, 56-98% (US DOE 2026b).

SMUD is promoting gas to electric conversions for space conditioning because they mutually benefit customer, community, and SMUD interests. First, SMUD is committed to a 100% carbon-free power supply by 2030. This means that all the electricity used for heat pump operation will be carbon-free, at any hour of the day, strongly benefiting the community. Second, SMUD is an electric-only utility, so any conversion from fossil fuel consumption to electricity use yields increased revenue for SMUD. Because SMUD is a publicly owned municipal utility, this increased revenue goes toward ensuring reliable, affordable, and clean electricity delivery, directly benefiting rate-payer customers. Lastly, due to its rate structure, SMUD's customers benefit through lower net energy bills.

Heat Pump Types Studied

This study considered three basic types of space-conditioning heat pumps, with different associated efficiencies. Single-stage heat pumps are the most basic: they run at a constant speed while operating, providing a constant amount of heat. They cycle on and off to provide the right amount of heat for the home and conditions, providing additional heat, when needed, by being on more often. Dual-stage or two-stage, heat pumps can operate at two different speeds. Finally, variable-speed heat pumps operate at a range of different compressor speeds and are designed to provide efficient heat over their operating range. These heat pumps change the speed at which their compressor is operating to adapt to different heating or cooling needs, turning off only at a low threshold of output need.

Reported efficiency ratings, which are based on measured operation under specified laboratory conditions, indicate that variable speed heat pumps should use the least energy per unit of heat transferred for heating or cooling. For example, in a 2015 paper, Holloway et. al. consider a range of heat pumps for analysis: the dual-speed heat pumps have an average efficiency rating (SEER) of 16, and the variable-speed heat pumps have an average rating of 21, about 30% higher (Holloway 2015). Similarly, the dual-speed heat pumps have a HSPF of 8.5 and the variable-speed heat pumps have a HSPF of 10, about 19% higher (Holloway 2015). In this study, the average SEER was 16 for dual-speed heat pumps, and 17.5 for variable-speed heat pumps. Additionally, the US Department of Energy reports that variable-speed heat pumps "keep the air moving at a comfortable velocity…maximizing electrical savings" (US DOE 2026c).

SMUD Electrification Programs

SMUD's decarbonization goals mean that it is focused on electrification incentive programs, and heat pumps have played a central role in those programs. That includes its Advanced Homes Solutions programs, which provides rebates on HVAC system replacements to

[1] This process is analogous for water heating, except that water is heated instead of air

single-family residents or homeowners of up-to-four-unit multi-family dwellings. This includes rebates for customer switching from electric resistance heating (“electric-to-electric”) and from gas heating (“gas-to-electric”). SMUD chose to provide higher incentives for variable-speed heat pumps, under the assumption that they would provide more energy savings relative to the systems they replaced by requiring less electricity per unit of heat output, relative to single- or dual-speed heat pumps. There is no requirement that these be whole-home conditioning systems. The incentive structure for the program is shown in Table 1, below.

Table 1. Rebates available by measure and customer type (during evaluated years, 2020-2022)

Customer type	Intervention	Eligible rebate
Electric-to-electric	Two-stage heat pump	$750
	Variable-stage heat pump	$750
Gas-to-electric	Two-stage heat pump (15 SEER2 minimum[2])	$2,000
	Variable-stage heat pump	$3,500
	Panel upgrade	$3,500

Program Evaluation

It is important for SMUD to understand the impact of its programs on customer electricity use and whether these programs can be improved. In this case, SMUD sought an evaluation to quantify the different impacts associated with different types of heat pumps. The evaluator, DNV, measured differential impacts on:

- Peak kW usage
- Total annual kWh usage

DNV also conducted a process evaluation, surveying participating customers and interviewing contractors to provide insights to help explain impact results and improve the program. This evaluation was conducted for program years 2020 through 2022.

