Variable-Speed Residential Heat Pumps to Improve Grid Resilience

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ABSTRACT

A U.S. electric utility offers free energy-efficiency upgrades for income-qualified households. The utility conducts home energy audits, then ranks and installs measures that can save energy and improve comfort. Typical measures include adding attic insulation, replacing windows, sealing air ductwork, water heater replacement, and installing all-electric heat pumps. A pilot project was conducted to install high-efficiency variable-speed heat pumps (VSHPs) with little-to-no electric strip heat instead of single-speed heat pumps (SSHPs) with conventional heat strip levels. Home improvements were applied to 24 homes, and indoor comfort and VSHP performance were monitored. Homeowners were surveyed to determine the heat pump impacts on comfort, noise levels and electric utility bills. Summer 2023 survey results indicate high customer satisfaction. The VSHPs were sized to meet all or nearly-all of the design heating load. Therefore, the electric resistance auxiliary elements installed were >50% smaller than for SSHPs, and 9 of the 24 homes had no resistance elements installed. This study took advantage of the utility's existing contractor network. The project's five participating HVAC contractors were trained to properly size VSHPs, highlighting differences compared to sizing single-speed equipment. Further in-person training and training materials will be completed for additional network members, incorporating lessons learned. Early pilot results allowed the utility to offer incentives to all customers to promote properly-sized VSHPs. Inflation Reduction Act (IRA) incentives should further promote these more efficient heat pumps with little-to-no resistance heaters. Utilizing this technology should allow electrification of residential space heating with much smaller impact on winter peak electric demand.

Introduction

Both in the U.S. and worldwide, there is strong interest in efficiently electrifying residential end-use energy consumption to decarbonize and reduce greenhouse gas emissions. Of particular interest is replacing space heating by fuel-based combustion furnaces with electric heat pumps. In the U.S., air-to-air heat pumps are often used for residential space heating, while air-to-water heat pumps are more common in Europe.

Residential space heating load increases as outdoor air temperature decreases (Figure 1, black dotted line). However, the heating capacity of SSHPs drops significantly as outdoor temperature decreases (Figure 1, brown line), roughly 35-45% reduction when the outdoor air temperature drops from 47°F to 17°F. Therefore, auxiliary electric resistance heaters (coefficient of performance [COP] ~1, Figure 1, orange shaded area) are often used to supplement the decreased heating capacity from the high-efficiency compressor with COP ~1.5 to 3.5.

VSHPs are available in the marketplace, providing higher seasonal efficiency but with higher first cost compared to SSHPs. For mixed and cold climates with larger design heating loads than design cooling loads, VSHPs can be sized to efficiently meet a higher portion of the home heating load with less need for auxiliary heat (compared to SSHPs), while providing

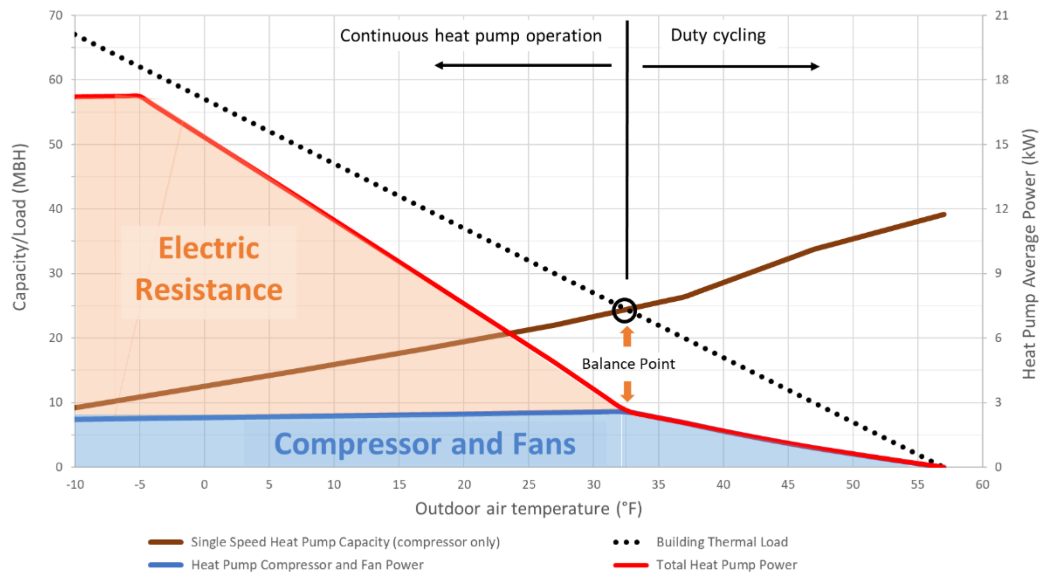

Figure 1. Illustrative example of heating system behavior. *Source*: EPRI 2021.

excellent cooling and dehumidification during summer months due to the heat pump's ability to operate at a lower speed. Figure 2 shows the heat capacity of a VSHP with compressor overspeeding at low outdoor air temperature (purple line), compared to a conventional SSHP (brown line). For this example, the green shaded area between the two lines is the home heating load met by the VSHP (with COP ~1.5 - 3.5) instead of less efficient electric resistance auxiliary heaters (COP ~1.0). While reducing seasonal heating energy consumption, VSHPs can also be sized to meet most or all of the home heating load. This method of sizing can significantly reduce the electric power requirements compared to conventional SSHPs which normally have much larger electric heat strips installed, significantly challenging the reliability of the electric grid on cold winter mornings.

