Getting Heat Pumps Under Control: The Success of the Heat Pump Revolution Requires Getting Heat Pump Controls and Sizing Right

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ABSTRACT

With efforts around electrification and decarbonization and layers of incentives to install heat pump technology, one thing is clear – the heat pump revolution is coming. The success of this revolution will depend on how much we are able to maximize the main advantage of a heat pump – its compressor. Much research is focused on getting high capacity and efficiency at colder temperatures, which is critical, but so too are heat pump sizing and backup system controls. This paper explores recently metered heat pump homes to highlight the issues contributing to poor overall heat pump performance, and they are the same issues that have plagued heat pump performance for decades, such as improper heat pump sizing and improper backup system lockout and control. The paper will also explore monitored internal temperature data captured from the same metered dataset, which highlights other challenges for heat pumps, such as deep nightly setbacks, which lead to large demand spikes during the morning warm up period. From the observed data, we will summarize what we see as the recipe for the success of the heat pump revolution, which includes better default OEM control strategies, including predictive controls, better field installation practices, such as sizing and system lockout settings, and better consumer education.

Introduction

Heat pumps are increasingly making their way into homes and businesses across the U.S. and the globe. According to the International Energy Agency, global heat pump sales saw their second year of double-digit growth in 2022, growing 11% from the year prior (IEA 2023). In the United States, heat pump sales overtook gas furnace sales in 2022, and the number of apartments using heat pumps as their primary heating source more than doubled between 2015 and 2020 (IEA 2023).

There are a variety of factors contributing to the rapid growth of this technology:

- Heat pumps allow many homeowners to reduce their energy use, energy bills, and carbon footprint (Wilson 2024).
- Heat pumps provide air conditioning, which, due to rising global temperatures, is expected to become the fastest growing energy end use in buildings (EIA 2020).
- Modern building codes increasingly require or incent the use of heat pumps for space and water heating (McNichols 2023).
- Decarbonization and clean energy policies shift fossil fuel-based technologies to electric, and largely heat pump-based, technologies (Moore-Bloom 2022).
- Financial incentives at the utility, state, and federal levels are available for the installation of heat pump technologies (ETO 2024b; ODOE 2024; ENERGY STAR 2024).

The potential efficiency gains of heat pumps are substantial. Modern heat pumps can reach efficiencies of 300 to 400% or higher (Crownhart 2023). That means that heat pumps can reduce energy relative to electric resistance-based heating systems by 75% or more. These efficiency gains, however, are not guaranteed. Most residential centrally-ducted air-source heat pumps ("ducted heat pumps"), the focus of this paper, have two heating sources – the heat pump's compressor, which is the 300-400% efficient source, and an auxiliary or backup heating system, commonly either an electric resistance heating element with 100% efficiency or a natural gas or propane furnace with typical efficiencies of 80-90% (DOE 2024). The efficiency, then, of the overall heat pump *system*, is a function of the amount of heat provided by the compressor versus the backup source.

The authors of this paper assert that the interplay between the compressor and the backup heating system, and the drivers leading to excessive backup heating system use, have not received sufficient attention in the conversation around the coming heat pump revolution. While the authors have observed much recent focus centered around specific heat pump technologies, such as variable speed heat pumps, cold climate heat pumps, and "smart" thermostats, they have observed less focus on some of the long-standing heat pump "fundamentals" that, when ignored, continue to degrade real-world heat pump performance, such as:

- proper heat pump sizing to ensure sufficient capacity at lower temperatures (Yoh et al. 2023);
- proper compressor and backup system "lockout" settings (McHugh et al. 2022);
- proper assessment of the home's duct system (Winkler and Ramaraj 2023);
- proper consumer education of heat pump technology (Bastian and Cohn 2022); and
- proper home weatherization prior to a heat pump installation (ETO 2023).

The Problems: A Look at the Causes of Excessive Backup Heating

This paper focuses primarily on two factors that can lead to dramatically lower overall heat pump system efficiency – namely, 1) improper lockout controls and 2) the use of deep nighttime setbacks; however, the importance and relevance of all of the heat pump fundamentals listed above will be included throughout the paper with the goal of providing a wholistic view of both "the problems" and "the solutions".

Lockout controls and deep nighttime setbacks are selected as the focus of this paper, as they were identified as two of the leading drivers of backup heating use in an investigation conducted by the Northwest Power and Conservation Council's Regional Technical Forum (RTF) and led by the authors of this paper (Douglass 2023). The primary dataset used by the RTF, and to present the arguments in this paper, is from the Home Energy Metering Study (HEMS) conducted by the Northwest Energy Efficiency Alliance (NEEA) (NEEA 2024a). The HEMS is a five-year research effort, collecting minute-level power data on individual circuits in hundreds of residences in the Pacific Northwest. In addition to power data, the study dataset also includes metered interior and exterior temperature data, as well as building audit data captured in NEEA's Residential Building Stock Assessments (NEEA 2024b).

Other field research and data from the Pacific Northwest is also used in this paper to supplement the HEMS dataset.

Improper Lockout Controls

The HEMS data provides insight into the behavior of heat pump controls, including the use of the compressor heating coil versus the backup heating elements. A study performed by the RTF and led by the authors of this paper looked at ducted heat pump sites in HEMS to detect heat pump lockout settings (Douglass 2023). Ducted heat pumps are often able to lock out the compressor and/or the backup heating source at a particular outdoor air temperature (OAT), by not allowing the backup source to run *above* a given OAT and/or not allowing the compressor to run *below* a given OAT.

A study conducted by the Bonneville Power Administration (BPA) in 2019 found that most heat pumps observed did not have a backup heat lockout enabled (SBW Consulting et. al. 2019). Of the heat pumps installed under a utility program requiring backup lockouts, only 65% were found to be in compliance. For heat pumps installed under other utility programs or outside of utility programs, backup lockouts were observed in 14% and 25% of homes, respectively (SBW Consulting et. al. 2019).