Methods

At a high level, this evaluation compared observed whole-home electricity use before and after heat pumps were installed. This energy impact of heat pump installation was then compared for dual-speed and variable-speed systems.

In addition to looking at the raw electricity usage data, DNV used statistical methods to correct the data for factors, aside from the heat pump installation, that could cause changes in electricity usage between the pre- and post-installation periods. First, they corrected for societal-level changes in energy use, as we saw with COVID or might see with increased technology use. Second, these methods adjusted for any differences in weather between the two periods.

To compare energy use changes between heat pump types, DNV also used statistical methods to correct the data for possible differences between households that choose two-stage or

[2] This is the only category with a minimum SEER2 rating

variable heat pumps. This includes pre-installation differences in demand for heating and cooling.

Because DNV did not have data on gas usage, in cases where homes switched from gas to electric heating, it was only possible to look at post-installation electricity usage. In these cases, other data was used to estimate of pre-installation gas heating energy usage.

The specific methods used for each of these analyses are described below. This begins with a description of statistical adjustments to calculate corrected pre- to post-installation period usage differences, followed by methods used to adjust for differences between households, allowing comparison of impacts by heat pump type. Finally, we discuss the process evaluation components.

Electric-to-electric impacts

To explain the steps in this process and the purpose of each step, we start with the analysis of electric-to-electric installations, as the electric Advanced Metering Infrastructure (AMI) data[3] for these contains all the information on both heating and cooling, before and after the heat pump was installed.

Step 1: Customer matching, which adjusted for population-level pre-installation to post-installation energy usage trends outside of the program influence (e.g. COVID-19 changed all customers' energy use). Participating customers were matched to similar customers who did not receive a heat pump in the analysis period. Energy usage deltas observed in these similar customers were assumed to be a result of societal-level trends, rather than heat pump installation impacts, and could be, essentially, subtracted from participant deltas to leave only heat pump impacts.

- **Goal:** Allowed the removal of population-level trends in energy usage (non-program effects) from the estimate of pre-installation to post-installation heat pump effects.

Step 2: Weather adjustment, which adjusted for pre-installation and post-installation differences in temperatures. This was done by creating a customer-specific regression model of how each system's energy usage changes with temperature. For each customer and HVAC system, energy usage was then predicted for a typical temperature year.

- **Goal:** Removed differences in energy usage associated with different weather (temperatures) in the pre-installation and post-installation period.
- **Output:** Weather-normalized energy consumption. That is, hourly energy use associated with each customer and HVAC system, normalized to a typical temperature year.

Step 3: Difference-in-difference regression model. In this step, the weather-normalized energy consumption for both participating customers and matched comparison customers was used in a regression model that estimated the impact of the heat pump installation. In particular, weather-normalized pre-post differences for

[3] i.e. SmartMeter hourly usage data

both participant and matched comparison group customers were modeled as a function of a treatment dummy variable, which captures the difference-in-difference or program impact estimate.

- **Goal:** Estimated heat pump installation impact on energy usage, relative to pre-installation usage.
- **Output:** Estimate of heat pump installation impact on energy usage.

For electric-to-electric customers, this process was performed for each metric of interest – total and seasonal kWh impacts, as well as peak period impacts.

Gas-to-electric impacts

Unfortunately, for gas-to-electric customers**,** no gas data was available for winter heating load before the heat pump was installed. Therefore, to estimate the impacts of these heat pump installations *on winter load*, DNV used available household characteristics to estimate the pre-installation gas usage. This estimation was based on California Residential Appliance Saturation Survey (RASS) data for SMUD's climate zone. This survey collects information on energy-using appliances, behaviors, and household characteristics from representative respondents throughout the state. Based on this data, the RASS database provides estimates of gas-heating unit energy consumption (UEC). Gas heating UEC reflects specific occupant and household characteristics, including home size, home age, type of home (standalone single-family or duplexes/row houses, etc.), the number of occupants, and the type of heating system present in the home (central furnace, wall furnace, gas baseboard).