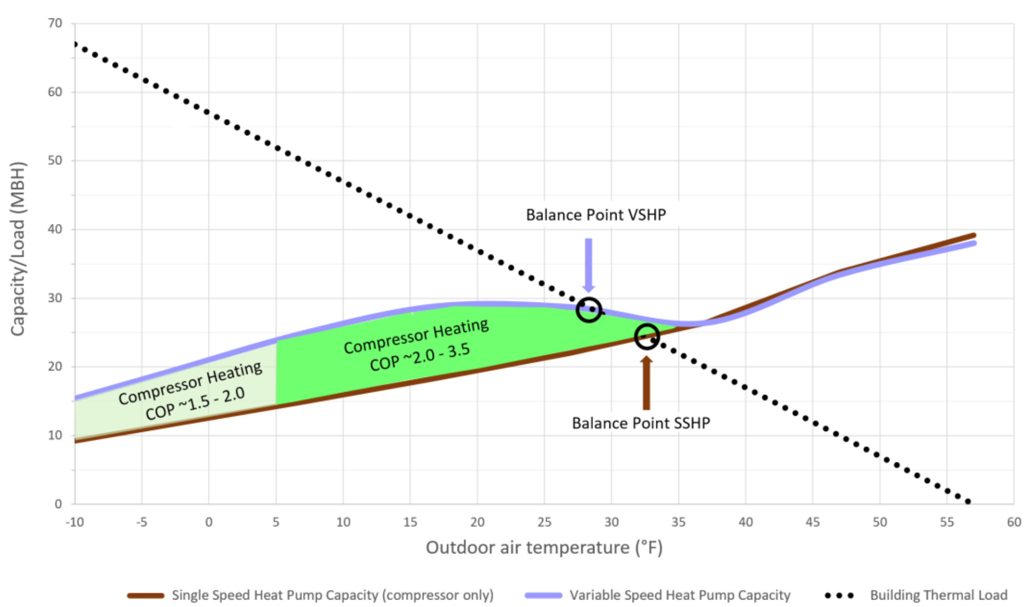

Figure 2. Variations in compressor heating capacity for single- and variable-speed heat pumps

A large percentage of Tennessee Valley Authority (TVA) residences already use single-speed heat pumps for space heating (approx. 45%) and they are heavily promoted through customer incentives. With their rather large contribution to winter electric grid peak demand and emphasis on electrifying residential space heating even further, continuing to install all-electric SSHPs would further stress the existing electric grid and likely require expensive upgrades to electric generation capacity and the transmission/distribution network. The goal of this project was to evaluate the overall performance and cost effectiveness of VSHPs with little-to-no auxiliary electric strip heat as compared to SSHPs with conventional amount of electric strip heat, with particular emphasis on reduction in electric power draw during peak winter demand.

Project Overview

TVA currently offers a robust and successful EnergyRight® program (TVA 2024a) to provide various services for residential customers across seven southeastern states. Services include an energy evaluation to assess the home's current energy efficiency and a customized and prioritized list of recommendations for improving efficiency and comfort. The program also provides financing options and a list of TVA-vetted contractors to complete efficiency upgrades. TVA audits roughly 10% of homes after the upgrades are completed to assure the efficiency measures have been implemented to TVA standards.

Under the Home Uplift program (TVA 2024b) similar services are provided, including an average of $10,000 in free home energy upgrades to income-eligible customers. Upgrades can include new or repaired HVAC units, attic/wall insulation, efficient appliances, and electric water heaters. This program targets single-family homes and manufactured homes. Overall, the program has saved participants $500/year on average, reduced overall home energy use by 25%, and improved overall quality of life.

Within the framework of the Home Uplift program, 24 households were identified in east Tennessee (8 in Chattanooga, 16 in Knoxville) to participate in a pilot project to evaluate the costs and benefits of high efficiency split-type VSHPs over conventional SSHPs. Selection criteria for participating homes included focus on single-family homes, preference for homes with existing electric heating (resistance or single-speed heat pump), and meeting income eligibility requirements. TVA-vetted contractors completed the identified energy efficiency upgrades, including installation of the VSHP at each home (December 2022 – August 2023). Home occupants agreed to participate in periodic telephone surveys to provide customer insights into heat pump performance, indoor comfort levels, noise level and impact on electric utility bills.

A datalogger and multiple sensors were installed in each home to monitor VSHP performance and the resulting indoor air temperature and humidity. The list of monitored parameters is provided in Table 1. The data are stored as average values at 1-minute intervals. At least 12 months of data will be collected for each participating home.

Heat Pump Sizing Methodology

Sizing VSHPs is significantly different from sizing SSHPs. For SSHPs, the heat pump is often sized to meet the home's design cooling load. During heating operation, the compressor delivers efficient space heating, but at low outdoor temperatures often requires a supplemental heat source to meet the home's entire heating load. If the SSHP is instead sized for a higher design heating load, then it may be oversized for cooling mode, resulting in inefficient on/off cycling and poor dehumidification.

Table 1. Monitored Parameters

Parameters	Comments
Indoor air temperature and humidity	• Adjacent to thermostat • Main living space (if distinct from thermostat location) • Master bedroom • 1 or more other bedrooms
Outdoor air temperature and humidity	• With gill plate to minimize solar impacts
Temperature and humidity of air entering the heat pump air handler	• Plenum upstream of air handler
Temperature and humidity of air leaving the heat pump air handler	• In ductwork, minimum distance downstream from air handler to avoid line-of-sight radiation impacts from electric resistance heat strips
Heat pump electric power input	• Outdoor section (compressor and outdoor fans) • Indoor air handler • Electric resistance heat strips (if present)
Whole home electric power	• 11 of 24 homes, better understand daily profile
Electric resistance storage water heater power	• 10 of 24 homes, better understand daily profile

For this project in a mixed climate zone, the goal was to utilize VSHPs to meet most or all the design heating load with efficient compressor operation, with little-to-no heat strip required. Due to variable speed compressor capability, these heat pumps can slow down during the cooling season and readily meet the design cooling load with very high efficiency due to the heat exchangers (indoor and outdoor coils) that are sized to meet the larger design heating load. In addition, the VSHP operates continuously during most of the summer to provide excellent cooling and dehumidification, only cycling on/off when the load is extremely low (e.g., <20-30% of max). Sizing SSHPs focuses on the design heating and cooling loads with respect to the "max" capacity of the heat pump at the design temperature and humidity conditions. Conversely, sizing VSHPs entails comparing the heating and cooling loads of the building with respect to the heat pump heating/cooling capacity at both the maximum and minimum operating speeds. This allows the HVAC contractor to better estimate how the VSHP will perform at design (peak) conditions and part-load operation at milder temperatures.

For both SSHPs and VSHPs, proper sizing is also influenced by available heat pump sizes and installed first cost. For example, a manufacturer may only offer heat pumps in 1.0-ton increments (e.g., 2.0, 3.0, 4.0 and 5.0). For VSHPs, if the design heating load falls midway between 2 adjacent sizes (but can meet the design cooling load with either size), and there is a significant cost difference between the 2 sizes, it may be more cost effective to select and install the smaller system rather than the larger system. Selecting the larger size might also result in the heat pump being severely oversized for cooling operation. Supply chain delays also influenced the selection of certain heat pumps for installation.