The findings from the 2019 BPA study appear to be consistent with the ducted heat pump homes in the more recent HEMS data, namely, backup lockouts appear to be rare in the field. Figure 1 below shows an example of a real home in the HEMS data *with* a clear backup system lockout. Since HEMS metered electric energy only, all the homes in the following examples have electric resistance heating as their backup heating source.

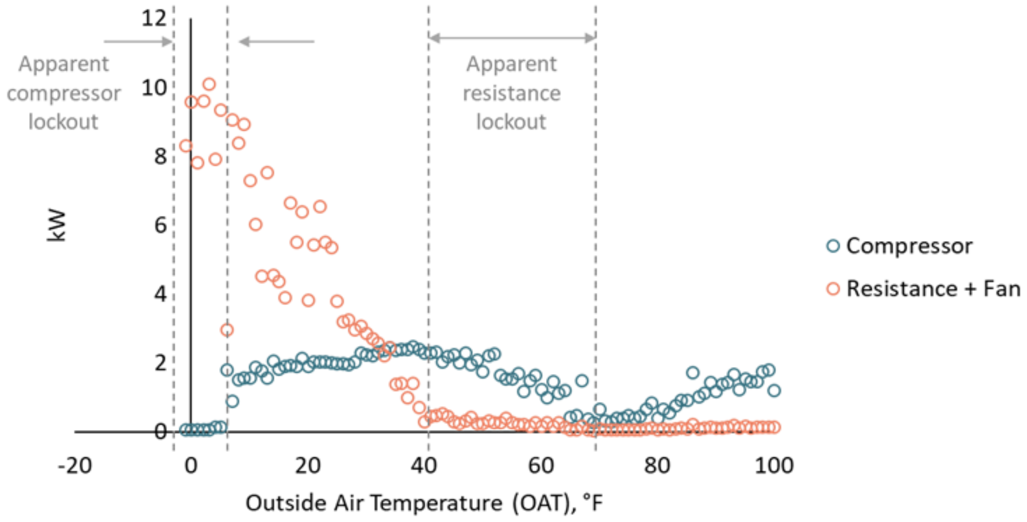

Figure 1. Observed maximum hourly power draw at various outside air temperatures for an example ducted heat pump home in HEMS. Here, “Fan” refers to the indoor air handler fan. *Source*: Douglass 2023.

Figure 1 presents maximum hourly power draw observed for the compressor circuit and the backup resistance heat plus indoor fan circuit, over a range of OATs for an example heat pump home in HEMS. This home appears to have a resistant lockout enabled at a temperature of about 40 °F OAT. This is evidenced by the fact that between 40-65 °F OAT, the resistance plus air handler fan circuit shows very little power use. Starting at around 40 °F OAT, however, Figure 1 illustrates a sharp uptick in resistance plus fan power use for temperatures below that point. The heat pump in Figure 1 also appears to show the compressor locking out around 5 °F

OAT, as evidenced by the compressor circuit power suddenly dropping to zero, while the resistance circuit power continues to climb.

The system shown in Figure 1 represents a relatively efficient setup. There are many heating hours in much of the Pacific Northwest between 40-60 °F OAT, so meeting all these hours with the heat pump's compressor alone is a significant boost to overall heat pump system efficiency. A best practice heat pump in the Northwest, however, would likely have an even lower lockout temperature, closer to 35 °F OAT, and no compressor lockout (ETO 2024a).

Most of the heat pumps in HEMS studied by the RTF look less like Figure 1, however, and more like Figure 2 below. Notably absent in Figure 2 relative to Figure 1 is a temperature regime where the compressor coil is heating, but the resistance elements appear to be locked out. Even at OATs approaching 60 °F, the electric resistance elements appear to be providing heat at least some of the time.

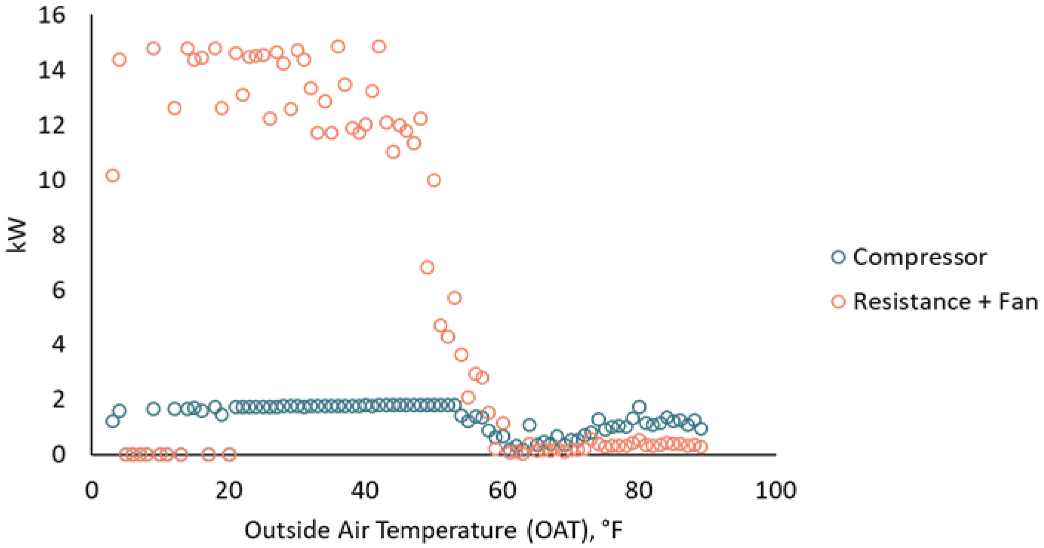

Figure 2. Observed maximum hourly power draw at various outside air temperatures for a second example ducted heat pump home in HEMS. *Source*: Douglass 2023.

The HEMS data provide valuable insights into *how* and *to what extent* the compressor and resistance backup heating are used in these heat pump sites, but it is often not fully possible from the dataset to conclude *why* they behave as they do. For example, for the site shown in Figure 2, it is possible that the system simply does not have a resistance lockout enabled, leading to the more aggressive use of resistance heating at higher OATs; however, that is not the only possible explanation. Even with a resistance lockout in place, the internal logic of some heat pumps may determine that resistance heating is still necessary for reasons such as:

- **significant heat pump undersizing**, if the heat pump's capacity cannot meet the requirements of the lockout temperature;
- **significant duct constraints**, if the heat pump's capacity is sufficient, but the carrying capacity of the ducts, due to their size and/or condition, is inadequate; and
- **deep nighttime setbacks**, leading to large morning demand spikes that may require significant resistance heating to overcome.

