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Variable Speed Heat Pump Load Flexibility Modeling

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EXECUTIVE SUMMARY

The heating and cooling demand in buildings represents a considerable share of the overall energy. The recent surge in policies promoting electrification and decarbonization have given rise to new residential heating and cooling technologies, including inverter-based variable speed heat pumps (VSHPs) and inverter-based variable speed cold climate heat pumps (CCHPs). Such systems are designed to vary the speed of compressors and fans to increase the efficiency of the heat pump system from part-load to full-load conditions. In recent years, VSHPs have gained increased attention for their demand flexibility by adjusting their output to match fluctuating heating and cooling needs. VSHPs can be programmed to respond to grid signals or time-of-use pricing, shifting the energy consumption to off-peak hours and thus potentially reducing summer and winter peak demand. In addition, by smoothing out electricity demand, VSHPs could contribute to a more stable and reliable power grid, particularly when integrating with renewable energy sources like solar and wind. Although VSHPs are mentioned as potential heat pump technology for demand flexibility, very limited data is available to quantify their capability, applicability, and use for improved customer experience and end-use flexibility. This project seeks to provide new insight and data on the operation of advanced VSHPs in typical space-conditioning applications where the equipment can serve as a flexible load.

The main objectives of the project are:

- Perform a technology and market assessment study, as well as an energy modeling study of residential VSHPs to assess and quantify the demand flexibility for Oregon and Washington
- Provide NEEA with new learning and inform NEEA's energy efficiency and demand management (including demand flexibility program designers) with information on capabilities and limitations of residential VSHPs

Specific research questions include:

- Who are the VSHP vendors/manufacturers offering Demand Response (DR) capability?
- Can VSHPs systems respond more effectively to DR signals compared to other types of HVAC equipment?
- Can standard communications protocols interact with various vendors' Application Programming Interfaces (APIs) to leverage the advanced technologies?
- What grid connectivity protocol is appropriate for VSHPs?
- What is the load shifting potential, in terms of power and the time duration without impacting customer comfort?

Key Takeaways from the Market Assessment:

- Some of the manufacturers have demonstrated the capability of their equipment to respond to DR events and are actively participating in research studies to improve DR programs and standards.

- Multiple manufacturers are leaders in DR development and are interested in future lab and field demo collaborative work.
- The technology of using VSHP for DR is in very early stages and still under development.
- Enhancements to AHRI 1380 are needed and need input from all stakeholders (manufacturers, researchers, policy advocates, standards developers, aggregators, grid operators, utilities, etc.).
- Value and opportunities for utilities, customers, and aggregators are not clear. In many cases, upper management is not upbeat on opportunities based on past similar investments in DR with no returns on investment.
- Some manufacturers want responsibility for just DR functionality of heat pumps. They do not want to take responsibility for how communication will be with the grid via an aggregator or other means.
- Lack of consensus amongst manufacturers and DR providers. A true end-to-end seamless solution is required for widespread adoption.

Key Outcomes and Lessons Learned from Modeling:

Overall, the modeling indicates that VSHP-based DR potential is strongly dependent on outdoor temperature, equipment sizing, and event parameters (curtailment level, maximum indoor temperature offset (MITO), and duration). As a result, AHRI 1380-style events can range from providing substantial kW reductions in select conditions to providing little or no reduction when systems are already operating below the requested power limit.

Heating – moderate outdoor temperatures (30°F (-1.1°C) and above)

- In all modeled climate zones, VSHPs/CCHPs frequently operated below 70% of RLP at these conditions, resulting in little to no incremental kW reduction during General Curtailment. (e.g., Seattle heating at 35–40°F (1.7°C–4.4°C): baseline peak ~1.24–1.42 kW (older home) and ~0.64–1.10 kW (new home), with no measurable kW reduction under curtailment).
- Critical Curtailment may be required to realize meaningful demand reductions during above-freezing events.

Heating – colder outdoor temperatures (25°F (-3.9°C) and below)

- Climate Zone 4C (Seattle/Portland): General Curtailment on colder (20–25°F (-6.7°C–(-)3.9°C)) days produced significant kW reductions relative to baseline. (e.g., Seattle 20–25°F (-6.7°C–(-)3.9°C) heating: baseline peak ~4.55–4.79 kW (older home) reduced to ~2.58–2.80 kW under General Curtailment, a ~1.97–2.16 kW reduction).
- However, larger MITO values and longer events increased comfort impacts and post-event snapback demand; shorter events (1–2 hours) with smaller MITO (2°F (1.1°C)) best balanced DR and comfort in these conditions. In those same Seattle 20–25°F (-6.7°C–(-)3.9°C) cases, indoor temperature dropped ~3.0–4.6°F (1.7°C–2.6°C) and snapback ranged ~1.7–3.4 kW, increasing with longer events and larger MITO.

- Climate Zones 5B and 6B (Bend/Colville): General Curtailment showed potential for kW savings in colder bins, but at around 10°F (-12.2°C) the CCHP often operated near ~70% RLP, limiting the available reduction. (e.g., Bend 10–15°F (-12.2°C–(-)9.4°C) heating: baseline peak ~2.46–2.48 kW reduced to ~2.31 kW under General Curtailment, only ~0.15–0.17 kW reduction).
- Because state-of-the-art CCHPs maintain capacity at very low ambient temperatures (e.g., ~5°F (-15°C)) and are commonly sized to meet heating loads at design conditions, the modeling suggests a 'sweet spot' for General Curtailment may occur between ~0°F (-17.8°C) and 10°F (-12.2°C) in colder climates.

Cooling – moderate hot days in the Pacific Northwest (90–100°F (32.2°C–37.8°C))

- In older homes, General Curtailment often had little or no impact on kW because systems sized for heating tended to operate part-load during these cooling conditions. (e.g., Seattle 90–95°F cooling in an older home: baseline peak ~2.34 kW with no measurable reduction under curtailment).
- In new homes, some kW reduction potential emerged because modeled heating and cooling loads were more comparable; systems operated closer to 60–80% of RLP, making curtailment more consequential. (e.g., Seattle 90–95°F (32.2°C–35°C) cooling in a new home: baseline peak ~2.13 kW reduced to ~1.68 kW under General Curtailment, ~0.45 kW reduction, with ~1.62°F (0.9°C) indoor temperature increase).
- For new homes, Critical Curtailment was consistently more impactful than General Curtailment. Longer events (3–4 hours) and larger MITO (4°F (2.2°C)) were generally feasible, with limited comfort impacts in the modeled cooling bins.
- Across vintages, hotter conditions (>100°F (37.8°C)) are more likely to produce measurable demand reductions, but these extremes are not well represented in a typical (TMY3) weather year. For context, modeled general/critical curtailment limits in Seattle were approximately 1.43/0.82 kW (new home) and 2.26/1.29 kW (older home). Illustrating why many mild-hour operating points fall below the 70% RLP threshold.

Comfort and snapback behavior

- Increasing MITO and/or extending DR event duration increases the magnitude of indoor temperature drift and can elevate post-event snapback demand. Shorter events and smaller offsets reduce these risks but also cap achievable DR.

Recommendations for Future Work

The recommended next steps to advance demand response (DR) implementation using VSHPs from the lessons learned from market assessment, standards discussions, and the parametric modeling results include:

1. Standards and interoperability

- Continue active engagement in the AHRI 1380 update process and advocate for broader stakeholder representation (utilities, grid operators, aggregators/DR providers, and

researchers) to ensure the standard reflects program implementer needs—not only manufacturer requirements.

- Support development of a more harmonious DR standards backbone to reduce fragmentation across residential HVAC, commercial HVAC, water heating, and other DER applications.
- Prioritize clarification in AHRI 1380 for: (a) the definition of Rated Load Power (RLP) in heating, (b) how MITO is set and enforced, (c) required behavior upon event exit (end of event, opt-out, or MITO reached), and (d) minimum reporting requirements (parameters and sampling rate).
- Work with distributed energy resource management systems (DERMS)/aggregators and OEMs to validate end-to-end communication pathways (Virtual Top Node (VTN) → Virtual End Node (VEN)/OEM cloud → device) and to identify a minimum viable set of interoperable messaging across candidate protocols (e.g., OpenADR, CTA-2045, Home Connectivity Alliance (HCA)/Matter as applicable).

2. Utility program design and customer experience

- Develop DR program rules that are adaptive by season, climate zone, and expected operating conditions at event onset. Modeling indicates that General Curtailment may provide little benefit when systems are already operating below 70% of RLP in mild conditions; Critical Curtailment or alternative strategies may be required for predictable shed.
- Keep the end-user experience central to program success. As indoor temperatures drift from setpoint during events, discomfort can increase opt-out rates. Pair event design (MITO and duration) with clear customer communication and incentives to offset occasional discomfort.
- Coordinate with utilities to identify priority grid needs (transformer, feeder, substation, or regional) and quantify how many DR-capable devices are available, expected opt-in rates, and achievable coincident load reduction under representative weather bins.
- Evaluate event exit strategies to mitigate secondary peaks and snapback demand, including ramped recovery, staggered event end times, or staged setpoint return.

3. Value assessment (utilities, customers, aggregators, and manufacturers)

- Conduct an economic and financial assessment of VSHP/CCHP curtailment programs, quantifying grid value (peak reduction, avoided capacity, reliability) and customer value (bill savings, incentive levels required for participation).
- Assess dual-fuel considerations where applicable, including the economic and emissions tradeoffs of engaging fossil backup heat during electric peak events and the potential role of multi-commodity price signals.
- Define performance metrics that matter for program ROI (kW shed magnitude, persistence over event duration, opt-out rates, and net load shape including snapback).

4. Validation through laboratory and field testing

- Near-term: conduct controlled laboratory testing to validate equipment performance maps and curtailment behavior at representative operating points, including low-speed operation, defrost/oil-management impacts, and event exit logic.

- Longer-term: execute larger-scale field demonstrations to quantify real-world kW reduction, persistence, customer comfort/satisfaction, and adoption barriers across utilities and climates.

5. Additional modeling and sensitivity analysis

- Extend simulations to more extreme ambient conditions (e.g., <10°F (-12.2°C) heating and >100°F (37.8°C) cooling) that are not well represented in typical meteorological year files, to bound curtailment potential during the most grid-constrained periods.
- Evaluate sensitivities to heat pump sizing practices (oversizing factors, balance points, cooling-driven sizing in milder climates) and quantify impacts on available shed and comfort outcomes.
- Assess alternative DR strategies such as pre-heating/pre-cooling, additional setpoint schedules, and staged recovery to reduce snapback while maintaining comfort.

INTRODUCTION

Home electrification is on the rise, offering new resources for flexible grid management. Overall energy consumption is growing, primarily in the commercial and industrial sectors [1]. Appliance use in the home can be curtailed during peak electric demand periods, helping grid operators maintain grid stability and avoid blackouts. One advancement gaining adoption in residential HVAC is inverter-based VSHP for space heating and cooling. Such systems are designed to vary the speed of the compressor(s) and fan(s) to increase the efficiency of the heat pump system from part-load to full-load conditions. Inherent with this capability is its application as a DER. During a DR event, VSHPs can be programmed to respond to grid signals or energy prices, shifting energy consumption to off-peak hours and potentially reducing summer and winter peak electricity demand.

In a conventional demand response scenario, the thermostat receives a DR signal and subsequently adjusts the setpoint temperature to reduce power consumption by effectively inducing the heat pump or air conditioner (A/C) to cycle off. At any point, participants may opt-out of a DR event to resume normal operation. If continuing in the DR event, once the space temperature drifts to the new setpoint, the HVAC system resumes normal operation at the new temperature until the demand response period concludes. VSHPs differ in their ability to continue heating or cooling during a demand response event at a specified power curtailment level by limiting the compressor and fan speed. If power is limited below the space heating or cooling demand, the space temperature will still drift away from the setpoint as in the temperature setback approach, but over a longer duration to do so compared to cycling the equipment off. Partial heating or cooling through a demand response event can prolong occupant comfort and reduce participant event opt-outs.

Despite the inherent potential of VSHPs for demand flexibility, limited data is available to quantify their capability, applicability, and use for improved customer experience and end-use flexibility. This project aims to provide new insights and data on the operation of advanced VSHPs in typical space-conditioning applications where the equipment can serve as a flexible load. Specific research questions addressed by the authors included identifying VSHP vendors offering Demand Response capability, assessing the effectiveness of VSHPs in responding to DR signals compared to other HVAC equipment, and evaluating the interaction of standard communication protocols with various vendors' APIs to leverage advanced capabilities.

Background

Grid operators must balance power generation supply with power demand. At times, demand may exceed supply, requiring corrective actions such as operating peaker power generation plants, purchasing power from the open market, or curtailing load. Options to curtail load are grouped under the term "Distributed Energy Resource" (DER). DER devices include batteries, smart thermostats, electric vehicles, and other appliances that can interact with the grid. VSHPs are an emerging option with enhancements over conventional demand response methods for interaction with space conditioning equipment through smart controls.

Figure 1 demonstrates a communication sequence for a demand response event. When there is high demand on the local electric grid (from transformer level up to regional RTO/ISO (US electric Regional Transmission Organizations and Independent System Operators)) relative to the available power supply, an automated system at a grid monitor generates a DR event. This Demand Response Provider (DRP) broadcasts the DR event, which is received by DER devices. Control logic within each device interprets the DR signal and responds accordingly, reporting status and various metrics. A successful event curtails sufficient power to maintain balance on the grid until high demand subsides back to normal operations.

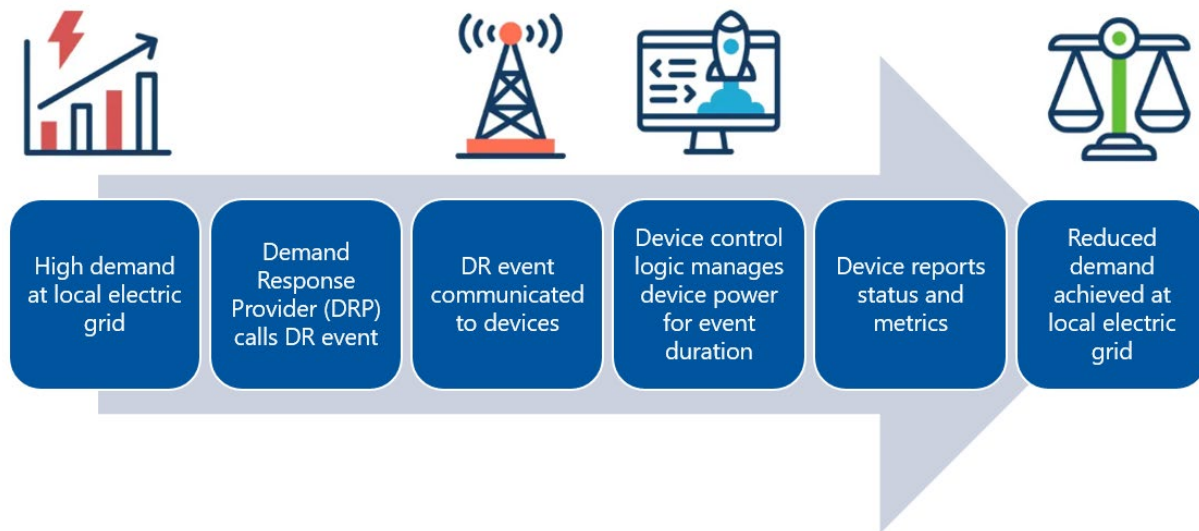


Figure 1: Demand Response Event Sequence of Communication

Communication protocols through the sequence described is a focus area for improved grid management. Each RTO/ISO can utilize its own preferred protocol, including OpenADR 2.0b [(2)], OpenADR 3.0 [(2)], CTA-2045-B [(3)], IEEE 2030.5 [(4)], or other custom or proprietary communication. The market has generally adopted different protocols by application. OpenADR is generally preferred for HVAC applications. Water heating applications typically implement CTA-2045. Other home appliances integrate with home energy management systems and Home Connectivity Alliance or Matter. DER devices such as electric vehicles (EV), solar photovoltaic panels (PV), and home battery backups use IEEE 2030.5. Mixed within any of these applications are devices using proprietary communication through the device manufacturer's cloud platform. The fragmented adoption of communication protocols from grid operators downstream to end use appliances presents a potential barrier to demand response implementation and optimization of the available resources.