For this project, the HVAC contractors performed Manual J design load calculations (ACCA 2016) to determine the heating and cooling loads for the home with design indoor and outdoor temperatures. Design outdoor temperatures from the ASHRAE Handbook of Fundamentals (ASHRAE 2021) for both cooling (0.4%) and heating (99.6%) were used. Two indoor conditions were assumed for heating mode (68°F and 70°F dry-bulb temperature) and for cooling mode (75°F and 77°F dry-bulb temperature, both at ~50% relative humidity). Multiple indoor design conditions allowed prediction of resulting indoor conditions if faced with choosing between 2 different heat pump sizes. Four Manual J design load calculations were completed for each home, with indoor and outdoor air conditions summarized in Table 2.

Table 2. Design Conditions for Air-Source Heat Pump Load Calculations

	Chattanooga	Knoxville
Heating Design Dry-Bulb Temperatures	Indoor: 68°F, Outdoor: 19.2°F	Indoor: 68°F, Outdoor: 16.4°F
	Indoor: 70°F, Outdoor: 19.2°F	Indoor: 70°F, Outdoor: 16.4°F
Cooling Design Temperatures (dry-bulb and wet-bulb)	Indoor: 75°F db/63°F wb (51% RH) Outdoor: 94.8°F db/73.9°F wb	Indoor: 75°F db/63°F wb (51% RH) Outdoor: 92.7°F db/73.6°F wb
	Indoor: 77°F db/64.5°F wb (50.4%RH) Outdoor: 94.8°F db/73.9°F wb	Indoor:77°F db/64.5°F wb (50.4% RH) Outdoor: 92.7°F db/73.6°F wb

It is often assumed that a home's heating and cooling loads are linear with respect to outdoor air temperature (AHRI 2020). For this project, it was assumed that the home heating load was zero when the outdoor air temperature rose above 60°F based on typical home construction and insulation levels for the project homes. For cooling, it was assumed that the home cooling load was zero when the outdoor air temperature fell below 65°F.

Five participating HVAC contractors selected and installed VSHPs produced by four different manufacturers. Four of the five contractors installed a single brand of heat pump, while one contractor installed two heat pump brands as requested for the project. The heating and cooling load lines and heat pump manufacturer capacity data at maximum and minimum speed operation were plotted as a function outdoor dry-bulb temperature. VSHPs that were significantly undersized or oversized were identified and eliminated, resulting in a refined selection of suitable systems, as shown in Figure 3.

Figure 3 illustrates some of the tradeoffs when selecting a heat pump type and size for this home. In this example, a 1.5-ton VSHP is being compared to a 1.5-ton VSHP with compressor vapor injection, both produced by the same manufacturer. The heating and cooling load lines are shown in purple, based on the Manual J design load calculations and assuming zero heating load at 60°F and zero cooling load at 65°F. In this example, the design heating load at 16°F outdoors is about 20% larger than the design cooling load at 93°F outdoors. Based on all homes in the study, the design heating load averaged 39% higher than the design cooling load for the home.

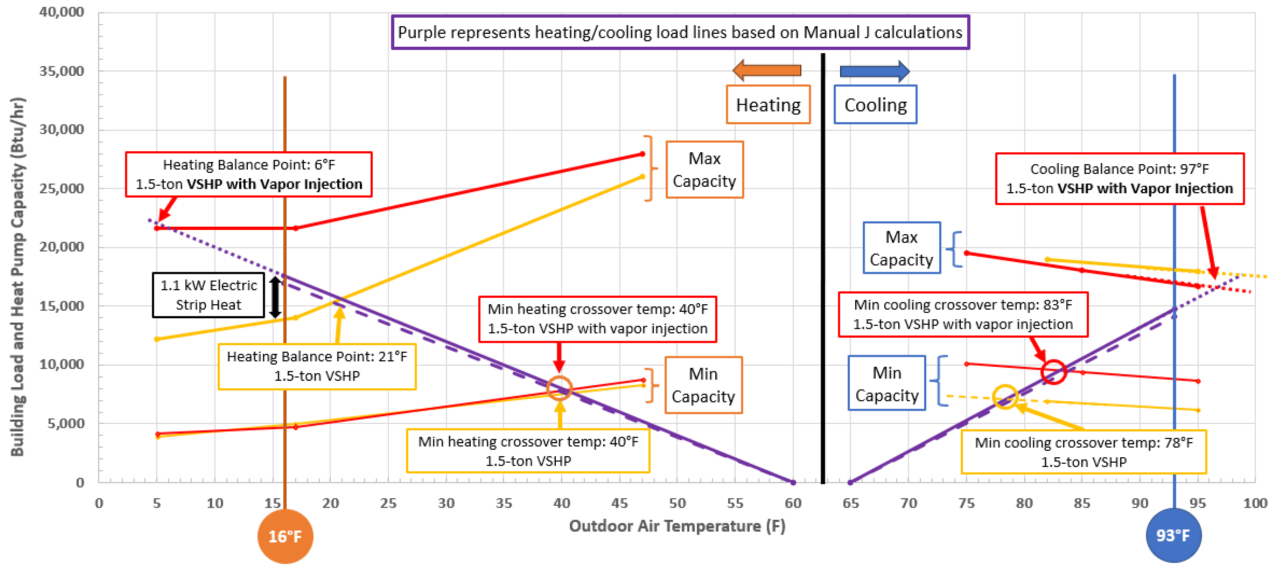

Figure 3. Home heating and cooling load lines and VSHP capacity versus outdoor air temperature

Concentrating on heating performance (left side of Figure 3), the solid red and orange lines on the top left represent that maximum heating capacity delivered at the corresponding outdoor air temperature and 70°F indoor air temperature based on manufacturer's performance data. In this case, the 1.5-ton VSHP with vapor injection (red solid line) intersects the purple heating load line at 6°F; therefore, this heat pump has sufficient heating capacity to meet the entire heating load at the design outdoor temperature of 16°F. For the standard 1.5-ton VSHP (orange solid line), the maximum heating capacity intersects the purple load line at 21°F, 5°F higher than the design outdoor air temperature. For this VSHP, 1.1 kW of electric strip heat is needed to supplement the maximum compressor heating capacity at the design heating temperature of 16°F outdoors.

The red and orange lines on the lower left of Figure 3 represent the minimum heating capacity for the two VSHPs. For this example, both lines cross the heating load line at 40°F (min heating crossover temperature). Below this temperature the heat pump will operate continuously at variable speed to meet the heating load. At outdoor air temperatures above 40°F the unit cycles on/off like a single-speed heat pump. On/off cycling of the heat pump is much less efficient than operating continuously at variable speed, so the goal is to have the minimum heating crossover temperature to be as high as possible (e.g., 45-50°F).