It is challenging to observe the direct effects of these first two reasons in the HEMS dataset; however, the inclusion of monitored inside air temperatures in the dataset allows a direct investigation into the effects of the third reason, deep nighttime setbacks.

Deep Nighttime Setbacks

Estimating setpoint schedules from internal temperature and power data. Assessing the effects of deep setbacks on heat pump performance in the HEMS dataset first requires estimates of the setpoint schedules used in the HEMS homes. Estimating setpoint schedules from internal temperature data, however, is not as straightforward as it may seem. This is due to at least two major factors:

- There can be considerable time lags between when a thermostat's setpoint value changes and the actual interior temperature changes; in other words, it can take a while for a house to significantly warm up or cool down.
- The internal temperatures observed in a home reflect not only the effects of the thermostat settings and HVAC system, but also other factors that cause inside temperatures to "float" away from thermostat settings, such as internal or solar gains.

The RTF developed a method to estimate HVAC thermostat setpoint settings that aimed to address the above factors. To address the time lag factor:

- The HVAC system's power data, not temperature data, are used to inform the *presence* and *timing* of a setpoint change event.
- The *presence* of a nighttime setback is tested by comparing the ratio of morning peak power demand to average nighttime power demand; a ratio of approximately 2:1 appears to be typically indicative of a nighttime thermostat setback event.
- If the presence of a setback is established, the *timing* of the setback event is determined by looking at the slopes of the HVAC power curve – using the maximum negative slope to determine the setback start and the maximum positive slope to determine its end.

To address the temperature float factor, the RTF devised the following method to estimate the actual setpoint and setback *temperatures*:

- In cases where a setback is detected, the nighttime setback temperature is estimated by looking at the setback hours just prior to the morning ramp period and using the 10th percentile inside air temperatures during the heating season and 90th percentile temperatures during the cooling season. The 10th percentile temperature is used for heating, as the thermostat's goal in heating is to keep the home above some minimum temperature, while the 90th percentile temperature is used for cooling, as the thermostat's goal in cooling is to keep the home below some maximum temperature. The 10th and 90th percentiles are used in lieu of the true minimum and maximum temperatures, respectively, as the latter could be more prone to capturing outlier events.
- The daytime setpoint temperature is estimated using the same method used for the nighttime setback temperature, except instead of using the period of hours just *before* the morning ramp period, the daytime setpoint algorithm looks at the hours just *after*.

The final product of this method is illustrated in Figure 3, using an example heat pump home in HEMS found to have a night setback. Using the winter average hourly heating power demand curve in black, the algorithm determines that a setback event is present and uses the slopes of the demand curve to color the bars of each hour as a "setpoint hr", in orange, or a "setback hr", in grey. Once this is established, the algorithm computes the 10th percentile inside air temperatures just before the morning ramp, in hours 5 and 6, with the goal of "seeing" the true heating setback temperature. Similarly, the algorithm computes the 10th percentile temperature after the morning ramp, during hours 9-22, to estimate the daytime heating setpoint temperature. The final resulting estimated heating setpoint schedule is shown by the yellow line, which does indicate an apparent nighttime setback of about 5.5 °F.

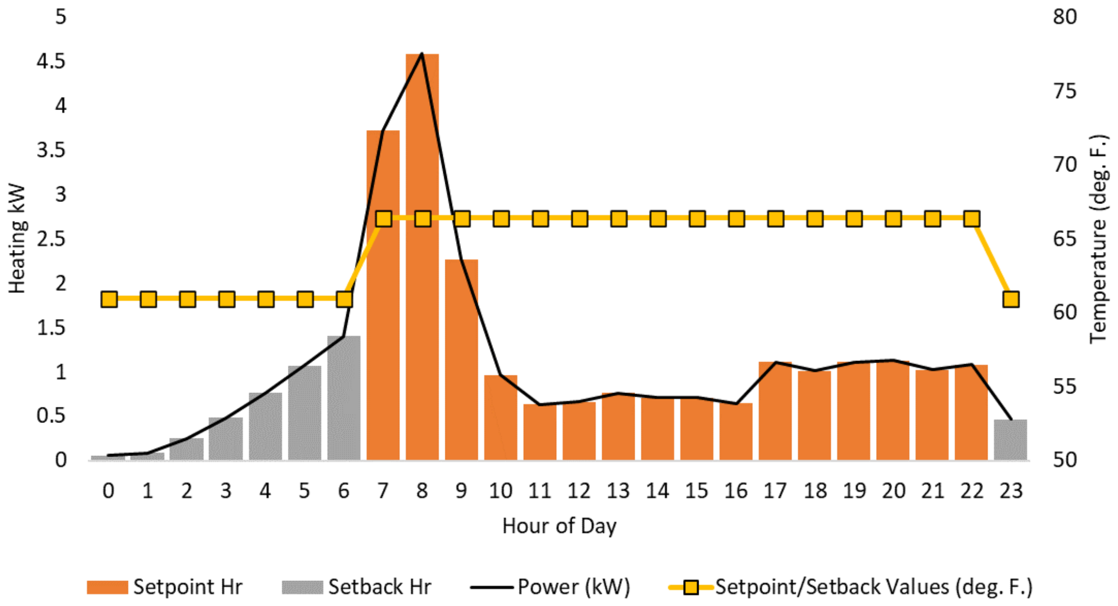

Figure 3. Average hourly heating power and estimated heating setpoint schedule for an example heat pump home in the HEMS dataset, believed to have a night setback. *Source*: Douglass 2023.