More specifically, the demand response for VSHPs is the focus of the present research. Demand response for residential A/C and heat pumps have evolved with technological advancements. Figure 2 highlights the stages of DR development for HVAC applications. Initially, Direct Load Control received a signal directly from the utility and switched a relay off to prevent operation of the equipment. This method did not have any feedback or safety measures in place to override and prevent extreme temperature offsets. Particularly concerning, it could be an event during winter operation if the home temperature drops too low. An advancement was setpoint control,

made possible by the advent of smart, grid-connected controls, typically proprietary smart thermostats. During a DR event, the thermostat setpoint is setback 1 to 4°F (0.5 to 2°C). During this period, the equipment coasts until the new setback temperature is reached and then resumes normal operation at the new setpoint. While this prevents excessive temperature offsets, during extreme weather conditions, the home can quickly reach the setback, limiting the effectiveness of curtailed power. Newer to the market are variable speed heat pumps. Instead of inducing equipment to cycle off while coasting to a setback temperature, the VSHP can continue providing heating or cooling up to a power limit, defined with AHRI Standard 1380 [(5)]. The duration of curtailed power usage is extended compared to setpoint control, with improved occupant thermal comfort.

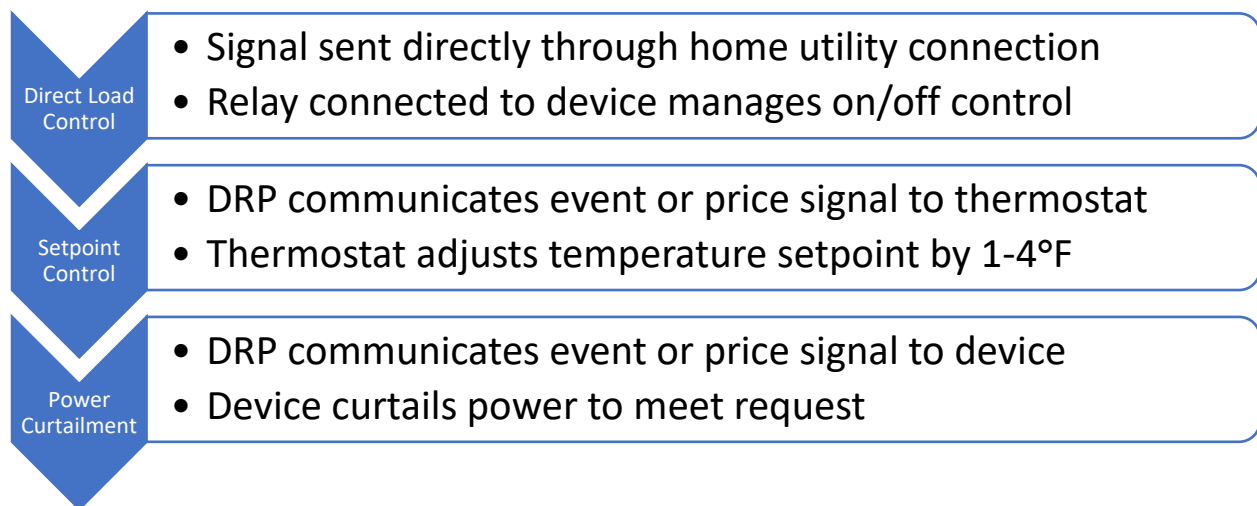


Figure 2: Demand Response Evolution

Compared with conventional demand-response temperature-setback methods, VSHPs maintain thermal comfort for longer by continually providing some load, even when it is still below the required space load. With a lower impact on thermal comfort, homeowners are more likely not to opt out of an event. Figure 3 models the impact on indoor air temperature (IAT) through 3 simulated demand response events for an 82°F (27.8°C) average outdoor air temperature. Each case represents a 3-hour DR event commencing as the afternoon outdoor temperature approaches the peak of the day (95°F (35°C)). In the upper chart, a direct load control relay turns the HVAC equipment off for the event duration, representing the maximum demand reduction (100%) but at the expense of the greatest impact on occupant thermal comfort with 8°F (4.4°C) space temperature rise and a recovery period in excess of 2 hours to return to normal operation. The middle chart is a conventional thermostat setback, 3°F (1.7°C). The space reaches the setback temperature 1 hour into the event and begins controlling to the new setpoint for the remaining 2 hours of the event. Following the event, operations recover back to normal in about 1 hour. The final chart shows a critical curtailment event where the power is limited to 40% of the Rated Load Power (RLP). The space temperature drift reaches 3°F (1.7°C) at the end of the 3-hour event in contrast to 1 hour when the equipment cycles off. Operating through the event at reduced speed curtailed power consumption by 32% and was consistent each hour. From the perspective of grid operators, the curtailment method results in more consistent power demand during the entirety

of an event with improved occupant comfort. In other demand response methods, either occupant comfort suffers or snapback occurs during the middle or immediately after an event.

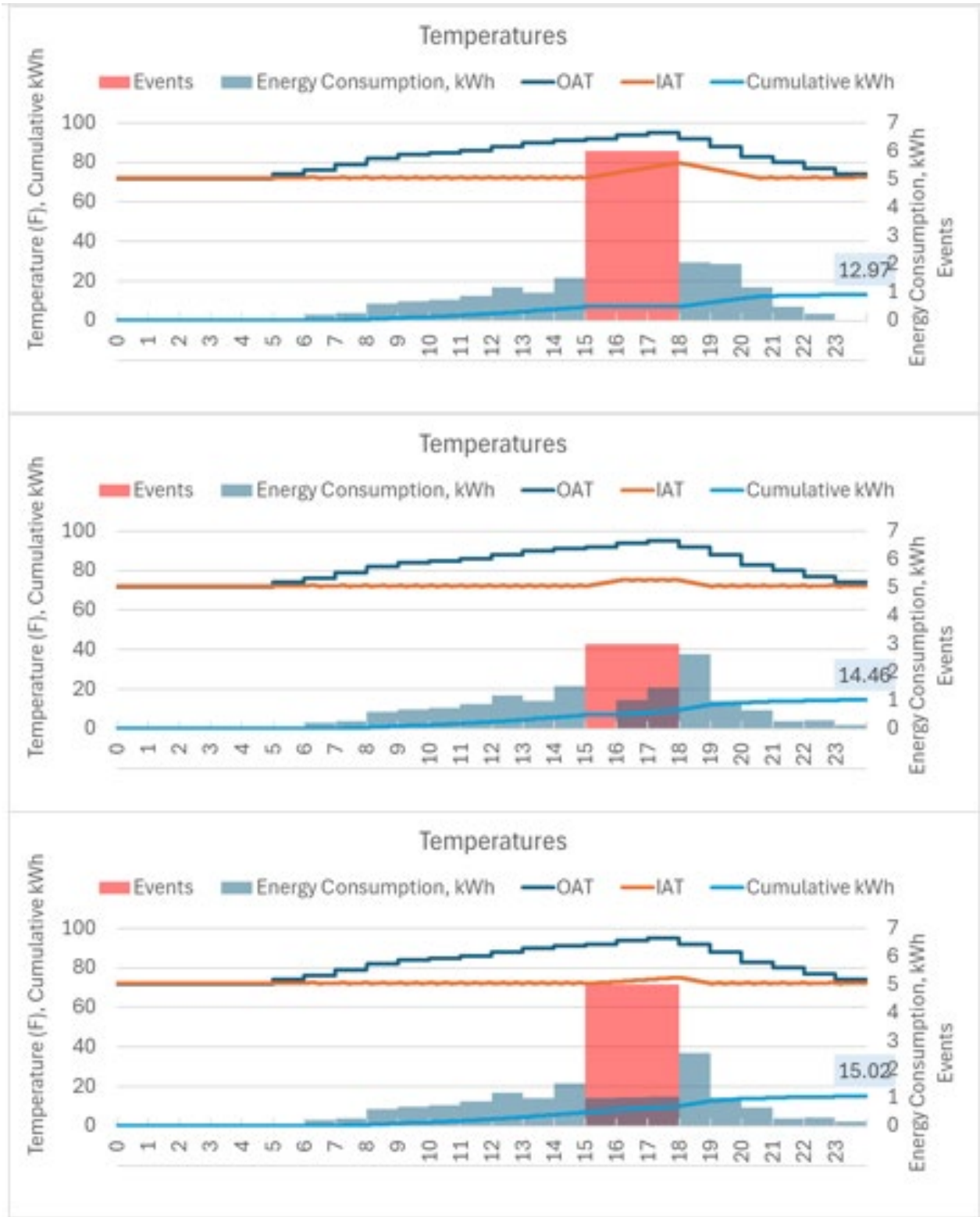


Figure 3: Simulated comparison of HVAC DR methods

VSHPs are typically only available with communicating controllers, which are generally proprietary to each manufacturer. As such, the product range is limited to premium products, a potential limiting factor in adoption and utilization. Overall, wholesale demand response resources represent 6.5% (33.05 GW) of peak demand as of 2023 [(6)] within RTOs/ISOs . The percentage isolated to VSHPs only is significantly lower.

Project Objectives

The objectives of the research team were to assess the current market landscape for VSHP demand response and model the impacts. Tasks entailed (a) reviewing existing research, standards, and communication protocols, (b) assessing manufacturer readiness for implementation and their approach, and (c) performing modeling simulations of key DR parameters for the Pacific Northwest region.

Specific research questions include:

- Who are the VSHP vendors/manufacturers offering DR capability?
- Can VSHP systems respond more effectively to DR signals compared to other types of HVAC equipment?
- Can standard communication protocols interact with various vendors' APIs to leverage the technology's advanced capabilities?
- What grid connectivity protocol is appropriate for VSHPs?
- What is the load shifting potential, in terms of power and the time duration, without impacting the occupant thermal comfort?

Addressing the research questions included literature review, numerous discussions with lead researchers and product manufacturers, participation in AHRI Standard 1380 sub-committee meetings, and modeling with EnergyPlus™ and custom post processing scripts to implement DR events.

TECHNOLOGY and MARKET ASSESSMENT

Certification and Communication Protocols

As of December 2025, demand responsive controls are currently optionally adopted by Authorities Having Jurisdiction (AHJ). Minimum requirements, if adopted, are specified in International Energy Conservation Code (IECC) 2024 Appendix CI [(7)]. All systems must be capable of automatically adjusting the thermostat setpoint up to 4°F (2°C). Equipment with 2 or more stages of control and cooling capacity under 65,000 BTU/h is needed to comply with the communication and performance requirements of AHRI Standard 1380. All other thermostats are expected to comply with certified OpenADR 2.0a or 2.0b VEN, IEC 62746-10-1, ANSI/CTA 2045-A or B, or other communication protocol specified by the controlling entity (utility or service provider).

The Consortium for Energy Efficiency (CEE) offers equipment specifications for advanced efficiency. New, effective January 1, 2026, is the inclusion of Air-Conditioning, Heating, and Refrigeration Institute (AHRI) 1380 compliant load management [(8)], with details in Figure 4. When discussing demand response with equipment manufacturers, offering qualified products for the CEE specification was a motivating incentive.

Effective January 1, 2026

2026 CEE Split ASHP Specification						
CEE Level	SEER2	EER2	HSPF2	COP at 5°F*	Capacity Ratio [~]	Load Management [†]
CEE Tier 1						
Path A	≥ 16.0	≥ 9.8	≥ 8.5	≥ 1.75	≥ 65% at 5°F/47°F	AHRI 1380
Path B	≥ 16.0	≥ 11.0	≥ 8.0	≥ 1.75	≥ 50% at 5°F/47°F	AHRI 1380
CEE Advanced Tier						
Refer to the DOE Cold Climate Heat Pump Challenge Specification						

2026 CEE Packaged ASHP Specification						
CEE Level	SEER2	EER2	HSPF2	COP at 5°F*	Capacity Ratio [~]	Load Management [†]
CEE Tier 1	≥ 15.2	≥ 10.0	≥ 7.2	≥ 1.75	≥ 45% at 5°F/47°F	AHRI 1380

Figure 4: 2026 CEE ASHP Specification

Originally released in 2019, and under review for an updated 2026 version, AHRI Standard 1380 establishes equipment specifications for demand responsive controls for multi-stage or continuously variable HVAC systems. Specifications apply to HVAC systems under 65kBTU, with two or more discrete cooling stages or continuously variable capacity control. Three DR events are defined: General Curtailment, Critical Curtailment, and Emergency. Each event designates a pre-determined maximum power consumption for the HVAC system relative to the Rated Load Power (RLP). RLP is separately defined for cooling and heating events [(9)] at conditions A_{FULL} for cooling (outdoor 95°F (35°C) and indoor 80°F (26.7°C) dry bulb / 67°F (19.4°C) wet bulb) and $H1_{Nom}$ for heating (outdoor 47°F (8.3°C) and indoor 70°F (21.1°C) dry bulb / 60°F (15.6°C) wet bulb).

General curtailment limits power consumption to less than 70% of the RLP and critical curtailment limits power consumption to less than 40% of the RLP. In a grid emergency, HVAC systems responding to the DR event do not run, with power consumption allowed only for the control board and crankcase heater. During any event, users have the option to opt-out at any time, or the HVAC system will automatically exit the event if the MITO is reached. The MITO value is not explicitly defined in the current 2019 specification and open to being set through the communication protocol, however 4°F (2°C) is generally recognized as an appropriate value.

AHRI Standard 1380-2019 specifies CTA-2045-A or OpenADR 2.0 as acceptable communication protocols. Each has variances in their respective implementation and interface, but ultimately reflect similar messages delivered and equipment acknowledgements and responses. CTA-2045 is a modular communications interface (MCI) to facilitate communications with residential devices for applications such as energy management. The MCI provides a standard interface for energy management signals and messages to reach devices. Described as a “USB for appliances,” the MCI plugs-in to an CTA-2045 compliant appliance and allows two-way communications between the device and a utility. OpenADR provides a non-proprietary, open standard Demand Response (DR) interface that allows DR service providers to communicate DR signals directly to customer devices using internet.