In cooling mode, the maximum cooling capacity of both VSHPs (red and orange lines, upper right) cross the home cooling load line several degrees higher than the cooling outdoor design temperature of 93°F. At minimum speed operation in cooling mode (lower right of Figure 3), the VSHP with compressor vapor injection (red line) begins to cycle on/off when outdoor air temperatures fall below 83°F. For the standard VSHP (yellow), the minimum speed cooling crossover temperature is 5°F lower at 78°F. For this example, the standard VSHP should operate more efficiently in cooling mode due to less on/off cycling.

For each home, EPRI worked with the HVAC contractor to discuss the issues shown in Figure 3. In addition, the installed first cost difference between VSHP alternatives was considered, availability of specific heat pumps (supply chain delays due to COVID), as well as the contractors willingness to install a VSHP with no strip heat or with a small amount of strip heating. For the example in Figure 3, the standard VSHP with 3kW of electric strip heat (minimum heater size offered by the manufacturer) was selected for installation.

Table 3 summarizes the VSHP nominal capacity and efficiency metrics, along with the installed electric heat strip size, for all project homes. The average home had 1,286 ft^2 of conditioned floor area, installed VSHP was 1.9 tons nominal capacity with 2.3 kW of electric strip heat. Note that 9 of the 24 homes had no electric strip heat installed. For comparable single-speed heat pumps, 5 to 10 kW of electric strip heat would normally be installed depending on the nominal capacity of the SSHP. Therefore, the average of 2.3 kW installed with the VSHPs was

Table 3. Summary of installed variable speed heat pumps and electric strip heat size

Home #	Heating design outdoor temp (F)	Heat pump manufacturer	SEER2	EER2	HSPF2	Installed electric strip heat size (kW)	Nominal capacity (tons)	Home floor area (ft^2)
1	19	Manufacturer 1	16	9.9	8.4	0	2	1,300
2	19	Manufacturer 1	21	13.2	10.7	0	1.5	640
3	19	Manufacturer 2	17.05	13.35	8.9	0	1.5	1,224
4	19	Manufacturer 1	21	13.2	10.7	0	1.5	1,200
5	19	Manufacturer 2	17.25	12.3	9.25	0	1.5	1,200
6	19	Manufacturer 1	21	13.2	10.7	0	1.5	1,164
7	19	Manufacturer 4	17	12	8.5	0	3	2,044
8	19	Manufacturer 4	17	12	8.5	5	3	1,248
9	16	Manufacturer 3	17.1	9.9	8.2	5	2.5	2,240
10	16	Manufacturer 2	17.05	13.35	8.9	3	1.5	1,000
11	16	Manufacturer 1	16	9.9	8.4	3	2	936
12	16	Manufacturer 1	20	13.9	9.5	5	1	950
13	16	Manufacturer 1	16	9.9	8.4	5	2	1560
14	16	Manufacturer 2	16.4	11.9	9.25	3	2	1394
15	16	Manufacturer 2	17.05	13.35	8.9	3	1.5	1179
16	16	Manufacturer 3	17.1	9.9	8.2	3	2.5	1582
17	16	Manufacturer 1	18.7	12.4	9.2	0	1.5	780
18	16	Manufacturer 3	17.1	9.9	8.2	5	2.5	1,632
19	16	Manufacturer 1	16	9.9	8.4	3	2	1,560
20	16	Manufacturer 3	17.1	9.9	8.2	3	2.5	1,300
21	16	Manufacturer 1	21	13.2	10.7	3	1.5	1,150
22	16	Manufacturer 1	18.7	12.4	9.2	0	1.5	1,342
23	16	Manufacturer 1	16	9.9	8.4	3	2	1,094
24	16	Manufacturer 1	16	9.9	8.4	3	2	1,144
		Average	17.7	11.6	9.0	2.3	1.9	1,286
		Minimum	16.0	9.9	8.2	0	1.0	640
		Maximum	21.0	13.9	10.7	5	3.0	2,240

significantly lower (~70%) than if SSHPs had been installed with conventional strip heat sizing. The seasonal energy efficiency ratio (SEER2) for all project heat pumps averaged 17.7, with a range of 16.0 to 21.0. The seasonal heating performance factor (HSPF2) for all heat pumps averaged 9.0, with a range of 8.2 to 10.7.

Measured Performance

Residential Heat Pump Demand Aligns with Electric Grid Peak Demand

It is well known that residential all-electric heat pumps contribute to the utility grid peak demand on both hot summer afternoons and cold winter mornings. Figure 4 shows TVA's electric demand (blue line) for 4 consecutive hot summer days in August 2023 (EIA 2024). During peak periods around 4:00-6:00 pm central time each day, the electric demand met or exceeded 31,000 megawatts, the highest summer demand in 15 years. The corresponding outdoor air temperature measured in Nashville, Tennessee (NOAA 2024) is also plotted (purple line), showing the electric demand peaks and valleys are approximately in alignment with the rise and fall of outdoor air temperature. Nashville weather was selected to represent the average outdoor temperature experience across TVA's seven-state service territory. For Nashville, the ASHRAE 0.4% cooling design temperature is 94.4°F (ASHRAE 2021), and the measured outdoor temperatures peaked at 95-98°F each of these 4 days. The red line in Figure 4 represents the summation of VSHP electric power for 23 project homes (the 24th home did not have its VSHP installed until later in August). The project homes are in the Eastern time zone while Nashville is in the central time zone, which explains why the demand for the project VSHPs peak approximately 1 hour earlier than the TVA demand from its entire service territory (most TVA customers are in the Central time zone). On the fourth consecutive hot day, the peak demand for the 23 project VSHPs was 36.6 kW, approximately 1.6 kW per heat pump.