Backup resistance use from deep nighttime setbacks. Once setpoint schedules are estimated for the HEMS sites, the relationship between the depth of nighttime setbacks and the effect on backup resistance heating use can be observed. For this paper, a "deep" setback is defined as a setback, or reduction in thermostat heating setpoint temperature, of 4 °F or more.

Setbacks look common from the HEMS dataset. Of the 36 ducted heat pump sites observed in the dataset for the RTF's analysis, 21 were estimated to have at least some setback and 9 were estimated to have a deep setback, as defined here.

To see the effect that a deep setback can have on a ducted heat pump home, consider Figure 4 below that shows an example of a heat pump home with a deep setback in the HEMS dataset. Figure 4 shows the average power demand of the compressor and backup resistance heat plus air handler fan circuits for each hour of day in January and February. For this home, the RTF analysis estimates a daytime setpoint temperature of about 69.5 °F, and a nighttime setpoint temperature of about 60 °F – a nearly 10 °F setback. The effect of the deep setback on the backup resistance use is rather apparent – the "Resistance + Fan" circuit shows large 8 to 11 kW spikes during the morning hours of the peak heating months of the year. These power spikes have significant grid implications, both in terms of their magnitude and timing – as they often occur coincident with periods of higher net system demand, and higher market prices, in the Northwest (EIA 2024).

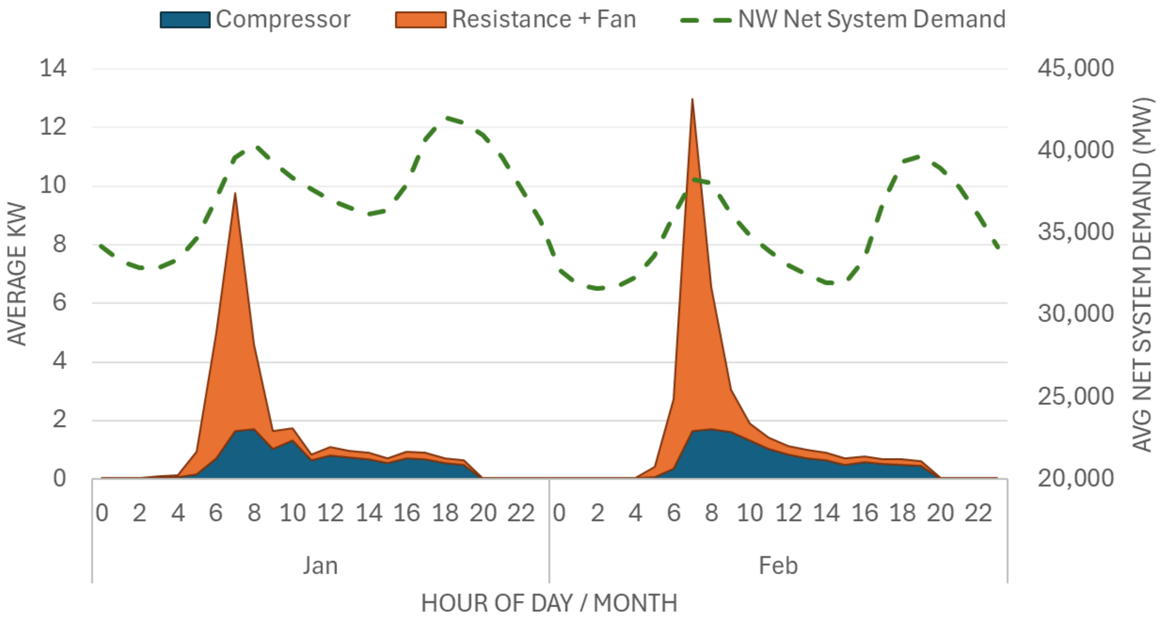

Figure 4. Average hourly compressor and resistance + fan power usage for winter months, for an example heat pump home in HEMS with an estimated nighttime setback of 10 °F. Average net system demand for the Northwest (NW) is overlaid for comparison. Source: Douglass 2023.

One interesting factor to note about the home in Figure 4 is also where you do *not* see significant backup electric resistance use, which is all hours of the day except for the morning spike. Aside from the morning ramp hours, the "Resistance + Fan" circuit shows average hourly values near or below 0.5 kW, which is likely related to air handler fan power; meanwhile, the compressor circuit shows that the home is still heating throughout much of the day.

To illustrate how commonly this morning ramp issue arises for heat pumps, consider the heat maps in Figure 5 below, which show average hourly compressor and resistance plus fan demand, across a range of OATs, for all ducted heat pump homes in HEMS analyzed by the RTF (Rushton 2024). The top heat map shows average hourly compressor and resistance plus air handler fan use across all non-morning hours, while the bottom map shows the same information, but only over the typical morning ramp hours of 6 – 10 AM. The colors of the heat map are defined such that any color band that is yellow or red is indicative of significant resistance heating on the "air_handler", i.e., resistance plus fan, circuit. With that context, notice the significantly higher presence of yellow and red color bands in the bottom chart, showing the morning ramp hours only, compared to the top chart, showing all non-morning ramp hours. The bottom chart shows significantly higher backup resistance use, and backup resistance use occurring at milder temperatures.