DNV generated average RASS gas UEC estimates for the different combinations (bins) of participant home sizes, ages, and types among these respondents. For some participant combinations that did not exist in RASS (such as standalone single-family homes with 1,001 to 1,250 square feet with central gas furnaces built between 2006 and 2012), DNV used fitted values from regression models of gas UEC values on these characteristics. DNV assigned the average or predicted bin-level RASS gas heating consumption estimates to gas-to-electric households based on their bin values to approximate their gas heating consumption before program installation.[4] This is, undoubtedly, a very rough estimate, given the real-life variation in energy consumption between similar homes, so the results based on this method were considered less reliable than cooling impacts and electric-to-electric conversion impacts.

This gas usage data is already weather-normalized, so **Step 2**, above, was already accomplished. However, without actual gas usage data, customer matching (**Step 1**) was not possible. Therefore, the equivalent of **Step 3** was just a simple pre-installation (RASS gas use estimate) to post-installation (weather-normalized AMI data) difference. Therefore, in the gas-to-electric customer analysis, we cannot adjust for population-level trends, but (from analysis of

[4] DNV considered using the heating output of the newly installed system as an imperfect proxy for pre-period heating demand. While the heating capacity of the installed equipment needed to estimate heating output is available, obtaining accurate estimates of heating or effective full load hours (EFLH) to convert this capacity to heating output is challenging, especially for variable-speed equipment. It requires substantial levels of inferences based on disaggregated kW draw, indoor and outdoor air conditions, and product performance data. Additionally, information about the old system, including heating or cooling capacity, would also have been useful but was not available for the current analysis.

comparison group customers in the study with electric-to-electric retrofits) we have found they are small relative to the impact of the heat pump installation.

For summer loads and peak hour loads, gas-to-electric installation impacts were estimated in the same way as for electric-to-electric customers, as described above.

Heat Pump Type Effects

To estimate the influence of heat pump compressor type on program impacts, DNV attempted to remove any effects associated with other home and participant characteristics. To do this, the above weather-normalized pre-post energy usage delta was included in a multivariate regression model that included both an indicator for program participation, heat pump type, and home/participant characteristics. In this model, the interaction of heat pump type and program participation yielded the estimated difference in impact between heat pump types.

This statistical modeling allows the analysis to remove differences in impact that may be due to the tendency of different compressor types to be installed in, for example, different size homes. We can then isolate the impact specifically associated with compressor type. The variables included in this regression are:

- compressor type (dual or variable speed)
- home size (square feet of conditioned space)
- home age
- home type (standalone versus attached single-family homes)
- number of occupants

Process evaluation

For the process evaluation, DNV used data from two sources:

1. **A participant web survey** conducted by SMUD to learn more about customer satisfaction, reasons for purchasing a heat pump, changes to utility bills since installing the heat pump, sources of information, attitudes, and household and demographic information. Survey respondents included 146 two-stage system owners and 248 variable-speed system owners.
2. **In-depth interviews (IDIs)** with HVAC contractors. These IDIs provided important insights into the differences in installation, maintenance, and customer satisfaction with different heat pump types. After multiple rounds of outreach for a total of 13 contractors, four participated in in-depth interviews.

Results

Because of the importance in this evaluation of examining how savings differ with heat pump compressor type, we report both (1) differences in savings after only weather normalization (no difference-in-difference correction for population level trends or regression correction for different types of homes tending to get different types of heat pumps), and (2) differences in savings after all the analysis steps to correct for potential sources of bias. In neither the examination of energy nor that of demand impacts was there a statistically significant difference between dual-speed and variable-speed heat pumps. It is important to remember that winter (cooling) load results for gas-to-electric conversions are less precise than the other estimates because no customer-specific pre-installation gas usage data was available, so estimates based on similar homes were used for pre-installation period energy consumption.