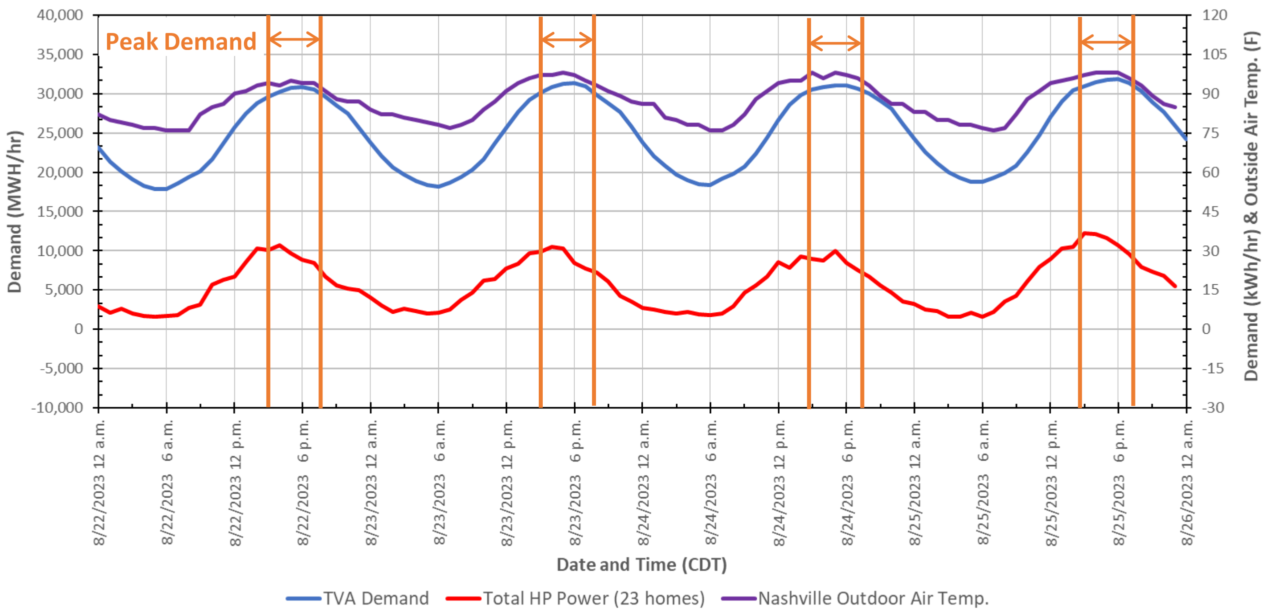

Figure 4. Electric utility and home heat pump hourly demand in August 2023

In mid-January 2024 Winter Storm Heather hit portions of the U.S., with severe cold weather gripping the southeastern U.S. and heavy snowfalls in both Nashville (6-8 inches) and Knoxville, TN (9-12 inches). Figure 5 shows TVA's electric demand from January 16-21, 2024 with record demand over 34,000 megawatts on the mornings of January 17 and 21 (blue line) (EIA 2024). On these two days, the low outdoor air temperatures in Nashville were 0-5°F (purple line) (NOAA 2024), well below the ASHRAE 99.6% heating design temperature of 14.9°F. As expected, TVA demand falls as the outdoor air temperature rises on winter day afternoons. The red line in Figure 5 represents the summation of hourly demand for 23 project VSHPs, including any resistance heat usage (1 project home was sold in Fall 2023 and the associated monitoring equipment removed). The peak power demand for the 23 VSHPs was approximately 77kW, coinciding with the two mornings with coldest outdoor air temperature, averaging approximately 3.3 kW per heat pump.

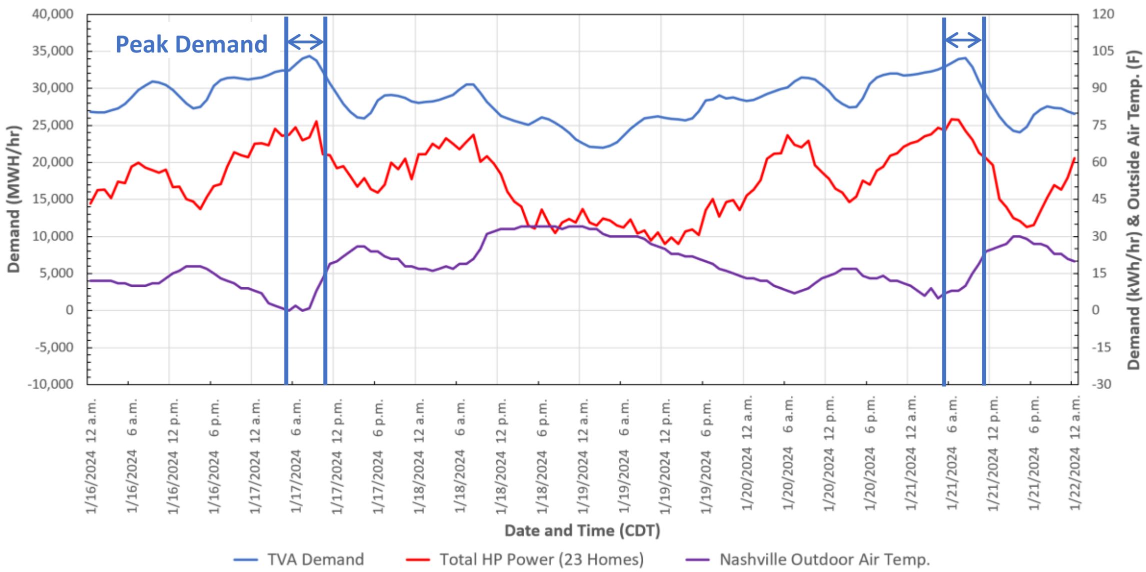

Figure 5. Electric utility and home heat pump hourly demand during Winter Storm Heather in January 2024

Preliminary Estimate of Winter Peak Demand Reduction

A key project goal is to determine the reduction in winter peak demand using VSHPs with little-to-no electric resistance supplemental heat instead of conventional SSHPs with standard amount of resistance heat. Initial reduction estimates are being performed using heat pump manufacturer's performance data for both the VSHPs used for this project and 2023 minimum efficiency conventional SSHPs, along with the Manual J design heating loads for the project homes. Preliminary results, based on 12 of the 24 project homes, indicate an average winter peak reduction between 1.1 and 1.6 kW per home (Table 4). The analysis will continue for the remaining homes and will be reported in future publications. In addition, the measured data from Winter 2023/2024 will be analyzed to determine winter peak reduction for comparison with the results based on manufacturer's performance data.

Table 4. Preliminary estimate of winter peak demand reduction due to variable speed heat pumps

Outdoor Air Temperatures	Average Winter Peak Demand Reduction
16/19°F (99.6% ASHRAE design conditions)	1.1 kW per home
5°F (Winter storm Heather)	1.6 kW per home

Occupant Survey Results

A comprehensive survey was conducted to gather insights on customer experience and satisfaction with the new variable speed heat pump and home upgrades. Near the conclusion of the heating and cooling season, participating homeowners were contacted via telephone for feedback. Key areas of inquiry included comfort throughout the home, noise levels, and overall satisfaction, measured on a scale of 1 to 10. Table 5 summarizes results gathered for the 2022-2023 heating season and the 2023 cooling season. In addition, homeowners were contacted shortly after Winter Storm Heather (January 2024) and asked about indoor comfort levels experienced during the severely cold and windy weather. Responses are summarized in Table 5 under "Winter Storm 2024".