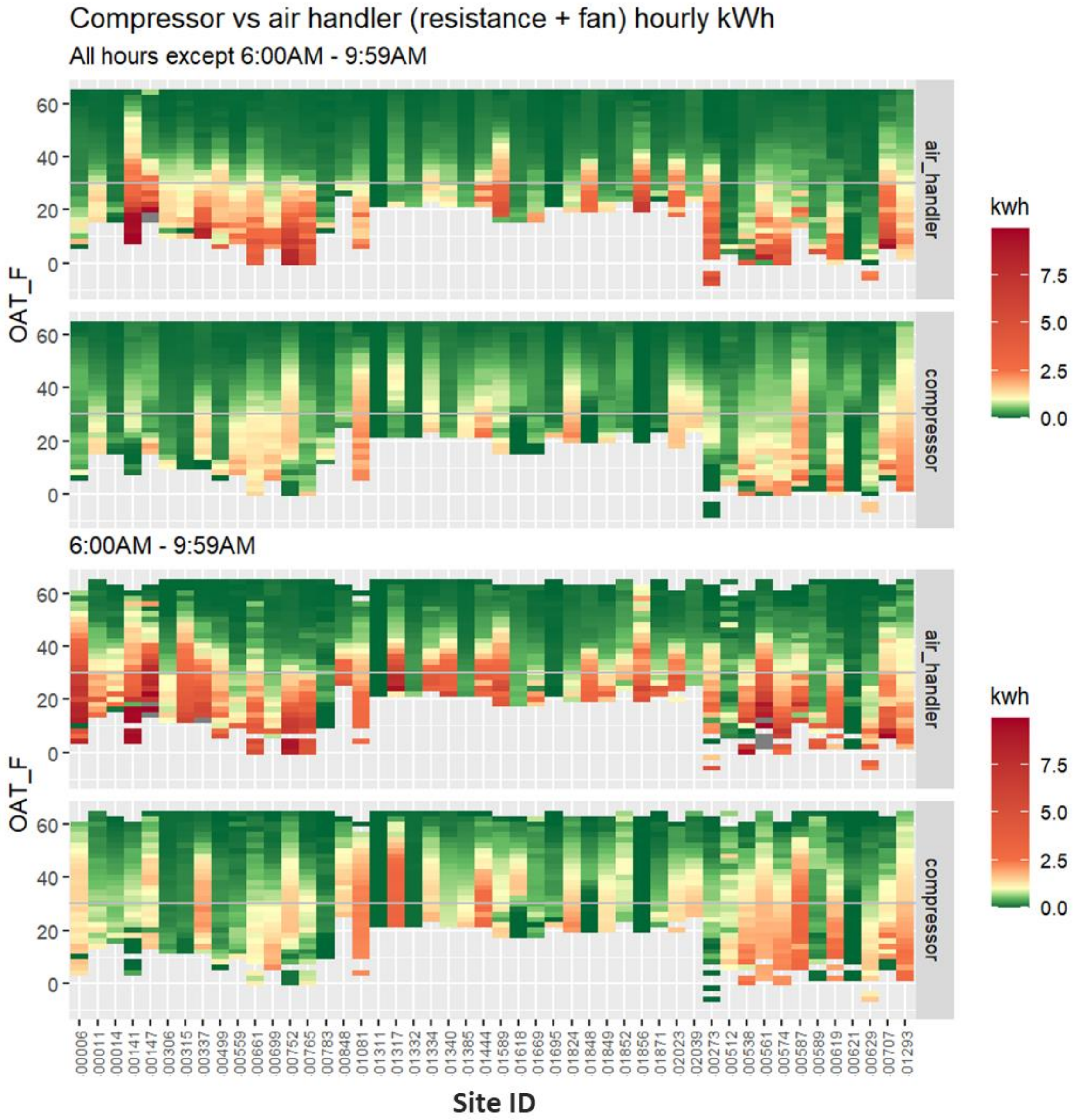

Figure 5. Average hourly compressor and resistance plus fan ("air_handler") demand, across a range of outside air temperatures in °F ("OAT_F"), for all ducted heat pump homes in HEMS analyzed by the RTF. Values separately shown for non-morning hours (top) and morning hours (bottom). *Source*: Rushton 2024.

Note that while most heat pumps in the HEMS dataset are single speed units, the authors have observed similar setback-induced behaviors from some newer, variable speed heat pumps in others' research (Koch 2024). Figure 6 below shows a newer variable speed unit in Bend, OR with an initial deep setback in January. When the homeowners were alerted to the issue and switched to a constant setpoint temperature starting in February, it resulted in peak demand reductions of about 10-15 kW. The heat pump system, post-thermostat changes, appears to be highly efficient, regularly staying below 3kW, even at OATs near 25 °F.

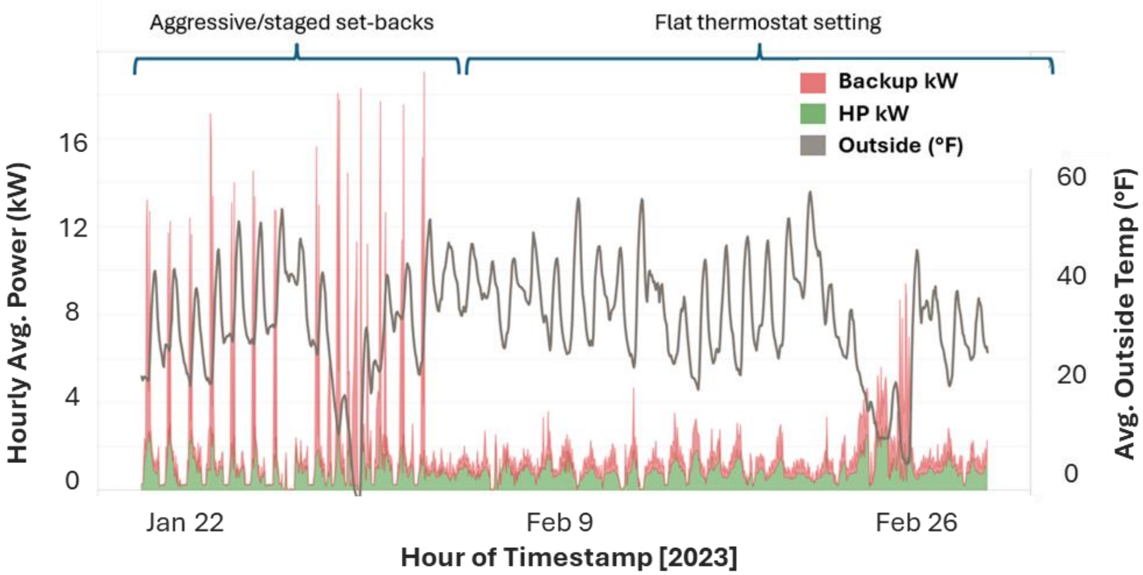

Figure 6. Average hourly power, for the compressor (“HP kW”) and backup resistance element (“Backup kW”), and average hourly OAT, for a variable-speed heat pump in Bend, OR. Home has a deep setback until approximately February 2nd and no setback after that point. *Source*: Koch 2024.