Energy Impacts

1. **Unmodeled pre/post differences.** Examining data that has only been weather normalized, there are only subtle (and not statistically significant) differences between the variable-speed and two-stage savings (see Figure 1).

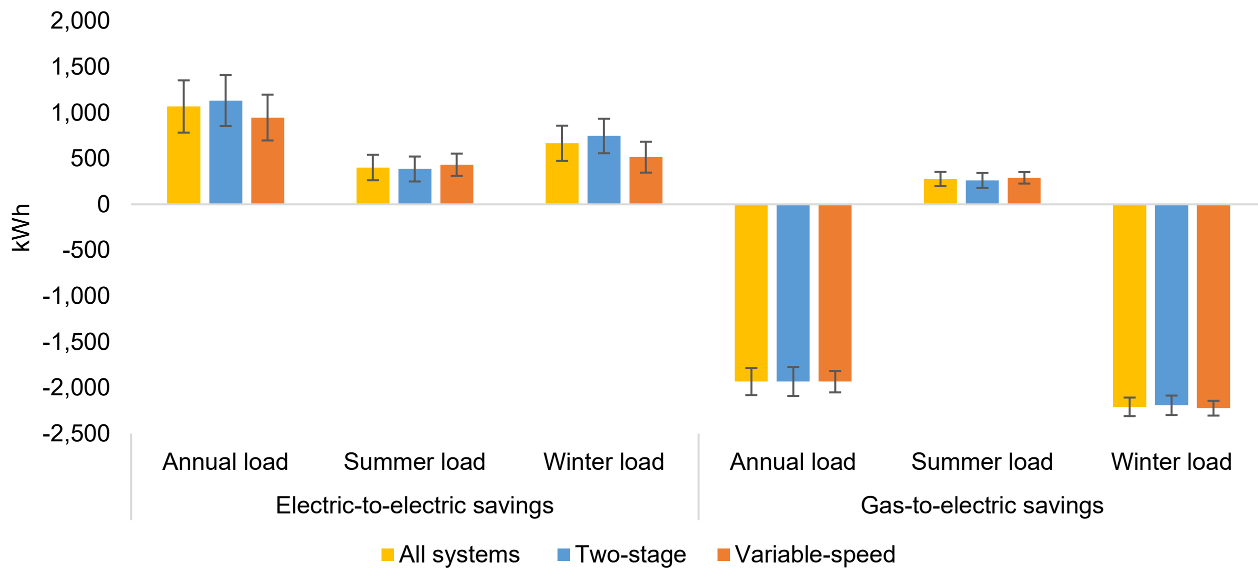


Figure 1: Weather-normalized energy consumption savings (kWh) – overall and by technology type, with 90% confidence interval

2. **Technology impact analysis.** When using methods that correct for population-level trends and other factors that might cause savings differences, the results for both electric-to-electric and gas-to-electric customers again show no statistically significant difference in savings between the two-stage and variable-speed heat pumps. Table 2 summarizes energy impacts by technology type.

Table 2: Summary of energy impact (kWh) by customer and technology type

Measure type	Model	Two-stage		Variable-speed	
		Savings (kWh)*	Relative precision**	Savings (kWh)*	Relative precision**
Electric-to-electric	Annual	1,305	0.22	1,128	0.31
	Winter	875	0.21	652	0.36
	Summer	431	0.33	477	0.37
Gas-to-electric	Annual	-1,544	0.08	-1,531	0.08
	Winter	-1,786	0.05	-1,800	0.04
	Summer	239	0.30	269	0.25