Since few VSHPs were installed December 2022 through March 2023, only six homeowners were able to provide feedback regarding 2022-2023 heating season performance. The home occupants highly ranked heating performance in terms of comfort, noise level and overall satisfaction, with averaging ranking ≥ 9 on a scale of 1 to 10 in each category. Representative customer responses are also provided in the table.

In late summer 2023, customers were contacted again to gather their perceptions regarding VSHP performance in cooling mode. At this point in the project, all participating homes had their VSHPs installed. Eighteen of 24 homeowners (75%) responded to the summer 2023 survey. Again, homeowners highly ranked VSHP cooling performance in terms of comfort, noise and overall satisfaction, with an average ranking of 8.9, 9.3 (very quiet) and 9.4 respectively.

Note that the minimum rankings for cooling (summer) 2023 were 1 (out of 10). One homeowner indicated that there were problems with the thermostat, the indoor temperature was inconsistent and there were extreme temperature differences throughout the home. In addition, the noise level was very high, to the point where visitors noticed. Unfortunately, the homeowner did not reach out for help to address the issues. After receiving their survey feedback, an HVAC contractor was sent to the home to repair/recommission the new heat pump. Once completed, the homeowner expressed high satisfaction with the new VSHP.

The most recent survey was completed immediately after Winter Storm Heather (January 2024). Customers were specifically asked about indoor comfort levels during this severely cold weather event. Based on 14 respondents (58%), indoor comfort during the event was highly ranked at 8.7 (out of 10) on average, with responses ranging from 4 to 10. For homeowners who experienced poor performance and based on detailed analysis of the measurements collected from each home, two specific issues were identified and are being corrected:

- The manufacturer's default compressor cutout temperature was too high, turning off the compressor at outdoor temperatures below ~15°F, leaving the supplemental heat strips to meet the large home heating load (impacted 4 homes)
- Supplemental electric strip heat not operating (improper setting of configuration switches during commissioning, impacted 2 homes)

Table 5. Homeowner survey responses

	Ranking						
	Comfort (1= poor, 10 = excellent)			Noise level (1 = noisy, 10 = quiet)		Overall (1= very dissatisfied, 10 = very satisfied)	
	Heating 2022 - 2023	Cooling 2023	Winter Storm 2024	Heating 2022 - 2023	Cooling 2023	Heating 2022 - 2023	Cooling 2023
# of responses	5	18	14	6	18	5	18
Avg.	9.0	8.9	8.7	9.7	9.3	10	9.4
Min	5	1*	4	9	1*	10	1*
Max	10	10	10	10	10	10	10

Heating season 2022-2023 representative comments:

How have you liked your heat pump so far?

- Wonderful, has made a huge difference!
- Great, absolutely love it.

How has indoor comfort changed with your new heat pump compared to your old system?

- First time this house has had a ducted heating/cooling system, keeps same temperature throughout the home.
- Maintains constant/consistent temperature within the home, doesn't freeze during cold winter weather. Temperature difference between rooms is small.
- Comfort is great until the thermostat malfunctions (thermostat has been replaced)

How is the noise level of the unit compared to your old system?

- Unit is much quieter!
- Very comfy and quiet.
- I can barely tell it is running, you can hardly hear anything.

Cooling season 2023 representative comments:

How have you liked your heat pump so far?

- Absolutely love it. Runs much better, has lowered my bill, and keeps the house cooler.
- This unit is a 100% improvement! It actually cools the house and doesn't freeze up!
- Love it! My best unit yet! Way better than my previous.

How has indoor comfort changed with your new heat pump compared to your old system?

- Prior to this I only had a window unit, [new unit] just keeps the house so comfortable!
- The temperature is consistent throughout the whole home, it's nice!
- This unit has been a blessing. It feels way better, I don't know how to explain it.

Has your electricity bill seen any changes?

- Extremely lower than before!
- A little bit. It took me a while to get used to this unit, so I was changing the setpoint all the time. I'd say it was more of a user error, it's definitely getting lower now.
- Yes! It has gotten much lower! Even when the rates went up, my electricity bill still decreased. My old unit was never able to cool the house and used up so much energy.

*Heat pump subsequently repaired/recommissioned, homeowner now extremely pleased with performance

Heating Performance during Winter Storm Elliott

In December 2022, Winter Storm Elliott hit the United States producing freezing rain, record low outdoor air temperatures and high winds in the South. The cold temperatures lasted for several days. On Friday December 23, the TVA's system average temperature of 3F at 8 am CST (TVA 2023), ranging from 7F in Chattanooga to 1F in both Memphis and Nashville. The afternoon high temperature averaged 11F across TVA's service territory, with overnight low of 8F. Back-to-back mornings with TVA system average temperatures in the single digits were last experienced in February 1996.

The first VSHP for this pilot project was installed and instrumented at a 1,300 ft^2 single story home located in Chattanooga, Tennessee a few weeks before Winter Storm Elliott. The system is a 2-ton VSHP with compressor vapor injection and zero electric resistance supplemental heat, replacing a conventional SSHP with 8 kW of electric resistance heat. Based on Manual J calculations and manufacturers performance data, the heat pump should have sufficient heating capacity to maintain 70°F indoors at an outdoor air temperature of 14°F.

Figure 6 shows measured indoor air temperatures in the home and the corresponding outdoor air temperature. At midnight on December 23, the outdoor air temperature (pink line) was near 50°F, then dropped to 6°F over a 9-hour period. During the afternoon, the outdoor air temperature rose to just below 15°F, then declined to a low of 11°F on the morning of December 24. The outdoor air temperature remained below 15°F for approximately 30 hours.

The indoor air temperatures near the thermostat (yellow), in the main living area (blue) and in the master bedroom (orange) are clustered near the middle of the graph with value shown on the left-hand vertical axis. Prior to the onset of cold weather, the indoor air temperature remained near the homeowner's setpoint of 78°F. As outdoor air temperature dropped 40°F, the indoor air temperature rose slightly to 79°F. A holiday lunch (cooking, baking, family gathering) was held midday on December 24, shown as increased indoor air temperatures exceeding 80°F. Once the gathering ended, the indoor air temperature returned to near normal.