Other Causes of Excessive Backup Heating

While this paper cannot possibly provide in-depth treatment of all causes of excessive backup heating in ducted heat pumps, it is worth speaking briefly to other major contributors of excessive backup heating. Consider this more extensive list of factors that can lead to excessive backup heating in a ducted heat pump, many of which have already been touched on:

- an uninsulated and/or leaky building envelope;
- uninsulated, unsealed, and/or undersized ducts;
- poor low temperature heat pump capacity;
- insufficient heat pump sizing;
- improper heat pump lockout controls;
- “reactive” heat pump and/or thermostat logic; and
- improper homeowner thermostat control.

As each of these factors is successfully addressed, it makes the success of the next factor and the overall system more likely (Winkler and Ramaraj 2023). The inverse of this is also true – a significant failure of any one factor can adversely affect the next factor and/or the overall system. Consider how these factors interact, and build upon one another, with the following examples:

- A home with leaky, uninsulated, undersized ducts and/or a leaky, uninsulated envelope will pose a challenge for even the best performing heat pump.
- A backup system lockout of 35 °F is inadvisable if the heat pump compressor is not sized to meet the total heating load at 35 °F or colder. This will be made even more difficult for heat pumps with poor low temperature capacity.

- Even homes with good insulation, good ducts, and a well sized heat pump will likely end up relying on significant backup system use if homeowners use deep night setbacks and are not educated on optimal system use. This will be most true for systems that use highly "reactive" logic, trying to make up for major differences in interior temperatures in an instant.

The Solutions: It Takes a Village

Better heat pump technologies will likely play a major part, particularly over the long term, in addressing and/or mitigating some of the problems laid out in this paper; however, the wave of heat pumps is already here, and the authors assert that the solution to optimize the value of heat pumps both to homeowners and to the electric grid, is going to take the collaborative effort of manufacturers, installers, utilities and efficiency program operators, and homeowners. What is everyone's role on this team?

Equipment Manufacturers

Better cold climate capacity (and efficiency). Equipment manufacturers are already producing technologies that will ease some of the challenges presented in this paper. Cold climate heat pumps, for example, provide both higher capacity and efficiency at temperatures well below freezing. These heat pumps can make backup system lockouts at lower OATs, or the reduction or removal of backup heating entirely, a reality. In many parts of the country, a heat pump with no backup heating system is already possible. The authors of this paper strongly suggest this as a real option for installers and homeowners to consider, as it is the only way to completely rule out the use of backup heating; however, it does carry a couple of important considerations:

- Proper sizing, good ducts, and a good envelope become even more critical in the absence of a backup heating source.
- Certain parts of the country, such as those with cold events of -20 °F or below, are likely not within practical reach of full backup heat removal, in most cases, currently.

Better control logic. The control logic of selecting compressor versus backup system heating is another critical area for manufacturers to continue to improve. While consumer comfort is always an important aspect of any HVAC system, this should be achieved in the most efficient way possible, maximizing the compressor to the greatest extent possible. Thermostat control logic should also be proactive and/or predictive rather than reactive – looking ahead at future setpoint changes and determining the most efficient way to get from one setting to another.

New efficiency features, operating modes, and system defaults. Hybrid heat pump water heaters (HPWHs) may offer some interesting lessons to heat pumps used for space conditioning. Most residential HPWHs work similarly to heat pumps used for space conditioning in that they have a more efficient compressor coil and a less efficient backup resistance element, and the relative use of each affects overall system efficiency. NEEA has been successful working upstream with HPWH manufacturers and helping reduce backup resistance use in HPWHs in several ways, including:

- creating an efficiency specification and corresponding Qualified Products List (QPL), with requirements related to maximum resistance use;
- shipping equipment with the most efficient settings as defaults; and
- requiring that equipment default back to the most efficient settings after power outages or a certain amount of time spent in "high resistance modes" (NEEA 2024c).

The following real scenario shown in Figure 7 highlights the value of having similar defaults or automated alerts in heat pumps used for space conditioning. A homeowner with a new heat pump installed in the Tacoma, WA area decided to switch their heat pump into a resistance-only mode in anticipation of a cold event around January 12th. The homeowner subsequently forgot to return the heat pump to its normal operating mode, and only did so once they were alerted around February 8th. Figure 7 highlights the dramatic difference in backup resistance use, in red, and peak kW, between the two operating modes.