CTA-2045-A requires a physical interface (communication module), whereas OpenADR 2.0 communicates via the internet through Ethernet or Wi-Fi with access to a cloud server. For OpenADR, the cloud server is referred to as the Virtual Top Node (VTN) and the HVAC equipment or OEM cloud as the Virtual End Node (VEN). The VTN is usually operated by utilities or aggregators and sends DR event signals. Version 2.0 utilizes Simple Object Access Protocol (SOAP) web protocols. Version 3 implements a more accessible application program interface (API) with Representational State Transfer (“RESTful”) web protocols. While not backward compatible, it enhances program management, real-time event prioritization, and improved integration for DER. In current implementations, each HVAC system manufacturer hosts a VEN in their cloud and then translates the event communication to registered devices via proprietary communication protocols.

Each event communicated includes timing (start time and duration), and status (FAR or NEAR where NEAR is at the start of the event ramp period), pertaining to OpenADR2.0 only. In all protocols, a MITO value is sent to the device, and the requested power curtailment (general, critical, or emergency). An optional feature is the ability to deliver a utility peak load price signal. Devices are not required to respond to a price signal; however, advanced controls may utilize it to shift load and reduce operating costs.

Updates under consideration for 2026 include expanded communication protocols, incorporating the latest versions of OpenADR (OpenADR 3.1) and CTA-2045 (CTA-2045-B), in addition to HCA. These will include appendices detailing methods for implementing necessary communication to comply with the AHRI 1380 standard. In addition to the more accessible API interface in OpenADR 3.1, additional messages are available, including a secondary price signal. The secondary price signal is open at the discretion of the VTN and could include natural gas for applications with dual-fuel heating (electric heat pump primary with fuel-fired furnace as auxiliary or backup). The standard subcommittee is aiming to develop a minimum viable list within the communication

capabilities of each of the referenced protocols, leaving open the possibility of future enhancements and new protocols entering the market.

Careful consideration is ongoing for defining the Rated Load Power (RLP), particularly in heating operation. Demand response events can occur at any time but are more prevalent during extreme weather conditions. In most regions of the U.S., A_{FULL} is representative of peak summertime design conditions and suitable for DR reference. However, in winter, $H1_{Nom}$ is a very mild condition and unlikely to coincide with DR events. For cold climate heat pumps, many utilize vapor injection and/or compressor overspeed techniques to maintain capacity at low outdoor temperatures. The actual power consumption at the onset of a DR event could exceed the RLP, labelled point 1 in Figure 5. The curtailed power request could reduce the compressor speed and capacity much lower than the actual demand, behaving closer to the thermostat setback method where a MITO value will be reached quickly within the DR event.

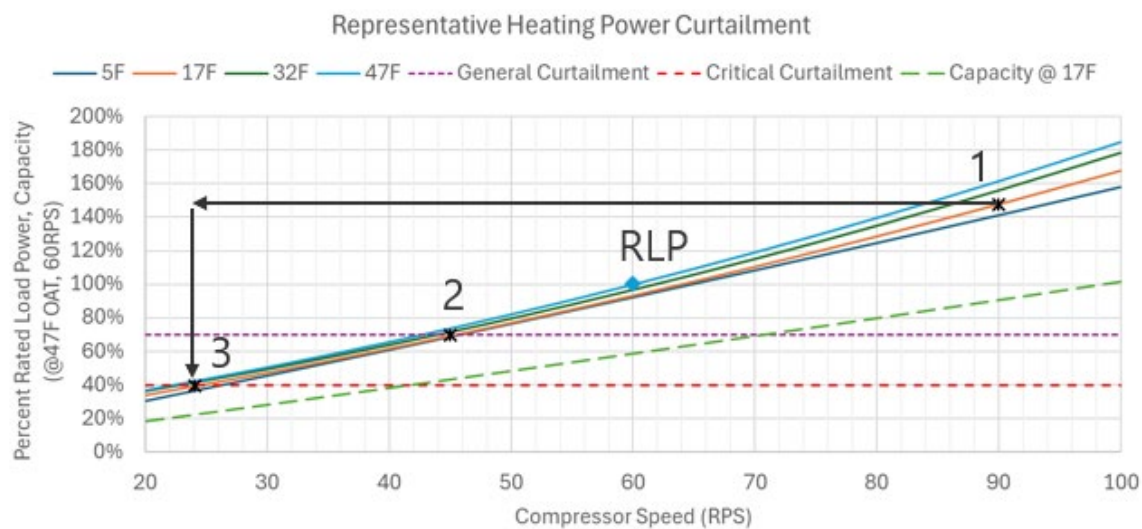


Figure 5: Representative Heating Power Curtailment

Table 1 summarizes an illustrative example of power consumption and capacity relative to the $H1_{Nom}$ rating point, with reference points labelled in Figure 5. Determining a suitable rated load point is critical for the success of VSHP DR programs. When a DR event occurs at more extreme conditions than the RLP, the low available capacity would be insufficient to meaningfully prolong the comfort period compared to thermostat setback methods. Conversely, if the RLP is defined at an extreme condition, DR events during mild conditions would already be operating at less than the prescribed power limits, providing no relief to the grid. Copies of the AHRI 210/240 [(9)] test conditions table are reproduced in APPENDIX A. $H3_{FULL}$ is a required test condition for all system types and under consideration as the RLP for AHRI 1380-2026. $H1_{FULL}$ is also a possibility. Modelling exercises presented later evaluate the implications for effective grid management where predictable load shed is desirable.

Table 1: Representative Heating Power Curtailment

Operating Point	Description	Compressor Speed (RPS)	Power % to RLP	Capacity % to RLP
Rating (RLP)	47°F / 8.3°C	60	100%	100%
Actual (1)	17°F / -8.3°C	90	150%	91%
General Curtailment (2)	17°F / -8.3°C	44	70%	42%
Critical Curtailment (3)	17°F / -8.3°C	24	40%	23%

Further specifications are needed to set equipment behavior upon exiting an event: a) when a user opts out, b) when the event duration ends, and c) when the maximum indoor temperature offset (MITO) is reached. Research led by NLR and PNNL, presented through the Better Buildings US Department of Energy (DOE) Peer Exchange Call series [(10)] explores where users begin opting out of DR events based on indoor air temperature, duration, and temperature offset. AHRI 1380-2019 currently guides to set MITO to 4°F (2.2°C) but leaves it as an open parameter to be communicated with each event. At an event exit, does the controller hold the offset temperature, ramp slowly back to the original setpoint, or immediately return back to the original setpoint? Further investigation to understand the power demand implications of snapback under each scenario must be considered by grid operators and is included in the modelling section later in this report.

Two other considerations are under discussion for AHRI 1380-2026: dual fuel applications and lab testing / certification. During DR events, engaging electric resistance emergency heat is not allowed unless the space temperature approaches unsafe levels, currently considered 62°F (16.7°C). Some applications have a fuel-fired furnace for backup heat. In these applications, can the HVAC system switch immediately to fuel-fired heating, or does the heat pump operate in a curtailed power state until MITO is reached? Fuel-fired backup heat is out of scope for the current AHRI 1380-2019 standard. For 2026, engaging fuel-fired heating would not be prescriptive but rather let the system behave normally where fuel-fired heating engages after a set time period without satisfying the thermostat demand for heat, or if the temperature offset falls outside a set range.

Lab testing and certification must consider specific combinations of indoor blower, outdoor heat pump, and controller. As the majority of VSHPs use proprietary communicating controllers, applications would typically require matching equipment sold as a package from a single manufacturer. Certification testing needs to validate DR communication and response by the equipment under specific operating conditions, including nominal power demand at RLP and demand response at conditions of an event. Discussions include if the DR communication must be initiated from a DRP or if it could be locally generated by a certification lab.

External Research Activity

Limited research has been completed for demand response for variable speed heat pumps despite release of the AHRI standard 1380 in 2019. Leaders in research include Pacific Northwest National

Laboratory (PNNL), Electric Power Research Institute (EPRI), National Laboratory of the Rockies (NLR) (formerly the National Renewable Energy Laboratory (NREL)), and Oak Ridge National Laboratory (ORNL). Individual manufacturers have also partnered with universities, private research organizations or both.

DOE Cold Climate HP challenge (ORNL / PNNL / NLR)

Announced in 2021 with the final report issued in January 2025 [(11)], the US DOE cold climate heat pump (CCHP) challenge is the primary resource for VSHP DR research. Three national laboratories coordinated efforts to conduct laboratory benchmarking and field validation from eight heat pump manufacturers. Specifications [(12)] for inclusion in the challenge are in Figure 6. HVAC systems were required to maintain 100% of rated capacity at 5°F (-15°C) outdoor ambient conditions with a COP greater than 2.1 for systems over 4 tons of nominal capacity and 2.4 for smaller systems.

HP nominal capacity (Btu/h) ¹	Seasonal Heating Performance		Heating at 5°F (-15°C)				Heating at -15°F (-26°C) (optional)	
	Minimum HSPF2	Min. Turndown ratio	COP at 5°F (-15°C)	Capacity Ratio	Low-temperature compressor cut-out at 5°F (-15°C)	Low-temperature compressor cut-in at 5°F (-15°C)	Low-temperature compressor cut-out at -15°F (-26°C)	Low-temperature compressor cut-in at -15°F (-26°C)
≥24,000 and ≤36,000	8.5 * (1 + Capacity factor ²) * (1 + COP factor ³)	30%	2.4	100%	≤ -10°F (-23°C)	≤ -5°F (-21°C)	≤ -20 °F (-29°C)	≤ -15 °F (-26°C)
>36,000 and ≤48,000			2.4	100%				
>48,000			2.1	100%				
¹ Capacity for the A2 test of Appendix M1 for a heating/cooling heat pump. Capacity of the H1 _N test of Appendix M1 for a heating-only heat pump. ² Capacity factor: 1 percent for every 10% H1 ₁ /H1 _N gap. The capacity factor for northern triple capacity HPs is 0. ³ COP factor: 2 percent for every 10% excess COP gap between the expected COP reduction and the measured COP reduction from the H1 ₁ verification test and the H1 ₁ regulatory test								
Additional Requirements:								
(1)	Unit(s) shall comply with electric heat staging requirements as set out in Table II-1							
(2)	Unit(s) refrigerant shall have a GWP no greater than 750 (AR4 100-year).							
(3)	Unit shall comply with Sections 3C, 4B, 4C, and 4D of the ENERGY STAR CACHP specification.							

Figure 6: Summary of DOE CCHP Challenge Specifications

The national labs included PNNL, ORNL, and NLR. PNNL coordinated the overall project and field testing. ORNL administered the lab testing to benchmark performance, including determining the RLP for later evaluation of DR events. Finally, NLR developed and managed a server implementation of OpenADR 2.0b VTN and communicated DR events to field installed prototypes. Lab testing included assessing the coefficient of performance (COP) and capacity at 47°F (8.3°C), 17°F (-8.3°C), 5°F (-15°C), and -15°F (26.1°C) outdoor ambient conditions, validating minimum turndown ratios for the inverter driven compressors, and demonstrating demand response capability. Controllers were proprietary communicating thermostats provided by each manufacturer matched to their equipment.

Participation in the challenge included Bosch, Carrier, Daikin, Johnson Controls, Lennox, Midea, Rheem, and Trane, representing more than 15 brands. Each successfully validated a cold climate

prototype. Three manufacturers of VSHP have advanced prototypes to be commercially available as of December 2025, with others anticipating product releases early in 2026 in conjunction with the inclusion of AHRI 1380 load management in the previously referenced CEE advanced air source heat pump specifications. Currently available AHRI 1380 compliant VSHPs are Lennox with S40 smart thermostat, Carrier with Infinity Controller, and Bosch with IDS Ultra, the lone participant using a cellular 4G connection.

DR testing in the CCHP challenge was a capability test. During selected hot and cold days, NLR generated a DR event, typically with a 2-hour duration. The research teams monitored communication responses from the HVAC systems, power demand before, during and after, indoor temperature offset during the event, and if any system engaged auxiliary backup heat (3 stage electric resistance for each system under test). An excerpt from PNNL's final report [(11), pg 23]:

Overall, all participating manufacturers were able to demonstrate DR curtailment in the field. This was confirmed by the data received by the NREL team that related to the opt-in status and operation state during the DR event. Depending on the outdoor weather conditions and the indoor temperature setpoints, some units showed a clear curtailment in CCHP power in the M&V data during the event, while some others did not show a clear impact. When the units did not show a clear curtailment, it was typically due to the CCHP being in idling mode just before the DR event window, or due to a low load on the CCHP due to a combination of indoor and outdoor temperature conditions and the heating load profile of the home.

Noted in the final report were concerns of electric resistive heating during snapback periods, an item to be addressed in the upcoming 2026 version of AHRI 1380. As previously discussed, some events had little or no impact on power demand compared to the period immediately preceding an event. This was due to operation at lower loads than the RLP, already adequate for the requested power curtailment level. While it is more difficult to standardize and measure installed systems, requesting power curtailment from the current demand in the time period immediately preceding a DR event would be more effective and predictable for grid management. Complications would include if the system were idle in the preceding period. Scheduled thermostat changes in the middle of a DR event also caused complications in DR response, sometimes triggering MITO and exiting the event. During heating, with dual-fuel systems, fuel-fired backup could be engaged to return the space to the setpoint temperature following reaching MITO or exiting a DR event. In systems with electric resistance backup heating, other strategies could be staging the temperature setpoint slowly back to the scheduled value in increments smaller than would trigger backup heating. Logic would need to be included in the system controllers.

Demand response conclusions from the PNNL final report [(11), pg 40]:

- *A greater share of the residential HVAC market would need to have variable-speed capabilities. Many ductless products are variable speed, but most centrally*

ducted products are single or two stage and could not provide the full set of capabilities within AHRI 1380.

- *Utilities would need to see the impacts and benefits of this demand response strategy compared to the more traditional options (e.g., smart thermostat setpoint adjustments).*
- *Utilities would need to see a near-term risk of peak demand issues during the winter heating season due to increased heat pump adoption and building electrification in their regions. Today, the vast majority of utility programs focus on summer cooling peak demand. Discussed below, our field testing identified some issues during summer cooling events.*
- *DERMS providers would need to develop the communication and controls capabilities to call such events. At this time, we are not aware of major DERMS providers offering AHRI 1380 capabilities.*
- *Manufacturers would need to standardize the number, type, and frequency of reporting channels to better support utility program implementation and impact evaluation. Our testing found that each manufacturer had its own reporting approach, which creates integration challenges for utility programs that are designed to be brand agnostic.*

In general, barriers to adoption include a very narrow range of applications. VSHPs with communicating controllers are a premium product offering. In 2023, EIA released data for 2020 space heating in U.S. homes, where 16.13 million heat pumps are estimated to be installed [(13)]. The market share consisting of variable speed heat pumps is 20% [(14)], or 3.2 million units installed. With an average 3-ton nominal size and 3.5 COP at the nominal rating point (47°F (8.3°C)), the total RLP of the United States market is about 1.08GW. Relative to the 30.5GW of wholesale demand response resources [(15)], VSHP represent 2.12% and 1.06% at critical and general curtailment levels, respectively. Specific to the Pacific Northwest (WA, OR, ID, MT), there's an estimated 118 thousand units installed, representing 3.45% and 1.73% of the Pacific Northwest region demand response resources. Table 2 provides a summary of the VSHP DR market assessment. Within these percentages, the previously described challenges further reduce the available power curtailment, namely if the units are already operating below the requested curtailment, or if the curtailment results in quickly reaching MITO and exiting the event. Either scenario would limit the effectiveness of implementing demand response with variable speed heat pumps. Utilities and demand response providers need incentives to create and advance DR programs above and beyond the current temperature setback method.