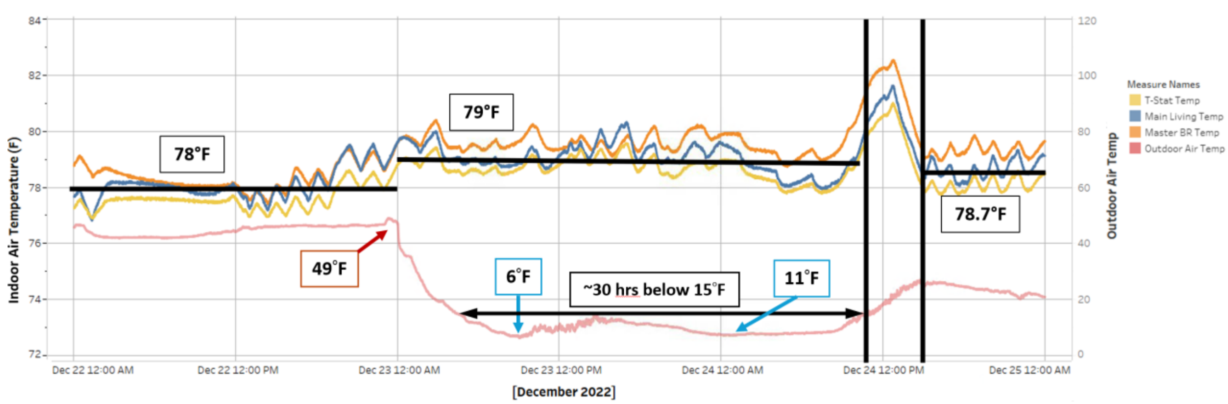

Figure 6. Indoor and outdoor air temperatures for Chattanooga home during Winter Storm Elliott in December 2022

Despite the calculated compressor balance point temperature of 14°F outdoors with 70°F indoor air, the home remained comfortable at the homeowners high indoor setpoint temperature of 78°F with outdoor air temperatures below 10°F. The homeowner was contacted after the event and expressed high satisfaction with the new variable speed heat pump:

- During the cold weather, the heat pump did wonderful, stayed comfortable the entire time
- I can hardly tell it's operating
- Indoor temperature stays constant, much more stable than previous system
- Very comfortable throughout the home

Installed First Cost Premium

VSHPs have significantly higher seasonal energy efficiency and can significantly reduce monthly electricity bills compared to SSHPs. When sized correctly, VSHPs can also reduce peak winter demand and contribute to improved electric grid reliability. However, the installed first cost for a VSHP is higher than for a SSHP.

Under TVA's Home Uplift program, 2.0-ton SSHPs are often installed by vetted contractors (members of TVA's Quality Contractor Network, QCN) at a cost of $7,250. The homes participating in the program are relatively small, and for this pilot project the average conditioned floor area was ~1,300 ft^2 per home. For the 24 homes in this project, the average cost to install the appropriately-sized VSHP was $9,200, a $1,950 (27%, ~$1000/ton) first cost premium over a conventional SSHP.

Pricing for these heat pumps may not necessarily reflect the costs for moderate-to-high income customers. Under the Home Uplift program, a program administrator locates the candidate homes, enlists them in the program, performs a detailed energy audit, and recommends energy efficiency retrofits. Therefore, QCN contractors have customers brought to them with no marketing required. In addition, a few of the HVAC contractors we worked with indicated they provide slightly lower pricing for Home Uplift heat pumps compared to the general public, as a community service to assisted low-income homeowners. VSHPs are a good option for most homeowners, but the specific cost premium of $1,950 for this project may not be representative for larger heat pumps (e.g., 3-5 tons) or for moderate-to-high income customers. As with any large purchase, homeowners are encouraged to obtain multiple quotes and conduct additional information searches to inform their final decision.

Compressor Cutout Temperature in Heating Mode

Heat pumps can be controlled to turn off the compressor below a certain outdoor air temperature and allow a supplemental heating source to provide all heating at colder temperatures. One common application is a dual-fuel heat pump. In this case, the electric compressor provides space heating down to a certain outdoor temperature, then the compressor shuts off and the gas furnace meets the entire home heating load at colder temperatures. This temperature setting is normally selected based on the home heating load, compressor capacity and efficiency as they change with outdoor air temperature, and the relative cost of fuel (e.g., natural gas or fuel oil) versus electricity. The compressor cutout temperature is normally adjustable via a setting within the thermostat, although the manufacturer provides a default value.

For one VSHP product used for this pilot project (installed in 4 homes), the default compressor cutout temperature is 15°F. With the ASHRAE 99.6% heating design temperatures in Chattanooga and Knoxville being 16°F and 19°F, there seemed to be no strong need to modify the default setting. However, during Winter Storm Heather in January 2024 outdoor temperatures dipped to ~0°F in Knoxville. These record low outdoor air temperatures were also experienced in TVA's service territory in December 2022 (Winter Storm Elliott). For these four

VSHPs, the compressor turned off below 15°F and electric strip heat attempted to meet the entire home heating load. With the project objective of installing little-to-no resistance heating, the heat strips for these heat pumps were sized to be "auxiliary" to supplement compressor heating when needed. They were not selected for 100% backup heating capacity, and therefore indoor air temperatures decreased below the homeowner thermostat setpoint when temperatures dropped below 15°F outdoors.

Based on manufacturer's documentation, the compressor cutout temperature is adjustable from -20°F to 65°F. Published performance data indicates that heat pump COP (without strip heat) varies from 1.6 to 2.0 at 0°F outdoors and 70°F indoors (varies by heat pump size/capacity). At -10°F outdoors, the COP drops to 1.4-1.6. At these cold outdoor temperatures, the heat pump efficiency is greater than electric strip heat efficiency (COP ~1). Given this information and the goal of replacing electric strip heat with efficient compressor operation to the extent possible, and reduce strain on the electric grid during severe cold weather events, the compressor cutout temperature is being reset to -20°F. This change will result in improved occupant comfort and less strain on the electric grid during future cold weather events.

Defrost Operation and Controls

The outdoor heat exchangers of air-source heat pumps must be defrosted periodically during cold weather to remove performance degradation due to frost buildup. For residential air-to-air heat pumps, the refrigerant cycle is usually reversed (effectively the heat pump reverts to air conditioning mode) for a period to warm the outdoor coil and melt the frost. During defrost, heat is pulled from inside the home to warm the outdoor coil, so a supplemental heat source (e.g., electric resistance or natural gas) is normally activated to offset the indoor cooling effect due to defrost. The defrost cycle duration is typically 8-10 minutes.

For all-electric air-to-air SSHPs in the U.S., the electric resistance coils are often sized equivalent to the capacity of the heat pump. For example, a nominal 3-ton heat pump has 36,000 Btu/hr of heating/cooling capacity, and the installed electric resistance heat would be 10 kW. The heat strips serve to supplement compressor heating when needed, offset the defrost cooling effect, and provide some redundancy if the compressor malfunctions.