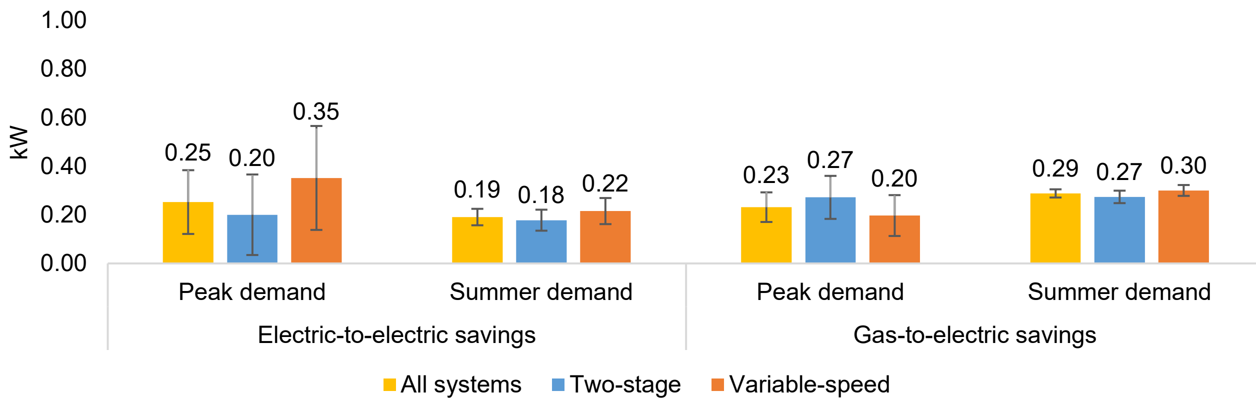
* Positive values indicate savings or decrease in consumption and negative values indicate increase in consumption
**Relative precision values with 90% confidence

Demand Impacts

As with energy impacts, for examining the effect of different compressor technologies on demand, this section includes both a comparison of impacts where the data has only been weather normalized, and a comparison of the final results that adjust for both population trends and differences in home characteristics and other heat pump attributes.

1. **Unmodeled pre/post savings**. Results that only account for weather normalization are shown in Figure 2, which shows program savings (positive impact values). There is no statistically significant difference in savings by technology type, as shown by the overlapping confidence intervals.

Figure 2: Weather-normalized peak and average 5 p.m. to 8 p.m. summer demand savings (kW) * – overall and by technology type, with 90% confidence interval



* Positive values indicate savings or decrease in demand

Technology impact analysis. Again, after adjusting for population trends and home characteristics, compressor technology type shows no statistically significant demand impact difference.

Table 3 summarizes peak and 5 p.m. to 8 p.m. summer demand impacts.

Table 3: Summary of demand impact (kW) by customer and technology type

Measure type	Model	Two-stage		Variable-speed	
		Savings (kW)*	**Relative precision***	**Savings (kW)***	**Relative precision***
Electric-to-electric	Peak	0.37	0.52	0.53	0.46
	Average summer demand	0.17	0.29	0.20	0.11
Gas-to-electric	Peak	0.38	0.27	0.29	0.33
	Average summer demand	0.24	0.11	0.27	0.08

* Positive values indicate savings or decrease in consumption and negative values indicate increase in consumption
**Relative precision values with 90% confidence

Additional Exploration of Potential Causal Variables[5]

Unfortunately, an in-depth analysis of additional variables that may have caused variable-speed heat pumps to be less effective than expected did not find a clear explanation of why this expected outcome was not observed.

First, a regression of winter energy consumption on building size, occupancy, age, duct leakage, and heat pump install cost found expected relationships between these variables (positive for all), where statistically significant. No differences between heat pump types or whether heat pumps were communicating or not pointed to a reason for lower-than-expected performance of variable-speed systems.

Second, the comparison of heat pump efficiency rating to energy consumption per building square foot, by communicating or non-communicating heat pump type, showed no significant differences between systems of different efficiency ratings. As the energy efficiency rating incorporates the theoretically-more-efficient operation of variable-speed heat pumps, this is in line with the finding that in installed settings, these systems are not saving statistically significantly more energy.

Third, energy consumption per square foot is found to increase with heat pump capacity per square foot, indicating that oversizing does tend to increase normalized energy consumption. (This effect was larger for two-stage, as compared to variable speed systems.) However, there was no indication that variable speed heat pumps are oversized more often than two-stage heat pumps, which would have explained overall lower-than-expected variable speed performance.