Table 2: VSHP DR Market Assessment

USA	Pacific NW	Description
3226000	118000	# VSHP units installed
3	3	Average Nominal Size, tons
1075333	39333	installed tons
3.5	3.5	average nominal COP
1080556	39524	installed RLP, kW
648334	23715	40% RLP, kW curtailment potential
324167	11857	70% RLP, kW curtailment potential
30.542	0.687	GW wholesale demand response resources
2.12%	3.45%	40% RLP, kW curtailment potential
1.06%	1.73%	70% RLP, kW curtailment potential

EPRI

EPRI has an ongoing research project to evaluate demand response capabilities of connected VSHPs in the field. Project proposal and initial review are in references (17) and (18).

Prior to the ongoing field study, EPRI reviewed the existing state of VSHP DR capability and identified gaps in AHRI 1380-2019 [(16)]. The review acknowledges enhanced DR performance with VSHP due to greater demand reduction potential, less impact on occupant comfort from continual operation (at reduced power), and resulting in fewer occupant opt-outs and event exits due to imposed temperature offset limits. Findings of the research identified inconsistent demand reduction with baseline temperature setback approaches, where the temperature offset is quickly reached, and then the unit resumes operating at full power. Limitations found in the current standard include overcoming operating differences between certification at fixed operating conditions and actual use cases with varying conditions and ramp periods. Use case scenarios vary widely, with individual setpoint schedules, nighttime setbacks, home/away schedules, and different comfort levels. Standardizing performance with the breadth of scenarios is challenging. Other gaps include setting a tolerance on curtailed power, developing methods to verify and enforce MITO, and resolving inconsistencies between communication definitions for CTA-2045 and OpenADR.

Taking lessons learned from the previous study, EPRI is conducting a field evaluation with the goal of having 100 host sites across 7 utility regions (Duke Energy Carolinas, Duke Energy Progress, Duke Energy Florida, Southern California Edison, Tennessee Valley Authority, San Diego Gas and Electric, and Salt River Project). Two manufacturers are actively supporting progress with the testing, with compatible heat pump customers identified by Daikin and Rheem. Initial tests are being conducted with manually triggered DR events by a VTN hosted by a 3rd party. As the testing progresses in summer 2026, EPRI will engage VTNs hosted by the participating utilities to deliver DR events, one of the first end-to-end tests. Results of the study will provide insights on actual

DR behavior in real use cases compared to expectations and lab testing. As discussed earlier, power demand at the time of an actual event will rarely be the same as the currently defined RLP at 47°F (8.3°C). How much power is actually available to be curtailed at the time of an event? How much impact does snapback have on event exits?

Texas A&M & Daikin

On the Texas A&M University Smart and Connected Home testbed are two identical, 1200 sq ft model unoccupied homes where Daikin supported testing mid-efficiency tier heat pumps. One of the homes has a VSHP model installed with a communicating controller, while the other has a single speed Daikin heat pump with third party Ecobee smart thermostat. The initial testing focused on heat pump performance with a paper released for ASHRAE winter conference 2024 [(19)].

Continuation of testing over the summer 2025 period evaluated cooling demand response comparison between the two units and implications for demand flexibility and building-to-grid integration. Results are expected to be released at the 2026 ASHRAE winter conference. The test plan included Daikin's involvement to communicate DR events through the manufacturer cloud and access to data logs to characterize the event. The single speed system implemented direct load control and temperature setback methods for comparison.

In the study, the heat pumps were sized based on ANSI/ACCA 2 Manual J Residential Load Calculation calculations. At 95°F (35°C) outdoor temperature, the actual building load at the test homes resulted in part-load cooling operation for both heat pumps. As a result, DR testing the VSHP focused on the critical curtailment (40% RLP) power limit strategy, as the general curtailment (70% RLP) power limit strategy would have been less impactful to evaluate.

OEM Readiness

Our project team had discussions with multiple manufacturers, several of which participated in the DOE CCHP challenge.

Most manufacturers are using OpenADR 2.0b communication protocols from demand response providers to their manufacturer cloud platforms, and custom proprietary communication from the manufacturer cloud to the individual devices registered within the DR event territory. Exceptions include a major manufacturer pursuing HCA API, and another utilizing cellular communication. Figure 7 provides a summary by manufacturer and Figure 8 an example of communication pathway from grid operator to device.

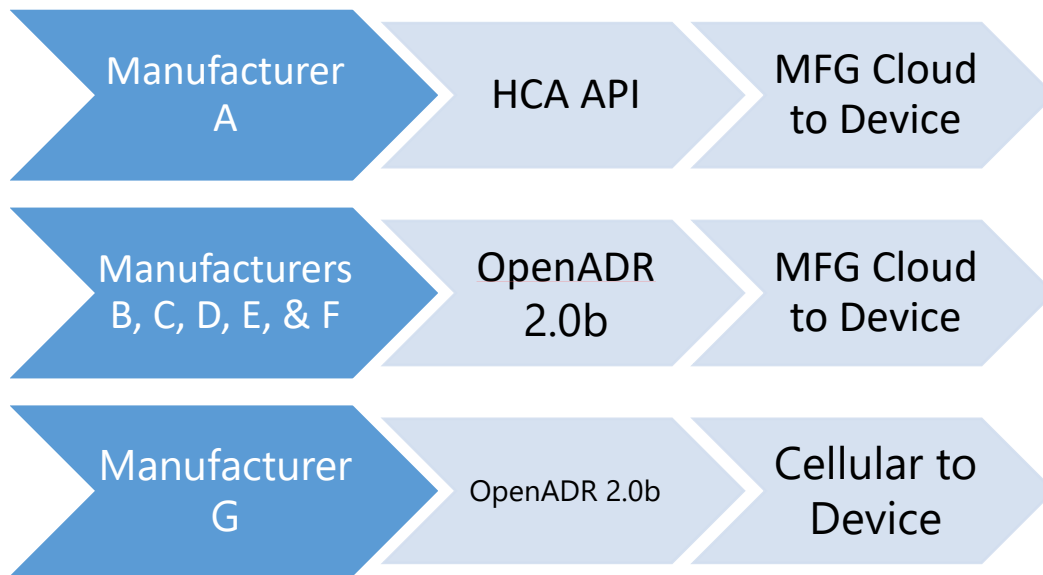


Figure 7: Manufacturer Communication Protocols

One manufacturer anticipates broader market adoption of HCA due to its implementation with other home connected appliances such as dishwashers, clothes washing/drying machines, smart refrigerators, and ovens/ranges. Demand flexibility with HCA would entail a whole home energy management system (HEMS). HEMS can receive DR event signals and prioritize power consumption by any connected device to achieve a requested power curtailment on a whole home level, instead of the individual VSHP.

Cellular communication by manufacturers removes dependence on home Wi-Fi connections to keep connected devices in communication with cloud servers and prevent stranded assets.

Requiring DR events to be communicated through the manufacturer's cloud was a common preference in each discussion. At the time a DR event is signaled, the cloud platforms can evaluate operating conditions and ensure installed systems are not pushed beyond their operating envelopes. At low operating speeds, typical of part load or power curtailed operating states, oil return to the compressor is a concern, sometimes requiring periodic speed ramp up. Manufacturers are reluctant to relinquish controls and risk damaging the equipment.. Brand perception is important. Manufacturers are concerned that if DR events lead to premature wear and reduced operating life, increased maintenance and service requirements, or thermal discomfort, homeowners are more likely to hold the equipment manufacturer liable rather than the utility.

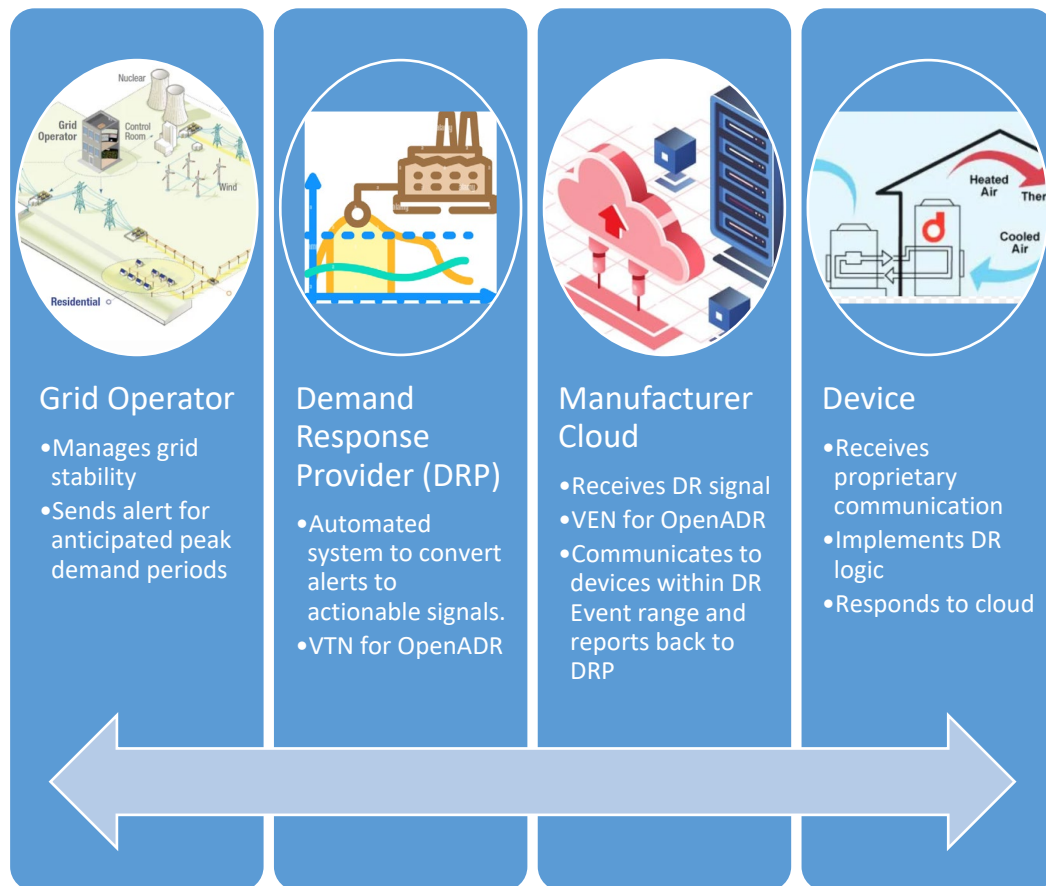


Figure 8: Demand Response Communication Paths

In addition to protecting equipment reliability, maintaining the AHRI 1380 compliant communication protocol at the cloud server level maintains a single interface for the manufacturer. At the time of the CCHP challenge, OpenADR was at version 2.0b. As of now, version 3.1 has been released. Discussed earlier, OpenADR 3 with RESTful web protocols is not backwards compatible with OpenADR 2.0 SOAP web protocols. Manufacturers can maintain and update a single interface as needed to keep up to date with new communication protocol(s) and/or versions. If the communication protocol were hosted on individual devices in the field, updates would only be available if connected over the air, adding potential for stranded assets. Instead, manufacturers prefer to maintain device communication with proprietary protocols that are under their internal, not external, control.

Common Themes

In discussions, a few themes were repeated, pointing to adoption barriers and DR program uncertainty. While a couple manufacturers were excited about the added capability and contribution to grid flexibility, others were more apprehensive about the balance of required resource allocation compared to return on investment.

Power Curtailment requires systems with communicating controllers

VSHP DR capabilities, as detailed in AHRI 1380, are limited to systems with OEM proprietary communicating controllers. Non-communicating systems generally lack data points sufficient for reporting requirements of AHRI 1380. Manufacturers shared that control logic to implement power curtailment within operating envelopes resides in their controllers, which may reside integral to the equipment or within the thermostat, with support from on-device sensors and cloud-supported local weather conditions. For most manufacturers, integration with third-party thermostats is not possible with the current structure and represents a significant limiting factor in market adoption. Prior research prepared for ACEEE [(20)] found that available communicating controllers are lacking in features compared to third-party commercially available smart thermostats, are more expensive, and have a perceived poor user interface and experience. However, they are required to optimize variable speed control of the compressor and/or fans, at a cost premium, another adoption barrier.

Consumer benefits are not clear

Grid management is a requirement to balance power demand with generation. Several discussions pointed to the imbalance of capacity upgrades by utility companies compared to growing power demand, with a significant culprit being the rapid growth of data centers. The onus of keeping a stable grid is shifting from utility companies and the largest industrial and commercial consumers to residential households. As a result, households may experience more thermal discomfort, and manufacturers may incur the related detriment to brand perception in order for utility companies to avoid investing in capacity upgrades. Continued electrification of space and water heating is also increasing peak winter loads, at times when solar availability wanes, exacerbating the power demand/supply imbalance.

Actual load shed could be small

Discussed earlier with preliminary simple models, and part of the modeling assessment to follow, the actual load shed at the time of a DR event is likely to be less than the requested power curtailment levels (70% of RLP for general curtailment, and 40% of RLP for critical curtailment). RLP is presently determined at AHRI 210/240 A1_{FULL} for cooling and H1_{NOM} for heating. A1_{FULL} is a peak design condition for most North American climate zones. Heat pumps would be operating at part load, under which cases may already be less than the requested power curtailment, offering no load shed in a DR event. H1_{NOM}, conversely, is a part load condition. When a winter DR event is requested, the heat pump may need significantly more power to maintain thermostat setpoint and therefore be severely limited during a DR event. This scenario would cause MITO to be reached quickly, similar to the temperature setback method, at which point normal operation and power demand would resume before the end of the DR event.

Lack of prior success for DR programs

AHRI standard 1380 was initially released in 2019, yet adoption has been minimal to date. Only with the DOE CCHP challenge were products developed specifically to comply with 3 models now commercially available in 2025. One manufacturer in particular stressed (paraphrased) “we have never sold a heat pump because of the added DR capable feature”. Each manufacturer, at the

request of policy or certifications such as CEE described earlier, has made large investments into DR capable product development. Each also stated they would ensure they can offer products that meet the requirements of the standard, but do not want to allocate resources to chase new hypothetical features and continual communication protocol version releases. Preference is to let the market catch up with current features, objectively validate what works and what lessons need to be learned. There is currently a lot of speculation of how systems and consumers will behave with limited data and field studies. Research such as EPRI's 100 site field demonstration will add tremendous value to implementing VSHP as a DER.

Standard Uncertainty

A new release of AHRI Standard 1380 is in progress, expected in 2026. The project team joined the standard subcommittee where many manufacturers are represented and collaborating. Several items open to discussion in the subcommittee have important implications for the potential success of VSHP DR programs.