For many heat pumps, the indoor fan operates at a nominal speed to rapidly defrost the outdoor coil, and supplemental heat operation prevents "cold air" (e.g., 40°F) from being supplied to the conditioned space during the defrost cycle. However, the objective for this project was to install VSHPs with little-or-no electric resistance supplemental heat, introducing the possibility of cold supply air during defrost. Some (but not all) VSHP manufacturers allow the central indoor air handler to operate at a very slow speed during defrost. While this may somewhat lengthen defrost duration, the much slower supply air significantly reduces any negative impacts associated with dumping a high volume of cold supply air into the occupied space. The vast majority of VSHPs installed for this pilot project operated the supply air flow at a very slow rate during defrost, by default. HVAC contractors should consider selecting equipment with this capability when trying to eliminate electric strip heat from the installation. In addition, during setup the installer should configure the system (or verify) "low airflow during defrost". Failure to verify may lead to occupant discomfort and unnecessary service calls.

Conclusions

Field testing of variable speed air-to-air heat pumps in 24 occupied east Tennessee homes has successfully demonstrated their ability to provide superior energy efficiency compared to single-speed all-electric heat pumps, while also reducing peak demand during cold winter mornings. This technology application provides a win-win scenario: reduced electric utility bills and excellent indoor comfort for homeowners while reducing peak grid demand, thereby enhancing grid reliability for the electric utility and all customers they serve.

Key to successful residential efficiency solutions is TVA's EnergyRight program which evaluates homes wholistically by, among other things, conducting a comprehensive energy audit at the outset to identify cost-effective energy efficiency improvements to the building envelope (e.g., add attic insulation or replace windows/doors as needed), air tighten the building envelope, seal ductwork used by the space conditioning system, and evaluate the need for replacing water heating or heating/air conditioning equipment. Improvements to the building envelope and ductwork are persistent and can significantly reduce loads on the space heating and cooling system. Therefore, the relatively expensive heat pumps being installed are often much smaller than they would be without the shell and ductwork upgrades, reducing the impact on overall home improvement costs.

Participating homeowners expressed high satisfaction with the new variable speed all-electric heat pumps, in both cooling mode and heating mode, with respect to comfort, low noise level and overall satisfaction with the equipment. On a scale of 1 to 10, the average ranking for these three categories ranged from 8.7 to 10. Supporting findings from other comparable projects, occupants indicated that the indoor temperature is more stable and there is less temperature variation between rooms with the new variable speed heat pump compared to their prior single-speed equipment. The telephone survey calls also allowed some improper heat pump operations to be identified, which were quickly addressed by the HVAC contractors who installed the units.

The project is ongoing through 2024 and data analysis is in progress. Preliminary results indicate an average winter peak demand reduction of 1.1 kW per home at design outdoor air temperatures for east Tennessee (16/19°F). At an extremely low temperature of 5°F, experienced in December 2022 and January 2024 with winter storms Elliott and Heather, the average peak reduction is estimated to be 1.6 kW per home.

Heat pump setup during installation is important to achieve the desired performance. This is especially true for variable speed all-electric heat pumps where the electric resistance strip heat has been sized to supplement heat pump compressor heating instead of sized equal or greater than compressor heating capacity. An especially important setting is the compressor cutout temperature in heating mode. In this study, the default setpoint for one heat pump manufacturer was only a couple of degrees colder than the ASHRAE design heating temperature for the area. While sufficient in typical winter weather conditions, during extreme temperatures experienced during winter storm Heather (e.g., 0-5°F) the compressor turned off at the design outdoor temperature (15°F) and the supplemental electric strip heat was unable to maintain the homeowner's thermostat setpoint. The setting was easily changed to a much lower setpoint temperature. Even at very cold outdoor air temperatures (e.g., -10°F), the variable speed compressor provides meaningful heating capacity at efficiencies significantly greater than the efficiency of electric resistance (e.g., COP ~1.5 vs 1.0).

With the push for electrifying residential space heating, it is important to understand that simply installing the conventional low-cost option of single speed heat pump with electric resistance supplemental heat does not ensure success, particularly in mixed and cold climates where winter heating loads are often much larger than summer cooling loads. While applying conventional SSHPs using conventional equipment sizing methods may work well in hot/mild climates, applying the same methodology in mixed and cold climates can lead to suboptimal compressor heating, high winter peak demand due to excessive supplemental resistance heat usage, and/or oversizing issues that may cause inefficient cooling operation and poor indoor comfort in summer. Efficient electrification, with the least impact on winter peak demand and positive benefit to electric grid reliability, can be achieved with properly sized and installed variable speed heat pumps, little-to-no resistance supplemental heating, and appropriate equipment configuration settings.

References

ACCA (Air Conditioning Contractors of America). 2016. "Manual J Residential Load Calculation, 8th Edition." https://www.acca.org/standards/technical-manuals/manual-j

AHRI (Air-Conditioning, Heating, & Refrigeration Institute). 2020. "AHRI Standard 210/240: 2023 (2020) Standard for Performance Rating of Unitary Air-conditioning & Air-source Heat Pump Equipment." https://www.ahrinet.org/search-standards/ahri-210240-performance-rating-unitary-air-conditioning-air-source-heat-pump-equipment

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.). 2021. "2021 ASHRAE Handbook - Fundamentals – Chapter 14: Climatic Design Information." https://www.ashrae.org/technical-resources/ashrae-handbook

EIA (U.S. Energy Information Administration). 2024. "Hourly Electric Grid Monitor: Tennessee Valley Authority (TVA) electricity overview (demand, forecast demand, net generation, and total interchange)." https://www.eia.gov/electricity/gridmonitor/dashboard/electric_overview/balancing_authority/TVA

EPRI (Electric Power Research Institute). 2021. "Quick Insight: Operating Dynamics of Heating and Cooling Systems During Extreme Temperatures — Thermal and Power System Considerations." Report 3002022772. https://www.epri.com/research/products/000000003002022772

NOAA (National Oceanic and Atmospheric Administration). 2024. National Centers for Environmental Information: Climate Data Online. https://www.ncei.noaa.gov/cdo-web/

Tennessee Valley Authority. 2023. "After Action Report: Winter Storm Elliott." https://www.tva.com/about-tva/reports

Tennessee Valley Authority. 2024a. TVA EnergyRight. https://energyright.com/

Tennessee Valley Authority. 2024b. TVA EnergyRight - Home Uplift. https://energyright.com/residential/home-uplift/