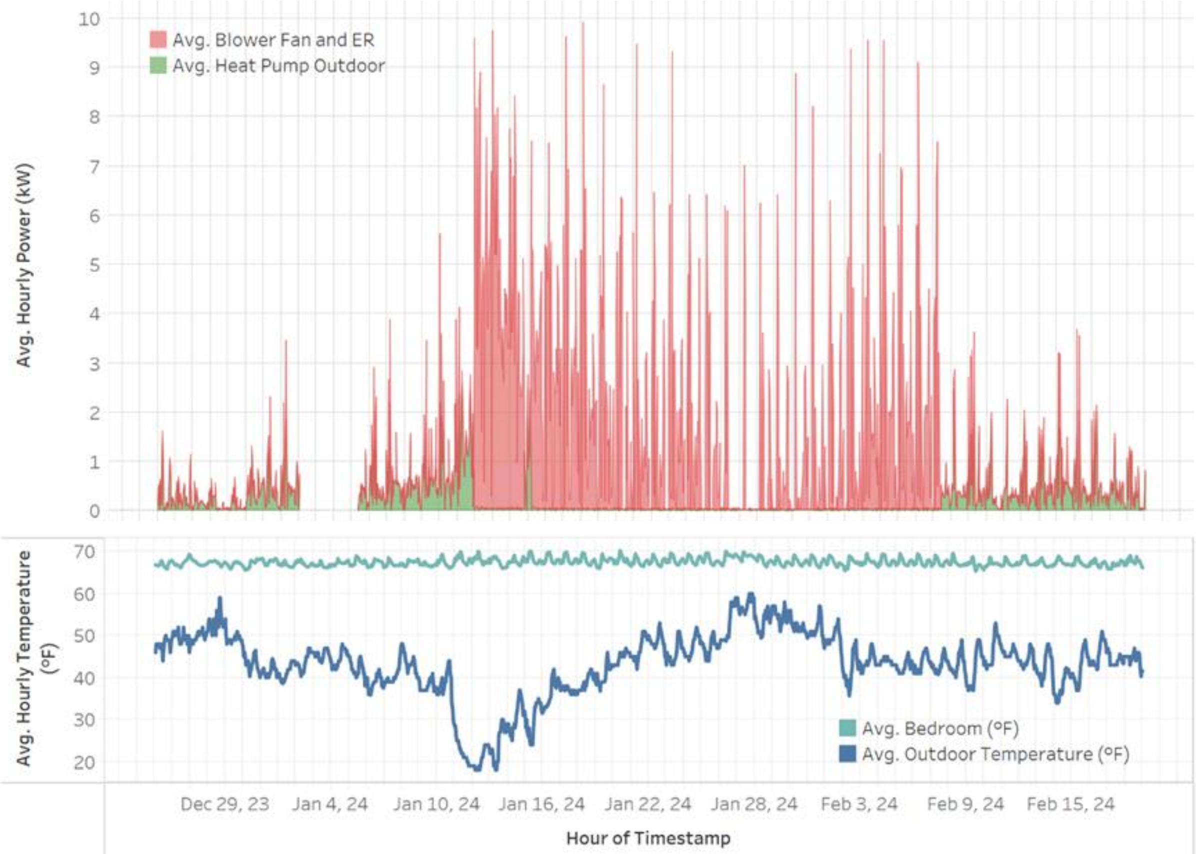

Figure 7. Example home in Tacoma, WA area, showing average hourly backup resistance ("Blower Fan and ER") and compressor power ("Heat Pump Outdoor"). The heat pump enters a resistance only mode around January 12th and exits it around February 8th, after being alerted by the utility. *Source*: Koch, 2024.

Installers

Installers currently play one of the most challenging and pivotal roles, but they can have some of the least incentives to make sure that equipment performs efficiently. Installers often err on the side of favoring backup heat, as this adds a perceived factor of safety and potentially fewer customer call-backs. Unfortunately, it can also leave significant benefits to the homeowner and the electric grid on the table.

Duct assessment. Ducts are the lynch pin of a ducted heat pump system. If ducts are insufficient to carry the amount of air needed for a successful ducted heat pump system, and too costly to retrofit, installers should discuss the possibility of abandoning the duct system with homeowners and considering a ductless system. If the duct system is deemed sufficient or fixable for a reasonable price, ducts need to be insulated, especially if running through highly uninsulated cavities, and should be sealed, if appropriate.

Recommendations for home weatherization. Efficiency program operators, considered later, should work with HVAC installers to make recommendations on home weatherization before a heat pump installation. This will lead to higher overall customer comfort and satisfaction, and a higher likelihood that an appropriately sized heat pump can be installed and cover most of the heating load with its compressor.

Discussing various backup system options with homeowner. One fundamental issue with ducted heat pumps is that homeowners do not understand the basic concept that their heating system has two heaters – an efficient one and an inefficient one – and they have options about how much the inefficient one runs – or whether it needs to be there at all. Installers are used to presenting homeowners with “good”, “better”, “best” options, but these are typically in terms of rated efficiency factors. Particularly in milder climates, installers should have discussions with homeowners about systems without resistance backup heating or smaller amounts of resistance heating (e.g., 5 kW or less).

Proper sizing. It is critical that installers perform proper load calculations to determine that the heat pump’s compressor can cover the entire heating load down to a sufficiently low temperature, typically 30-35 °F at a minimum for a system with backup heat, or even much lower, if backup heat is reduced or not present. This will set the stage for proper lockout controls to keep the system working at maximum efficiency. Care must also be taken to not oversize heat pumps, as this can lead to short cycling of the system.

Proper lockout controls. Lockouts, lockouts, lockouts – if systems include resistance backup heating, they need to be locked out down to where the heat pump’s compressor can cover the full heating load. If the collective industry agrees that backup heating should be present in most systems, then better methods should be determined to make lockouts more commonplace.

Utilities and Efficiency Program Operators

Marketing better products and installers. As all manufacturers will say: not all technology is equal – and not all installers are equal. Efficiency program operators can improve heat pump installation outcomes by identifying the best technologies, using a QPL or similar, and – just as important – the best installers, in their programs. Incentives and marketing can be used to encourage homeowners to make smarter and more efficient choices.

Research and verification. The authors feel that it is difficult not to overemphasize the importance of continued research and verification that heat pumps are operating in the field as designed. While research can be expensive, it is critical, and smart meter data can play a valuable role in identifying those systems that need assistance in a cost-effective way.

Homeowner education. One critical gap that utilities and efficiency program operators can address is better homeowner education on heat pumps. Homeowners should be empowered with basic information about their heating and cooling systems, so that they can make informed decisions about how they operate them. For example, homeowners should understand the typical operating settings of their system, including “emergency” (backup only) heat and its effect on system efficiency, the ability to lockout backup heating, and the effects and trade-offs of using thermostat setbacks with heat pumps.

Homeowners

Being informed users of heat pumps. The last line of ensuring that heat pumps work efficiently is end users themselves. Homeowners do not need to know the ins and outs of heat pumps, but they do need to know that there are efficient ways for heat pumps to operate and inefficient ways, and it is in their best interest and the grid’s best interest for them to operate optimally. Smart phones have shown that most people are not afraid of new technology, and perhaps even prefer having a certain level of knowledge and control over their products.

Demanding comfort *and* efficiency. Comfort and efficiency should no longer be an either/or with heat pumps. Homeowners should be armed with the knowledge that their HVAC system is both keeping them comfortable and doing so efficiently.