Finally, this analysis compared retrofit costs to summer efficiency gains but found no obvious correlation between the two. This is, again, in line with the finding that variable speed heat pumps (which tend to be more expensive) were not associated with higher energy savings.

Participant Web Survey

Overall, respondents are satisfied with both two-stage and variable-speed heat pumps, with slightly stronger favorability for variable speed. Variable speed owners:

- Were, overall, more satisfied
- Were more likely to recommend those heat pumps to others
- Reported greater comfort than respondents with two-stage heat pumps

The differences were small (between 0.2 and 0.3 points on a five-point scale), but statistically significant at a 10% or greater confidence level. Regarding reason for the heat pump purchase, perception of bill impact, and maintenance, responses were more similar than different, with the exceptions that variable-speed system owners were more significantly likely to buy a system with a goal of achieving noise reduction, and significantly more two-stage system owners perceived winter savings. Survey respondents included 146 two-stage system owners and 248 variable-speed system owners.

[5] We don't have information on whether manual J was used for sizing of these installations. The installations were sized to replace the entire load of the previous heating/cooling system. Sizing relative to load is an important factor in system efficiency and we recommend additional study that includes this as a factor in energy impacts.

Contractor Interviews

DNV conducted interviews with four participating contractors. The primary takeaways included the following:

- Most installations by interviewed contractors were variable speed. When contractors did install two-stage units it was due to:
  - Customer cost sensitivity (with the price difference being exacerbated by the fact that less-premium brands sold at lower price points are also more likely to be available with two-stage control);
  - Concern regarding the customer's ability to handle more complex variable-speed thermostatic controls, especially in multi-zone ducted retrofits; or
  - Belief that variable-speed systems are less suited to retrofits with wide-ranging duct run lengths.
- Variable-speed systems are somewhat more difficult to install, mostly due to the need for proprietary controls. Auxiliary heat strips and related electrical system work also increase installation difficulty and costs.
- Three of the four contractors reported the installation of heat strips in most to all heat pump installations. Switchover temperature setpoints were reported to be between 38°F and 45°F.
- There is no consensus among contractors about which type of system will require more maintenance. Contractors note that new units come with 10-year warranties.
- Contractors agree about the need to educate customers about heat pump systems, and that the best way to use variable-speed systems is "set and forget."
- Variable-speed systems are typically more comfortable but educating customers on how to use these systems is key to that comfort. Noise is as often a factor in determining where units are installed as the unit itself.

Conclusions and Recommendations

Overall, despite lower energy use by variable-speed heat pumps compared to two-speed heat pumps in controlled lab settings and theory that supports this premise, this study found no statistically significant difference in energy use between the two types of control in SMUD homes. Figure 3 illustrates the result, providing the range of results within the 90% confidence band and the almost complete overlap between these ranges for both electric to electric and gas to electric households.