MITO Setpoint

In the current 2019 version of the standard, there is one mention in details of CTA-2045 messages to limit maximum indoor temperature offset (MITO) to no more than 4°F (2.2°C). Questions abound on whom should be responsible for defining MITO: the standard committee, manufacturers through their cloud platforms, or occupants? Should MITO be the same for all situations or vary depending on outdoor conditions? At what temperature offset do occupants begin to notice discomfort and opt-out of the DR event? Research into DR programs and their impact on comfort have been conducted by NLR and PNNL, with results presented through the DOE Better Buildings Residential Network Peer Exchange Call Series in 2024 [(21)]. Discussions in the AHRI 1380 subcommittee included setting an absolute minimum temperature bound, but determining an appropriate value is also subject to debate. Minimum at 62°F (16.7°C) is most discussed, but others point out that devices could be installed in unoccupied homes (at the time of a DR event) where the desired minimum temperature is only to prevent frozen pipes within the home.

Backup Heat Utilization

Common heat pump installations include backup heat sources, either electric resistance or a fuel-fired furnace. While electric resistance heating should not be utilized during a DR event, if the space temperature falls outside of the MITO limits, heat is needed to keep occupants and homes safe from freezing. Suggestions are to first remove the power curtailment request and let the heat pump operate at full capacity. In such a scenario, should the space temperature return to the original setpoint (full DR event exit), or maintain the new setpoint offset by MITO? Raising the space temperature 4°F (2.2°C) or more under presumed adverse weather conditions when the grid is most constrained could be in excess of the VSHP capacity. A multi-tiered approach to calling electric resistance backup heat would be required. If space temperature drops below MITO, remove power curtailment for full VSHP capacity. If after a set duration temperature is still less than MITO, only then call for electric resistance heating.

Fuel fired backup heat sources can deploy different strategies than electric resistance. A caveat would be regions where gas demand is simultaneously constrained due to utilization as gas peaker plants to meet the power demand. OpenADR 3.0 implements a secondary price signal which can be gas if there is coordination between electric and gas utility companies in communicating grid management via OpenADR 3.0. From the project team's discussions, many implementations developed code for OpenADR 2.0b and have not committed resources to updating to OpenADR 3.0. Updates would require a cascade effect where both VTN and VEN's would need to be in sync. Engaging fuel fired backup heat sources could take multiple paths: a) at the onset of a DR event, switch heat source and maintain occupant setpoint, b) at the onset of a DR event, switch heat source and maintain MITO, c) prioritize VSHP at curtailed power levels until MITO is reached. Scenarios a) and b) have the benefit of completely shedding the heat pump load, with only power demand from the indoor supply fan and controls. Updates to the standard would also need to allow indoor fan operation during grid emergency events in order for gas backup to be used. Considerations would also be needed for scenarios where MITO exceeds thresholds for switching heat source under normal operations (i.e., if MITO is 4°F (2.2°C), and normal operation switches to gas backup at 2°F (1.1°C) offset); does the DR event request to control to MITO supersede the thermostat setting?

Strategies

Implementation of DR programs balances occupant comfort with load shed. VSHP, by continuing to operate in contrast with temperature setback or direct load control where the heat pump cycles off for a period of time, extends occupant comfort for longer durations, but maintains a higher base power demand. If MITO is too low, occupant comfort would be maintained at the expense of limited power curtailment. If MITO is too high, the inverse is true. The standard must set a priority between avoiding premature event exits (due to reaching MITO or customer opt-outs) and maximizing load shed potential. Some potential strategies to balance the two competing priorities could include pre-heating or pre-cooling a space when a DR event is communicated in advance. Implications of shifting load to secondary peak periods would need to be evaluated as well as if pre-heating or cooling could extend potential event durations and occupant comfort windows. In addition, particularly when operating at low load for durations greater than ~45 minutes, compressor oil return and/or defrost cycles (in the right winter conditions) would be expected to occur. When discussed in the sub-committee meetings, the prevailing expectation is within a DR event territory, the coincidence of VSHPs entering a defrost or oil return cycle would be low, and overall impact at the transformer level would be negligible.

DR Event Exit Considerations

Typical DR events have a set duration determined at the start when the grid operator anticipates power demand approaching or exceeding power supply. Presumably the largest power demand resources have subsided, or available peaker plant power supplies have come online by the end of an event to allow normal operation to resume. With increased electrification, there is a possibility for a secondary peak event if all devices resume normal operation simultaneously. While the VSHP market is small relative to the overall grid resources, DR event exit scenarios need to be considered. Some manufacturers, in the absence of specifications in the standard, will allow devices to immediately resume normal operation. Others are considering implementing ramp

rates to resume normal operation in a more controlled manner over a set time period. Ramp periods could be by power level (increasing allowable power demand in 10% increments every 10 minutes, for example) or by temperature setpoint (returning to the normally scheduled setpoint 1°F (0.5°C) per 30 minutes, for example). Grid operators could also systematically set varying event durations for a particular territory, allowing some devices to return to normal operation at the actual event end, and others 15 to 30 minutes later.

Additionally, a DR event exit must be defined. Does reaching MITO entail exiting the DR event or continuing in the event but at the MITO setpoint temperature (equivalent to the temperature setback method)? Is the use of fuel-fired backup heat considered an event exit, or are DR event constraints still maintained for the event duration (in the event the system switches back to heat pump operating mode before the end of a DR event)?

Reporting

Reporting requirements need additional clarity. Manufacturers have concerns regarding how much data is needed by grid operators. From the manufacturer's perspective, grid operators only need to determine whether the DR event territory has shed sufficient load to maintain grid stability. Any other parameters are superfluous, including individual devices. On the other hand, more available data could unlock innovative control schemes that deliver consumer benefits. With electric and secondary (gas) price signals available in OpenADR 3, controls could optimize heat source for operating cost, or pre-heat/cool ahead of elevated price periods, saving consumers money all year. With additional data reporting requirements, devices must be equipped with appropriate sensors, which could drive upfront costs (both development costs for manufacturers and average selling prices for consumers). Determining of appropriate data and requisite sensors is important for balancing costs, performance, grid management, and innovation.

Market Assessment Conclusions

Advancements in HVAC technology, controls and communications opens pathways for grid operators to include the HVAC equipment in Distributed Energy Resources (DER) for grid management. With VSHPs and communicating controls, occupant comfort can be balanced with more consistent demand reductions compared to existing thermostat setback methods. Challenges remain for determining appropriate benchmarks for requested demand reduction, defining desired behaviour under a multitude of potential scenarios, and communicating necessary information without overloading data transmission rate and storage constraints. Parametric modelling analysis follows to characterize expectations for equipment and occupant behaviours to inform policy and standards development. Manufacturers have demonstrated capability for their equipment to respond to DR events and are actively participating in research studies to improve DR programs and standards.

Key takeaways follow:

- Multiple brands are leaders in DR development and are interested in future lab and field demo collaborative work.

- The technology of using VSHP for DR is in very early stages and still under development.
- Enhancements to AHRI 1380 are needed and need input from all stakeholders (manufacturers, researchers, policy advocates, standards developers, aggregators, grid operators, utilities, etc.).
- Value and opportunities for utilities, customers, and aggregators are not clear. In many cases, upper management of the manufacturers is not upbeat on opportunities based on past similar investments in DR with no returns on investment.
- Some manufacturers want responsibility for just DR functionality of heat pumps. They do not want to take responsibility for how communication will be with the grid via an aggregator or other means.
- Lack of consensus amongst manufacturers and DR providers. A true end-to-end seamless solution is required for wide-spread adoption.

Other observations include:

DR Standard

- Individual standards for residential VSHP (AHRI 1380), commercial VSHP (AHRI 1390), HPWH (AHRI 1430) through AHRI, and separate standards for other global markets, residential/commercial appliances, and distributed energy resources may lead to a fragmented market and adoption barriers. Recommend for the development of a harmonious DR standard as the backbone for more specific applications.

Communication Protocol

- Letting the market decide the communication protocol is great in theory, but could lead to stagnation of the DR capability. Uncertainty in market adoption slows the allocation of resources into product development.

AHRI 1380 Stakeholders Representation

- AHRI 1380 working group has majority manufacturer representation, with NEEA representing their members, and the California IOUs are also regularly represented. Grid operators, aggregators, or Demand Response Providers are currently not participating in the standard's revision. Avoid speculation, find input from implementers and beneficiaries of DR programs.

Keep the End User in Mind

- As space temperatures drift further from the setpoint, occupants could get frustrated and opt-out of the program. Most utility programs pay a modest annual incentive for participating in a DR program and rely on the altruistic aspect of helping the greater good, such as grid stability. Including electric and gas pricing signals, at regular intervals and specific to the location, can open controllers for systems with dual fuel heating to innovation with the least operating cost optimization. Utility incentives and monthly savings for consumers can

offset thermal discomfort caused by occasional temperature setbacks for DR events.

Technical and Market Assessment

- Limited studies to date have been in the lab or small field demonstrations with manual DR events. A comprehensive technical and market assessment is needed for the potential impact of DR programs. Answering several questions for utilities can support the implementation of load flexibility programs. Some questions include, for each grid level, sub-station level, or transformer level region, how much power is typically used, normalized to weather conditions? How many DERs are available to participate in a DR program? What percentage of consumers with DR-capable equipment opt-in? For specified bins of weather conditions, what is expected power demand, and how much can reasonably be expected to actually be curtailed (from actual power as opposed to rated load power)?

Modeling - To be addressed in the following section

- What is the maximum duration under varying weather conditions that equipment can expect to maintain MITO limits by VSHP power curtailment?
- How does over/undersized equipment impact available power curtailment to General (70% RLP) and Critical (40% RLP) limits for varying weather conditions?
- Quantify VSHP power curtailment compared to temperature setback methods in terms of total power reduction over event duration and maximum duration before reaching new setback temperature or MITO.

Recommended next steps include the following:

Outreach

- Stay involved in future versions of AHRI 1380 Standard development.
- Work with DR aggregators for developing seamless integration between utilities and equipment manufacturers.

Assess

- Conduct a comprehensive study to assess the DR value for customers, utilities, and manufacturers.

Validate

- Conduct lab testing to validate all the way from DR event initiation to implementation.
- Conduct large-scale field demonstrations to quantify kW reduction, flexibility, and adoption in real-world applications.

MODELING OF VSHPs FOR DEMAND FLEXIBILITY

The project team performed a detailed building energy modeling analysis to investigate the potential of demand flexibility using VSHP-based power curtailment. Owing to the nascent nature of the technology, there is a lack of awareness regarding the DR potential of VSHPs. Moreover, controlled laboratory testing across all the different possible equipment configurations, building types, and ambient conditions are yet to be published by researchers and stakeholders. This makes energy modeling simulations crucial in the evaluation of this technology. Currently, utilities and aggregators do not have the means to compare VSHPs systems and predict the expected DR or thermal comfort ramifications to homeowners for specific applications or climate regions. This effort quantified potential DR impacts using different types of ducted air-to-air VSHPs, such as non-cold-climate and cold-climate rated VSHPs in residential buildings serving space heating and cooling.

Modeling Methodology

The primary objective was to provide decision-makers with a modeling analysis of the performance of VSHP systems subject to curtailment during DR events. This was accomplished by developing hourly energy models to simulate the curtailed performance of VSHPs during selected DR event spans in different climates. The goal was to assess the potential of VSHPs in DR programs for utilities to alleviate grid constraints during peak winter or summer events by identifying regions and conditions where they can generate the most peak demand benefits.

The modeled hourly simulations were run for multiple building models and climate zones. Table 3 lists the residential building types, and Table 4 lists the cities and associated climate zones covered in this study. The simulations in this study were performed using EnergyPlus 25.1.0. It is an open-source tool developed by the US DOE and NLR to estimate and optimize the energy consumption of buildings on an annual basis. It is commonly used on its own or on the backend of other building energy simulation software. It allows the simultaneous simulation of an entire building's energy consumption and interaction with the surrounding environment.

The building models used were based on existing, well-established reference buildings representing the existing population of code-compliant buildings. The U.S. DOE, in conjunction with three of its national laboratories, developed residential and commercial reference buildings, formerly known as building benchmark models¹. The residential prototype models include 2 base building types. By default, these prototypes accommodate four different heating systems (Electric Resistance, Gas Furnace, Oil Furnace or Heat Pump) types and four foundation types (slab, crawlspace, heated basement, unheated basement) typically found in new residential construction. The result is an expanded set of 32 models, which are available across 18 climate locations for each edition of the International Energy Conservation Code (IECC). These reference buildings play a critical role in energy modeling software research by providing complete descriptions for whole building energy analysis using EnergyPlus simulation software. The base models with a foundation type of slab, crawlspace, or unheated basement have a net conditioned

¹ <https://www.energycodes.gov/prototype-building-models>, DOE Prototype Building Models

area of 2,377 sq.ft. Out of these base models, Table 3 lists the residential building models that were chosen for this analysis.

Table 3 Simulated Building Energy Models

Residential Building Type	Source
Single-Family Home 2,377 sq. ft. conditioned area (with crawlspace)	DOE Prototype (IECC 2021)
Single-Family Home 2,377 sq. ft. conditioned area (with crawlspace)	DOE Prototype modified to 2000 vintage

By definition, the input parameters for the building model simulating a new home complied with IECC 2021. Similarly, the input parameters for the building model simulating an older home were typical of a home built in 2000. These models represent realistic building characteristics and construction practices and serve as potentially the biggest target market for state-of-the-art VSHPs. Residential homes with vented crawlspaces were chosen for the simulations in this study as the most prevalent home types in Oregon and Washington².

Table 4 Simulated Cities and Climate Zones

Climate Zone	City
4C Mixed Marine	Seattle, WA
5B Cold Dry	Bend, OR
6B Cold Dry	Colville, WA

Building internal loads, schedules, furnishings, lighting, and occupancy were assumed to be consistent with the DOE Reference models. The default HVAC equipment in these DOE reference building models were single-stage heat pump systems. They were modified to represent a VSHP and a CCHP, as applicable based on the climate zone being simulated. Annual simulations of the building energy consumption were performed for the Typical Meteorological Year (TMY3) weather data in each location. They were sized based on the Design Day loads and tended to be sized based on the peak design heating loads. Assumptions for each building type model are listed in APPENDIX D: and APPENDIX E:. The default cooling setpoint was 75°F (23.9°C), and the heating setpoint was 72°F (22.2°C).

² NLR Residential Building Stock Analysis,

<https://public.tableau.com/app/profile/nrel.buildingstock/viz/USBuildingTypologyResidential/Segments>.

Key performance indicators of this task included answering the following research questions for effective VSHP based DR implementation in NEEA's climate zones –

- What is the kW reduction potential from VSHP based DR by climate zone and building size?
- How does VSHP based DR compare to traditional DR approaches like temperature setpoint offsets?
- What are the best scenarios for using VSHP-based DR across different building types, climate zones, and electric grids?
- What is the impact on occupant thermal comfort during DR events?
- How long can a home stay comfortable with the VSHP running at reduced heating and cooling capacities?

EnergyPlus's whole-building energy modeling engine was used in conjunction with custom scripts to simulate VSHP curtailment effects during pre-determined DR events. The Energy Management System³ (EMS) feature in EnergyPlus and provides a way to develop custom control and modeling routines for EnergyPlus models. EMS provides supervisory control to override selected aspects of EnergyPlus modeling. An internal programming language intrinsic to EnergyPlus called EnergyPlus Runtime Language (Erl) is used to read these control algorithms. The software interprets and executes the custom Erl programs while the model is being run. The programs work by overriding existing features and operating parameters within the model rather than adding a new set of controls and component models.