Bringing It Together – An Example

A recent heat pump installation in Chelan County, WA shows what is possible when bringing the different elements of a successful heat pump installation together. In this example, an existing air source heat pump was replaced with a new cold-climate-rated, variable speed heat pump (VSHP). The new system was sized to meet the home’s heating load down to around 32 °F with its compressor alone. The system exhibits good control of backup heat, reasonably good airflow (~370 CFM/ton), and the home’s envelope is relatively well insulated (White 2024).

Figure 8 shows hourly whole-building power consumption pre- and post-VSHP installation (the blue and red lines, respectively), along with average OAT over this period (the green line). The pre-period in blue shows regular spikes exceeding 20 kW at the whole building level, likely indicative of backup resistance heating, even though OATs are relatively mild. The reduction in whole building power post-VSHP retrofit is easily detectable. For similar OATs, peak demand appears to drop significantly, by 5-10 kW on average; the new unit even uses less demand during a sub-zero cold snap event than the previous unit did at OATs around 40 °F. Furthermore, the homeowners reported that the new system kept the house very comfortable.

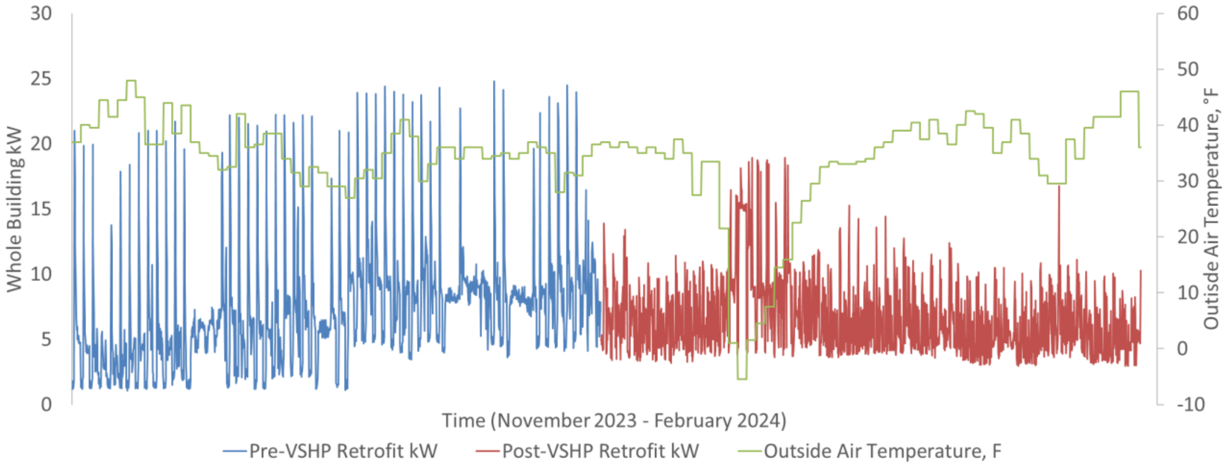

Figure 8. An example variable-speed heat pump (VSHP) installation performed in Chelan County, WA. Shows hourly whole building kW pre- and post-VSHP installation, along with average daily outside air temperature, during the same period. *Source*: White 2024.

Figure 9 provides a different look at the same data, showing average whole building hourly demand pre- and post-VSHP retrofit. The blue line again shows the pre-retrofit case, with morning ramps peaking around 18 kW; the shape of the line strongly suggests a deep nighttime thermostat setback, which the homeowner confirmed. The red lines show the post-retrofit case, with the solid line including all the data shown in Figure 8, and the dotted line excluding the cold snap, as this may be a more reasonable ("apples-to-apples") comparison to the pre-case. Figure 9 shows an average daily peak demand reduction of about 8 kW. Just as interesting, the morning ramp of the post-case starts earlier and persists longer. While the authors have not completely confirmed the cause of this shift, it appears at least plausible that the system is anticipating the return to setpoint to maximize efficiency. Removing the night setback in the post-case would further flatten the morning hour demand by about 2-3 kW, but the homeowner reported preferring the house to be cooler at night.

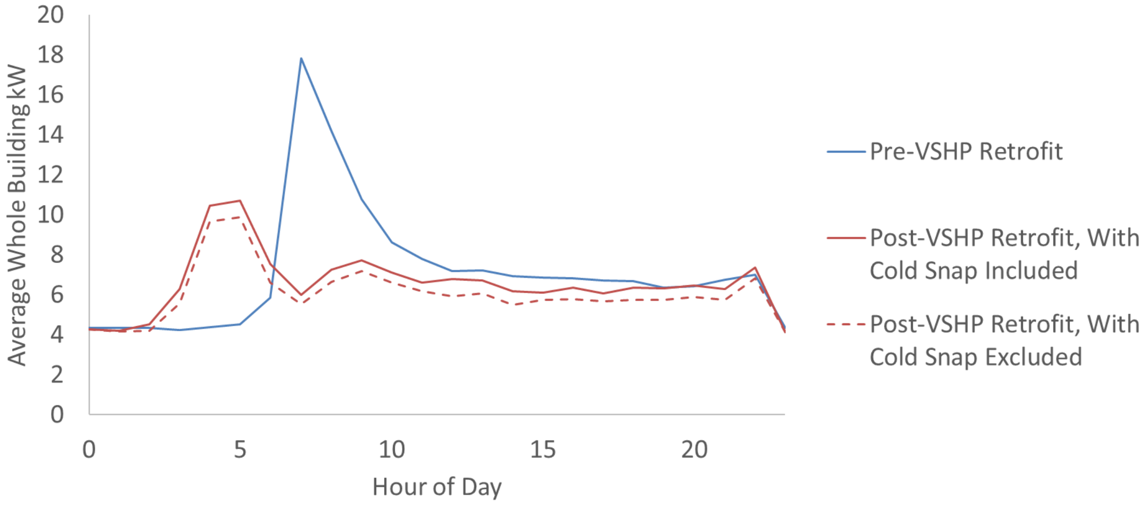

Figure 9. An example variable-speed heat pump (VSHP) installation performed in Chelan County, WA (same installation as Figure 8) showing average hourly demand for the pre- and post-retrofit cases. For the post-case, average hourly demand is shown with and without a January cold snap, for reference. *Source*: White 2024.

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