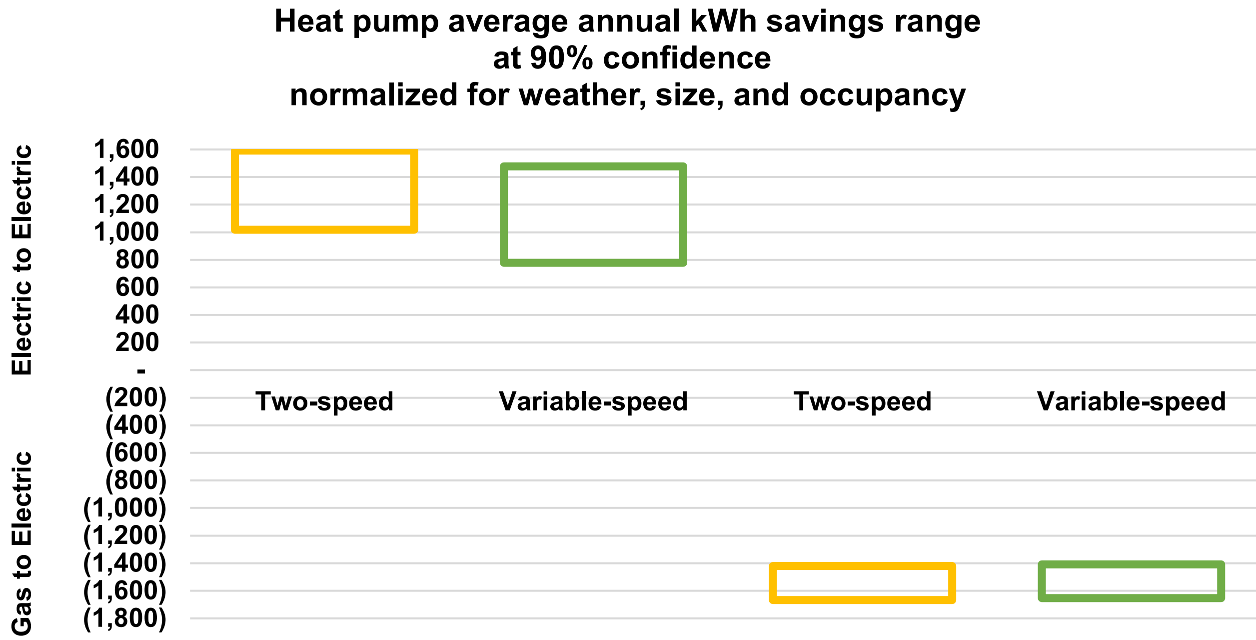


Figure 3: Heat pump savings as a function of part load control technology type

In following up on this result, an additional examination of potential explanatory variables, including installation site attributes, did not yield any further insights into the reason for this unexpected result.

As a result, further study is needed to understand this reason and possible ways to increase the installed effectiveness of variable-speed heat pumps. Areas for this further research, which could explain the results, include the following:

- There is a difference and variable speed saves more, but the difference is enough smaller than the statistical variability that it is not evident in the results. This possibility is exacerbated by the common inclusion of electric resistance coils with heat pumps by contractors in SMUD's territory, which increases overall load and therefore associated variability.
- The consumption data analysis will capture any differences in energy consumption behaviors between two-speed and variable-speed compressor installers. For example, if variable speed compressor installers perceive their systems to be more efficient and as a result adjust setpoints toward greater comfort more than two-speed installers, this differential takeback will be included in the impacts.
- Multiple contractors in this study emphasize the challenges of setting up variable-speed heat pump controls such that the highest efficiency and associated energy savings are achieved. Suboptimal control settings could contribute to reductions in the efficiency of variable-speed heat pumps.

In light of these results, utilities may want to, for the present, provide equal incentives for these two types of heat pumps. Resources may be better spent on contractor training and customer education on the most efficient way to install and use the units. Contractor training on the most efficient installation practices could include capacity sizing and setting up controls. Additionally, more education about the reduced need for heat stripping and continued sufficient operation of right-sized heat pumps at lower temperatures would help with winter efficiency. Customer and contractor education about the most effective thermostat settings, and consideration of the best way to employ smart thermostats, could also increase efficiency.

Further research on different heat pump types could yield additional information on the relative importance of the above heat pump type choices and settings. This could include submetering heat pumps, including separate metering of compressors and air handler units with heat stripping, to understand the energy use and frequency of resistance heat use. Airflow testing to better understand how the duct configuration, duct insulation, and duct sealing are impacting the overall system's performance could also be informative. Submetering of equipment also eliminates the statistical noise associated with analysis of whole-home electricity usage. However, it comes with a high cost, especially to sufficiently establish pre- and post-installation HVAC energy usage, and to obtain a large enough sample size to report representative and statistically significant results.

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