Building Characteristics

The prototype models have emerged as an industry standard for modeling potential benefits using a common set of assumptions. For the simulated homes, heating and cooling design loads were established using ASHRAE 99% design conditions, which represent outdoor dry-bulb temperatures exceeded only 1% of the time annually. This ensures that the HVAC system sizes are robust enough to meet extreme weather conditions. The design heating loads are listed in Table 5. The hourly heating loads for both homes across all simulated climate zones are presented in Figure 9 to Figure 14.

³ EMS Application Guide, EnergyPlus v25.1.0, <https://energyplus.readthedocs.io/en/stable/ems-application-guide/ems-application-guide.html>

(Accessed September 2025)

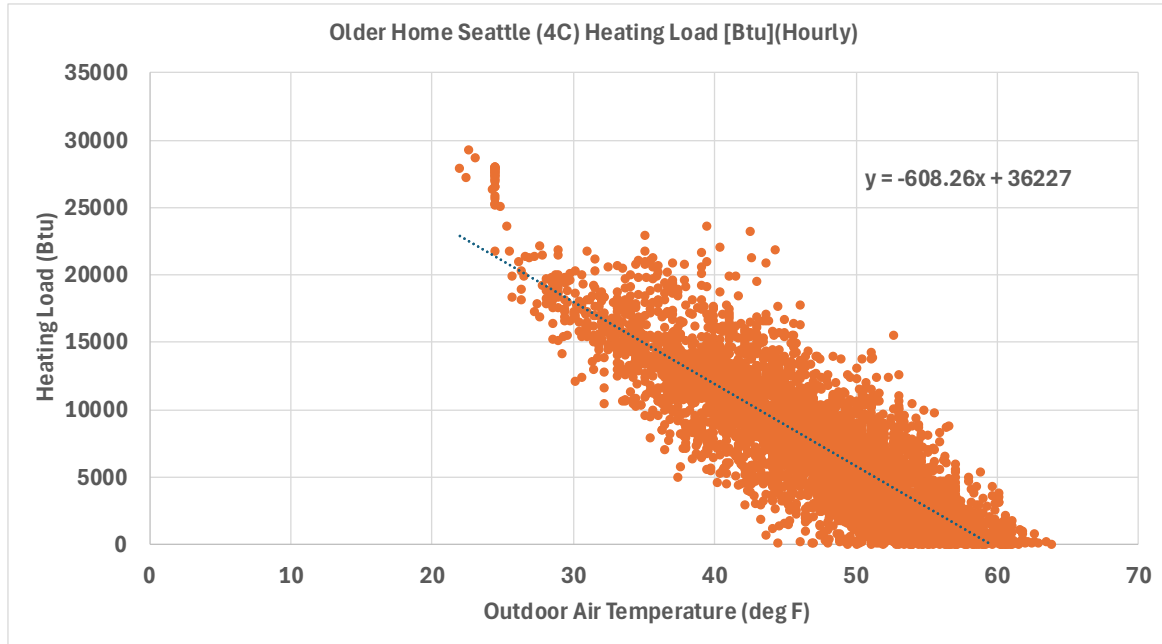


Figure 9 Hourly Heating Loads for the modeled older home in Seattle, WA

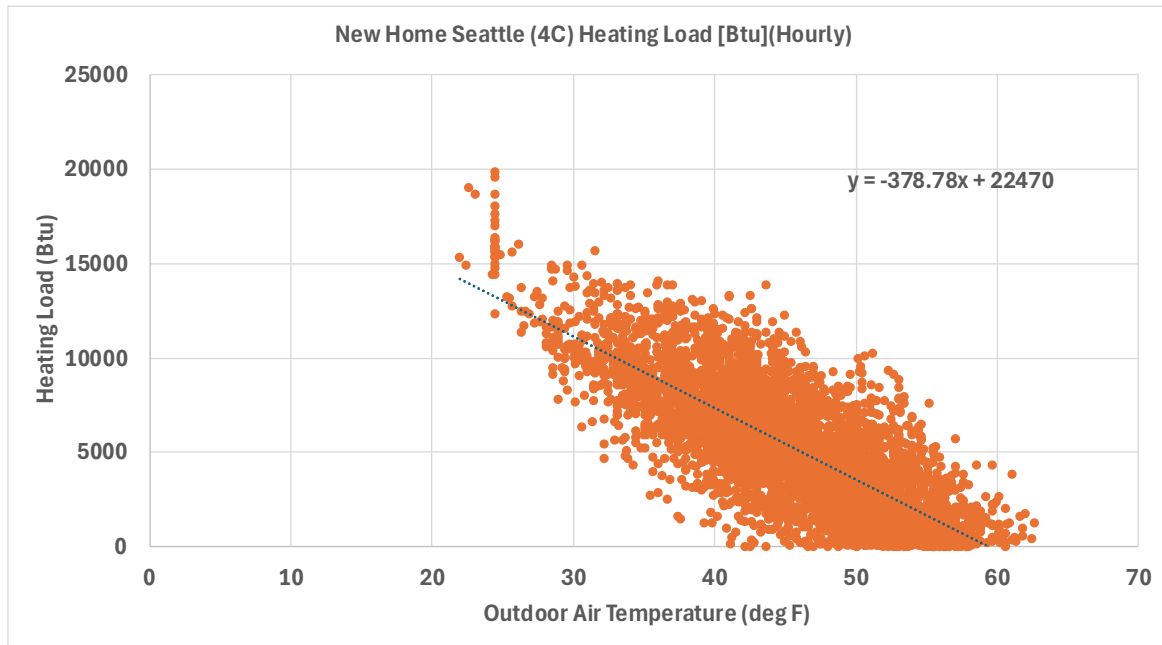


Figure 10 Hourly Heating Loads for the modeled new home in Seattle, WA

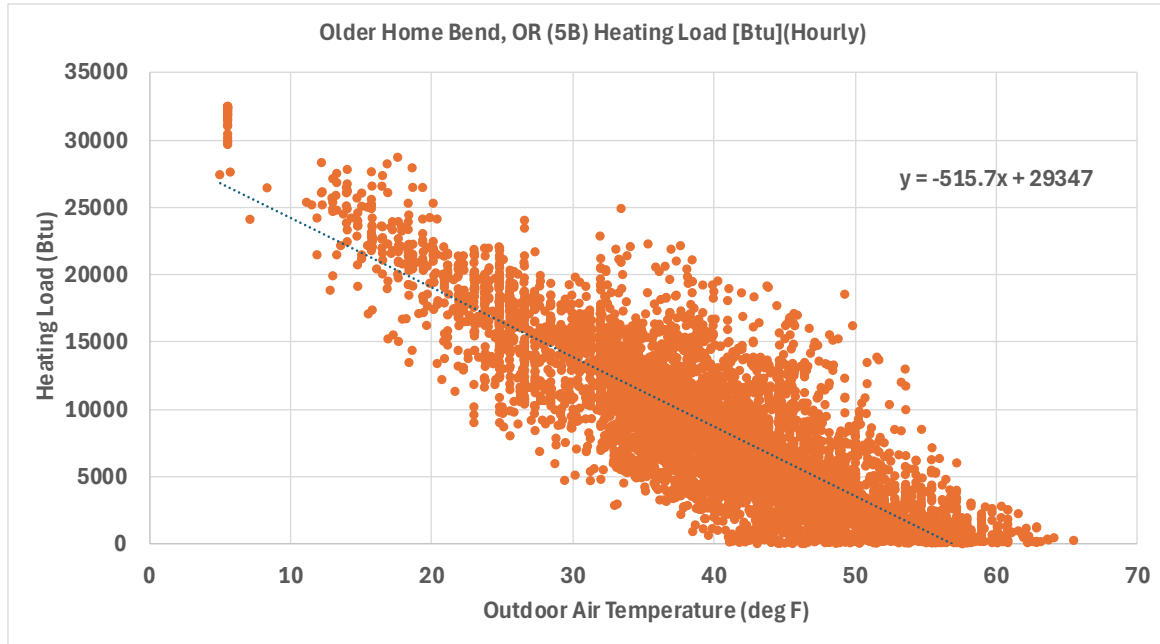


Figure 11 Hourly Heating Loads for the modeled older home in Bend, OR

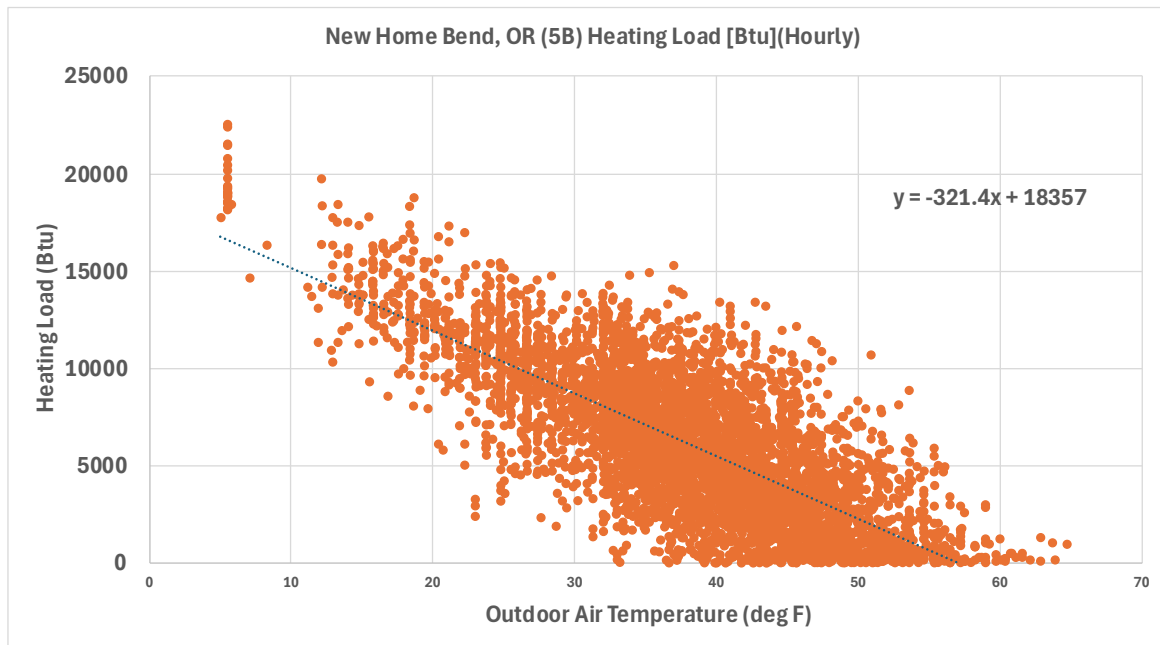


Figure 12 Hourly Heating Loads for the modeled new home in Bend, OR

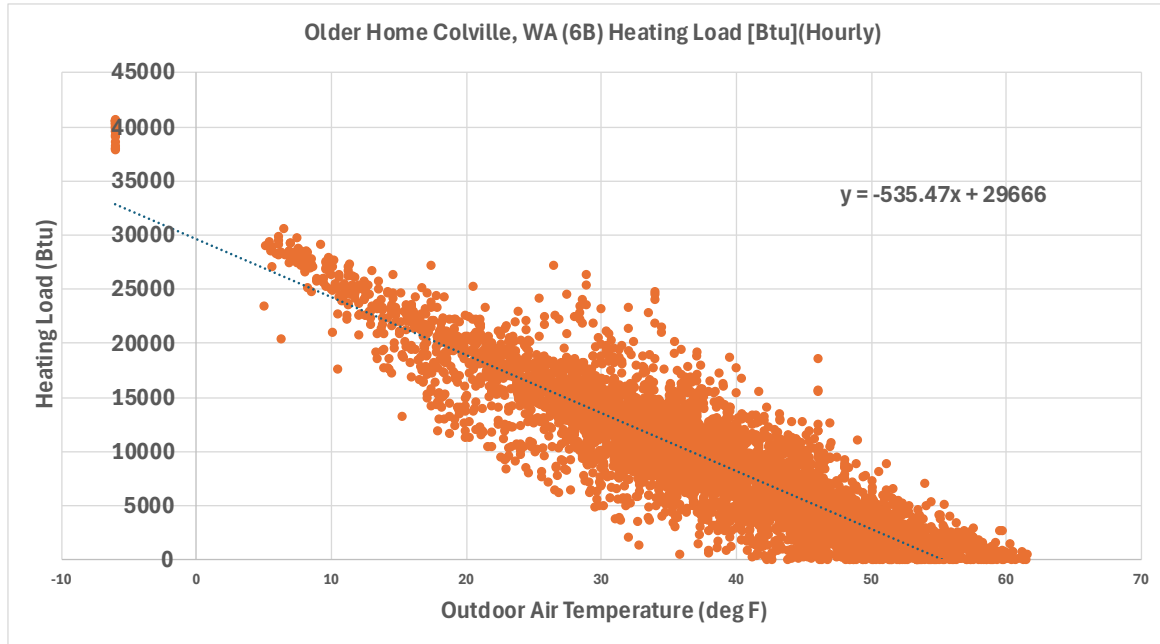


Figure 13 Hourly Heating Loads for the modeled older home in Colville, WA

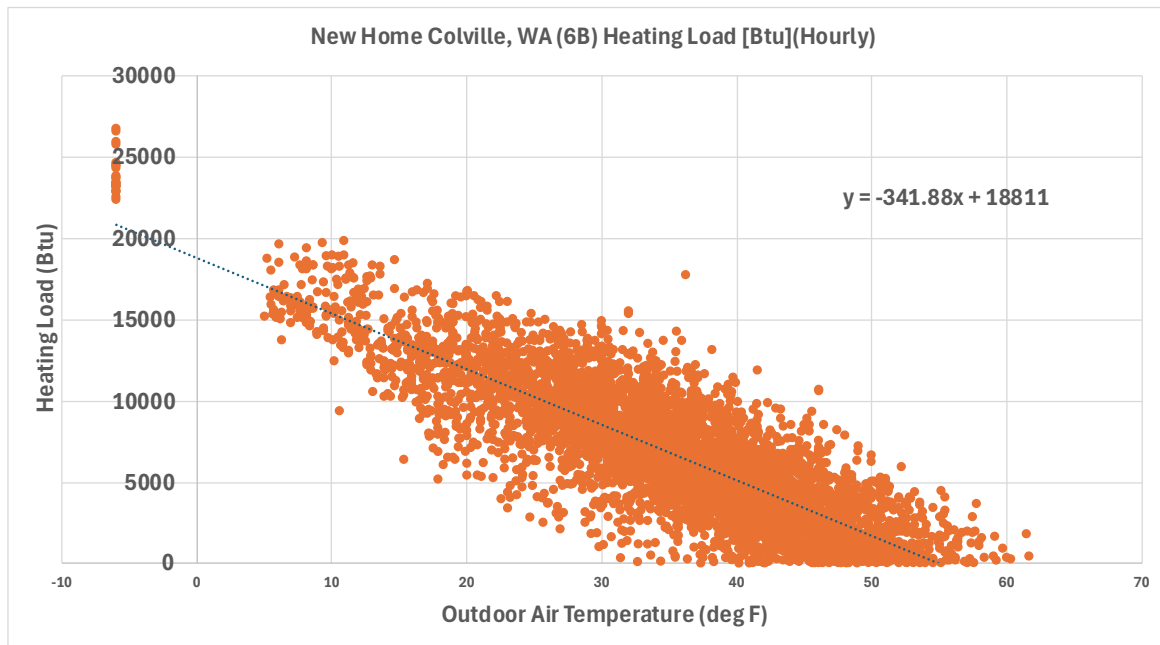


Figure 14 Hourly Heating Loads for the modeled new home in Colville, WA

Table 5 Design Heating Loads for the modeled homes

Building Vintage	Design Heating Load (MBH)		
	4C	5B	6B
Older	29.3	32.5	40.7
New	20	22.5	26.8

Table 6 Heating Design Temperatures based on ASHRAE

Design Temperature (°F)	Climate Zone		
	4C	5B	6B
	39.6°F (4.2°C)	5.5°F (-14.7°C)	-6°F (-21.1°C)

VSHP Sizing

To ensure the VSHPs were appropriately sized, GTI Energy sized them to meet building heating loads down to the design loads listed in Table 5 and Table 6. At temperatures below this threshold, auxiliary heating is expected to provide additional capacity. Avoiding significant oversizing or under sizing helps minimize part-load efficiency losses and excessive auxiliary heating operation, respectively. Supplemental heating is expected to operate only during the coldest conditions. Oversizing the heat pump with the aim to meet the few hours at extremely cold temperatures will be detrimental to the seasonal efficiency of the system.

Table 7 VSHP and CCHP sizing for modeled homes

Building Vintage	Climate Zone		
	4C	5B	6B
Older	3 ton	3.5 ton	4 ton
New	2 ton	2.5 ton	3 ton

VSHP Performance Curve Fits

Heating and cooling energy performance curves were leveraged from manufacturer datasets for specific VSHP models capable of modulating their compressor speed in response to a DR signal, per AHRI 1380 requirements. The parsed datasets used performance correlations between compressor speed, heating capacity, cooling capacity, and compressor power draw relative to ambient conditions for modeling real-time compressor modulation effects.

The CCHP was modeled based on the AHRI 1380-compliant, commercially available 4-ton cold climate heat pump. The performance data for this heat pump consisted of input power, heating, and cooling capacity as a function of the ambient and indoor air temperatures. The heating/cooling capacity and the corresponding power draw were scaled down based on the 4-ton CCHP for the CCHPs sized lower than 4 tons per Table 7.

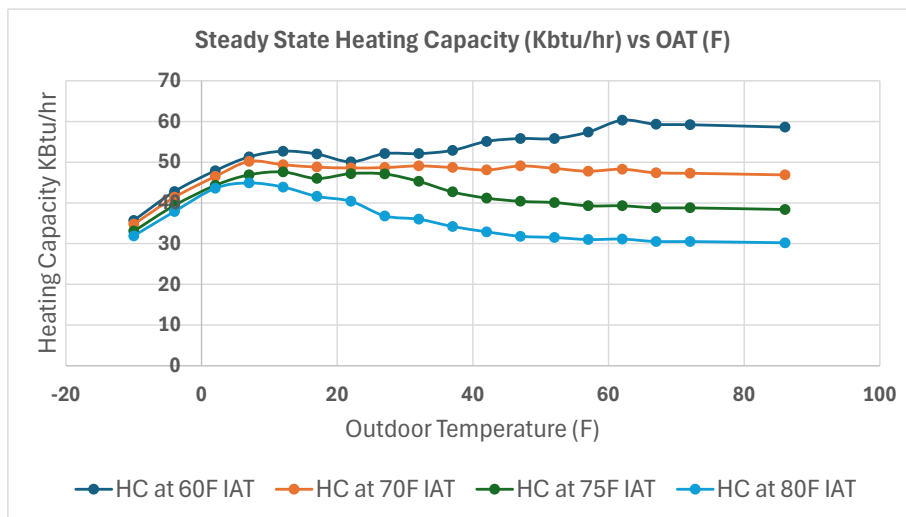


Figure 15 Heating Capacity relative to ambient conditions for modeled CCHP

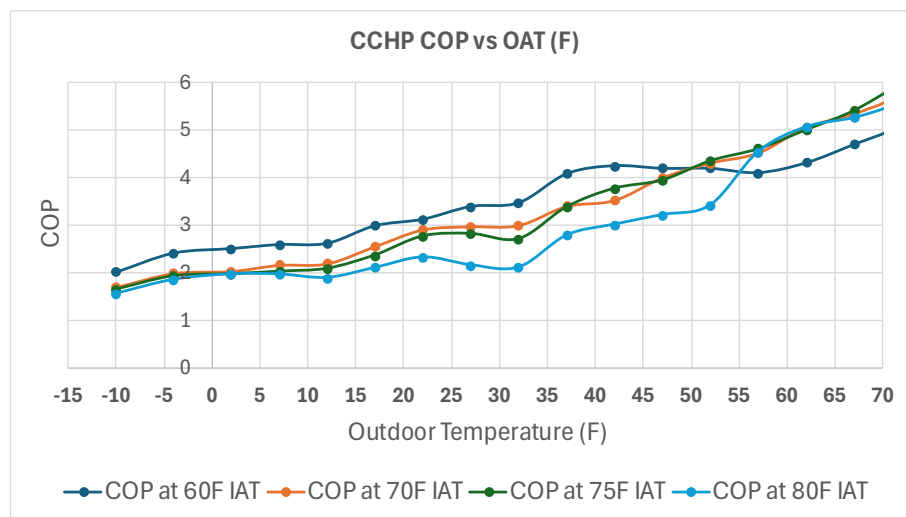


Figure 16 COP relative to ambient conditions for modeled CCHP

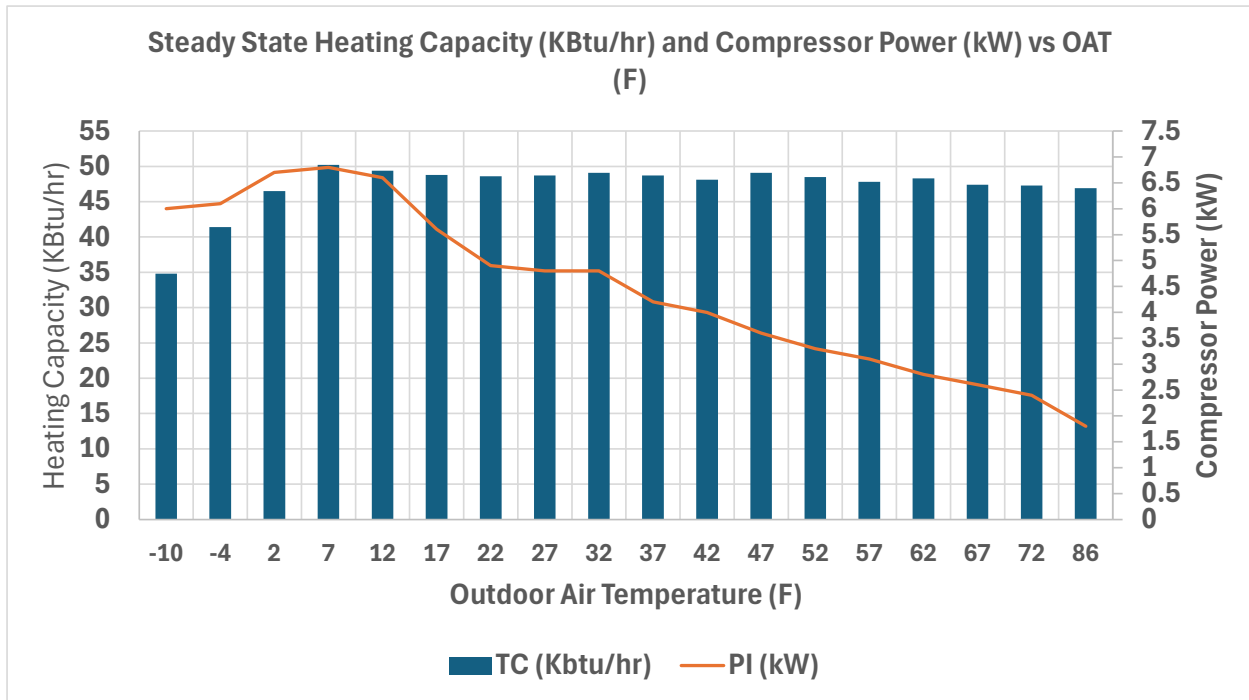


Figure 17 Heating Capacity and Power Draw relative to ambient conditions for modeled CCHP

The VSHP was modeled based on the AHRI 1380-compliant 4-ton model. The performance data for this heat pump also consisted of input power, heating, and cooling capacity as a function of the ambient and indoor air temperatures. The heating/cooling capacity and the corresponding power draw was scaled down based on the 4-ton VSHP for the VSHPs sized lower than 4-tons per Table 7.

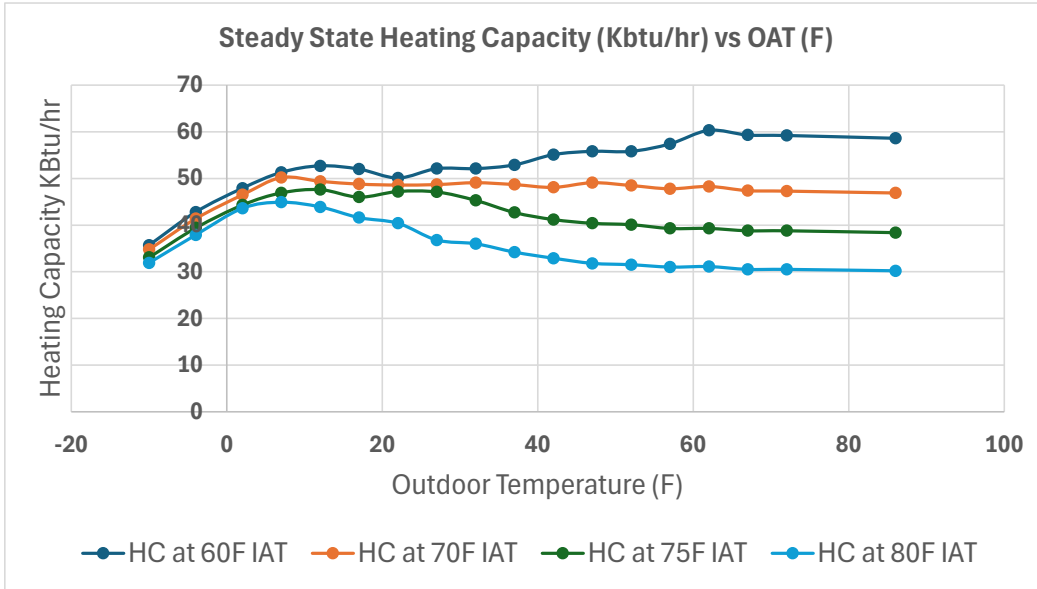


Figure 18 Heating Capacity relative to ambient conditions for modeled VSHP

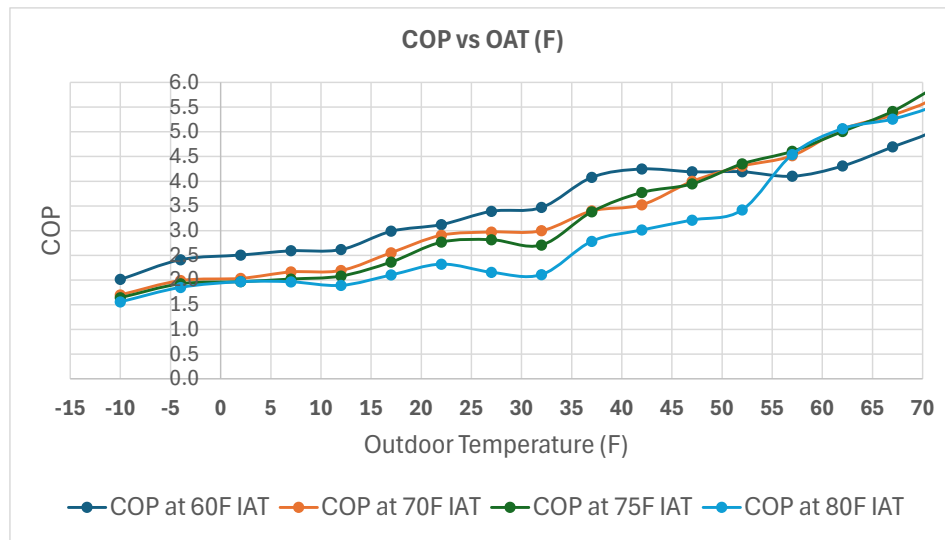


Figure 19 COP relative to ambient conditions for modeled VSHP

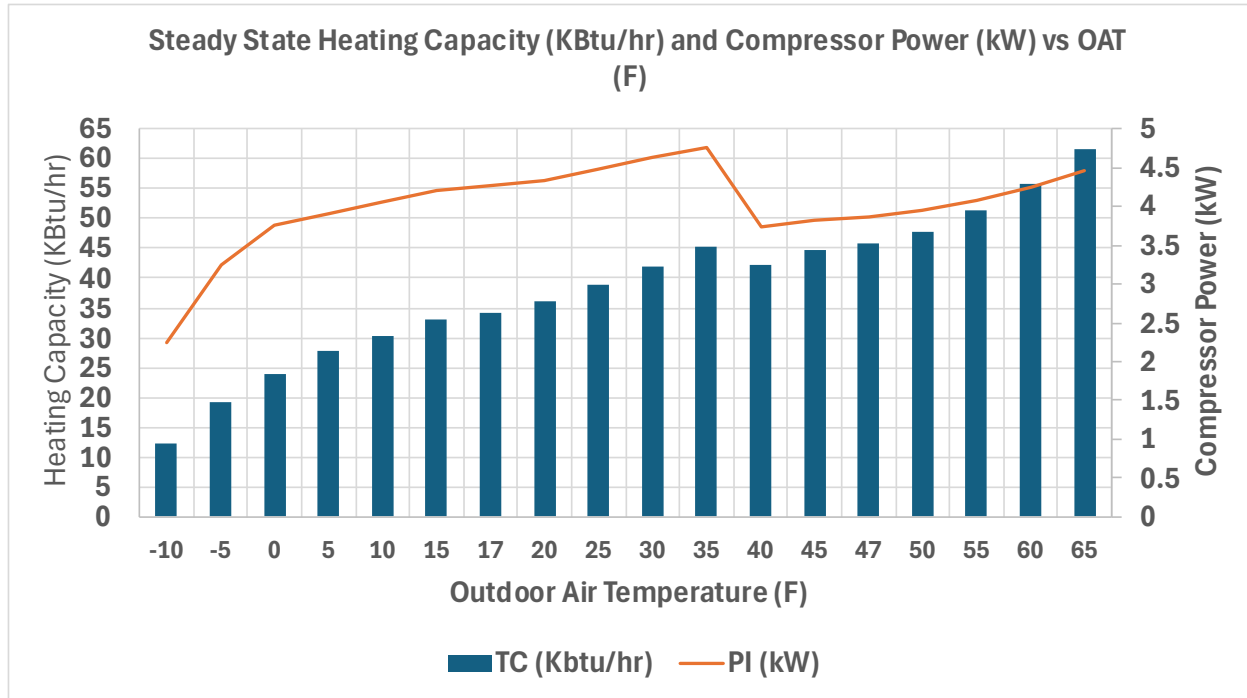


Figure 20 Heating Capacity and Power Draw relative to ambient conditions for modeled VSHP

Figure 21 to Figure 26 visualize the steady state heating capacity of the VSHP/CCHPs relative to the modeled heating loads (in green) and the outdoor air temperatures (x-axis). On the secondary axis (on the right), the power draws corresponding to full load (orange), general curtailment (70% of RLP) (in blue) and critical curtailment (40% of RLP) (in purple) are also visualized. Theoretically, at any specific outdoor air temperature, it can be surmised from the graph that the difference between the heating load and the heating capacity corresponding to the curtailment kW draw is the unmet heating load for that hour. The potential reduction in kW via curtailment would theoretically be the difference between the power draw (PI) and the curtailment kW.

For example, in Figure 21, for a General Curtailment event at 20°F (-6.7°C), there is a potential for reducing 1kW i.e. difference in orange and blue lines at 20°F (-6.7°C), at the cost of 8 KBtu heating being unmet in that hour. However, the actual kW reduction potential would be dependent on the instantaneous heating loads, time of day, part-load performance etc. These nuances were further explored and quantified via the modeling study.

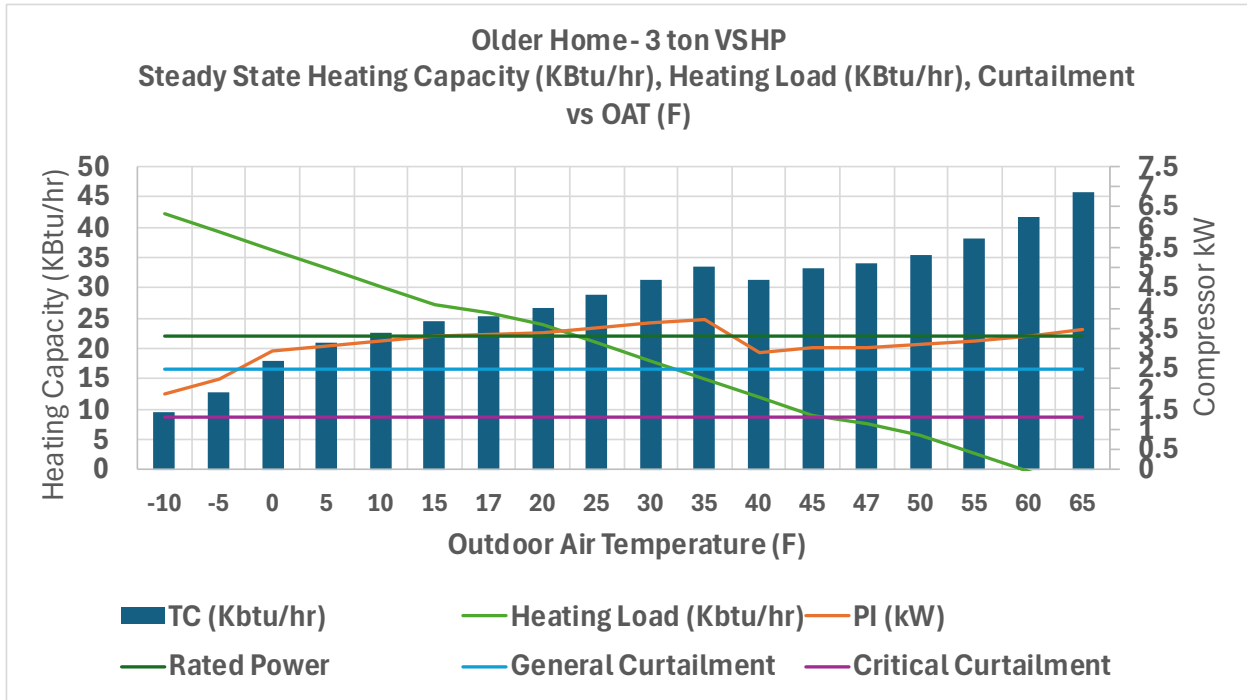


Figure 21 DR potential of modeled VSHP in an older home in Seattle, WA

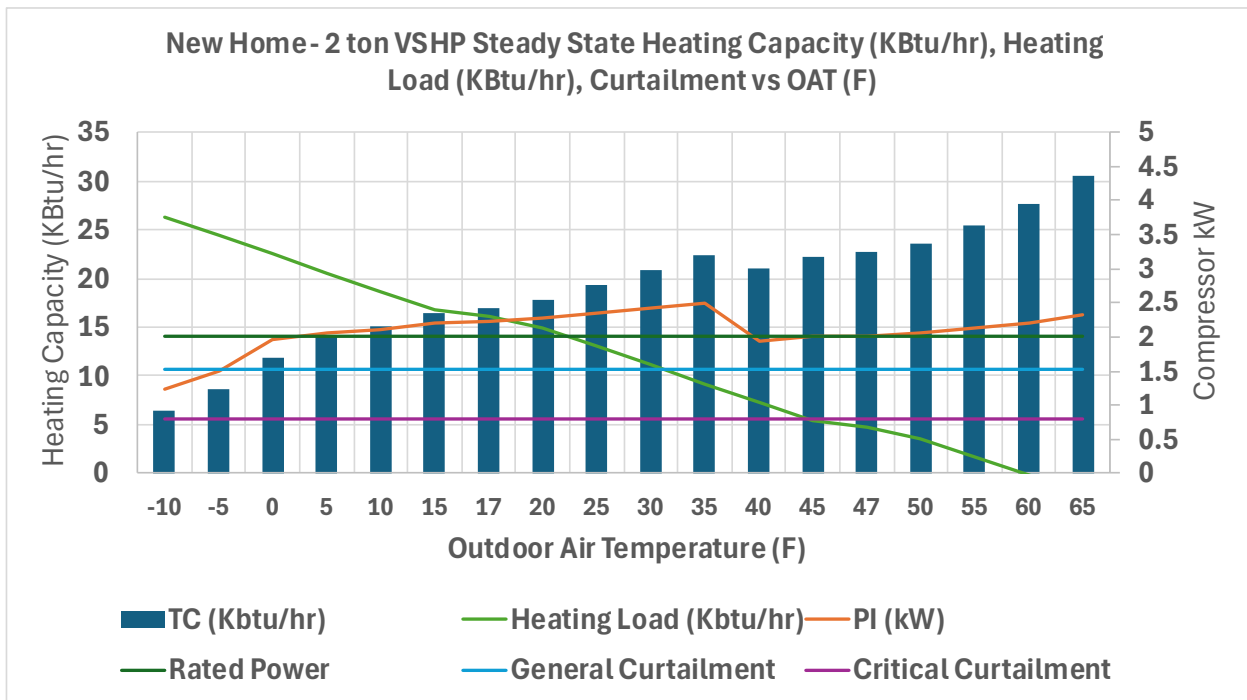


Figure 22 DR potential of modeled VSHP in a new home in Seattle, WA

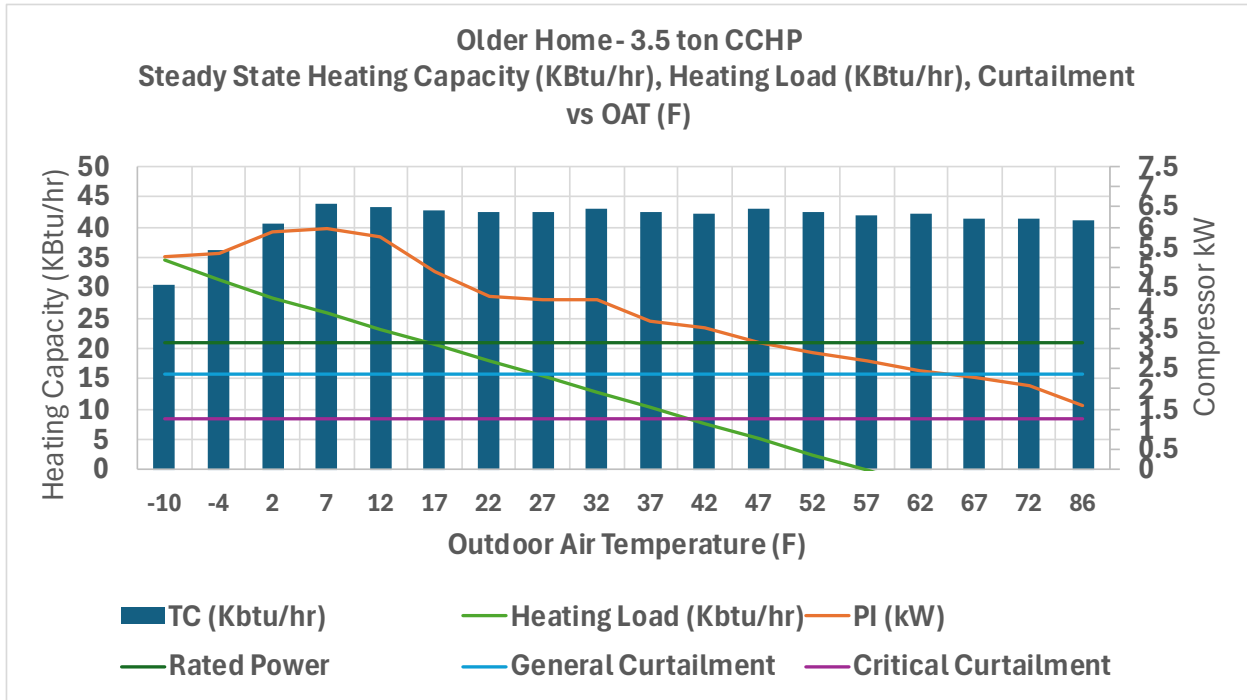


Figure 23 DR potential of modeled CCHP in an older home in Bend, OR

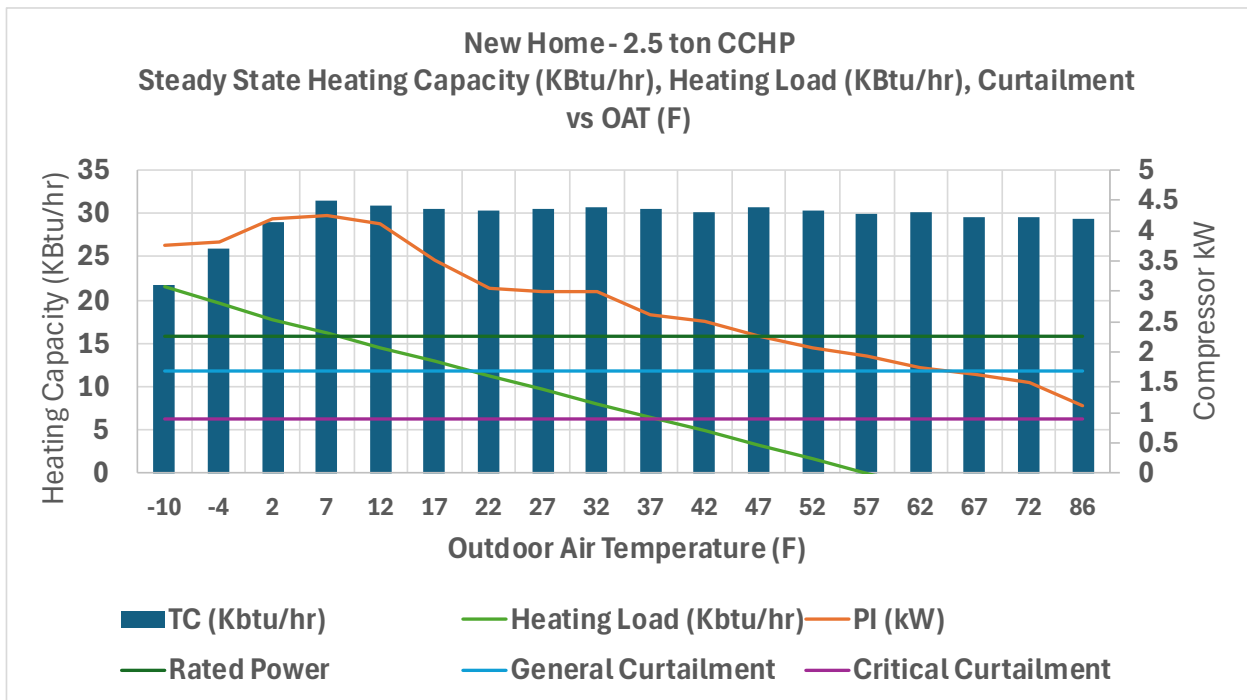


Figure 24 DR potential of modeled CCHP in a new home in Bend, OR

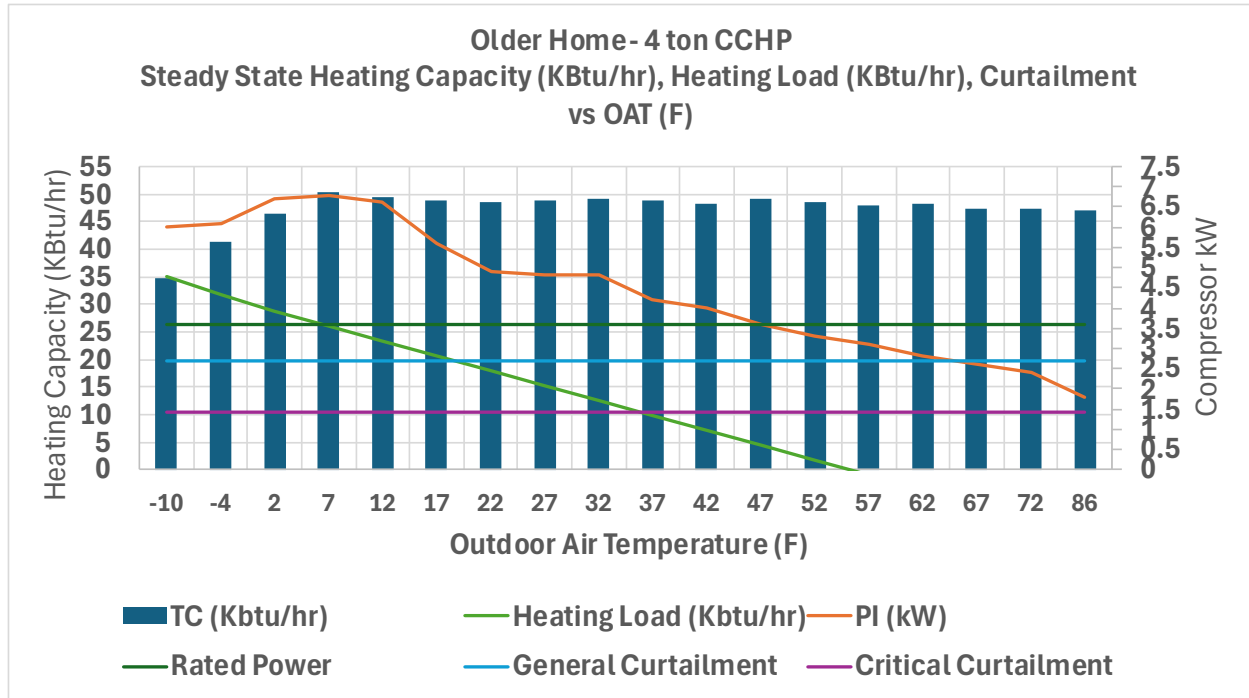


Figure 25 DR potential of modeled CCHP in an older home in Colville, WA

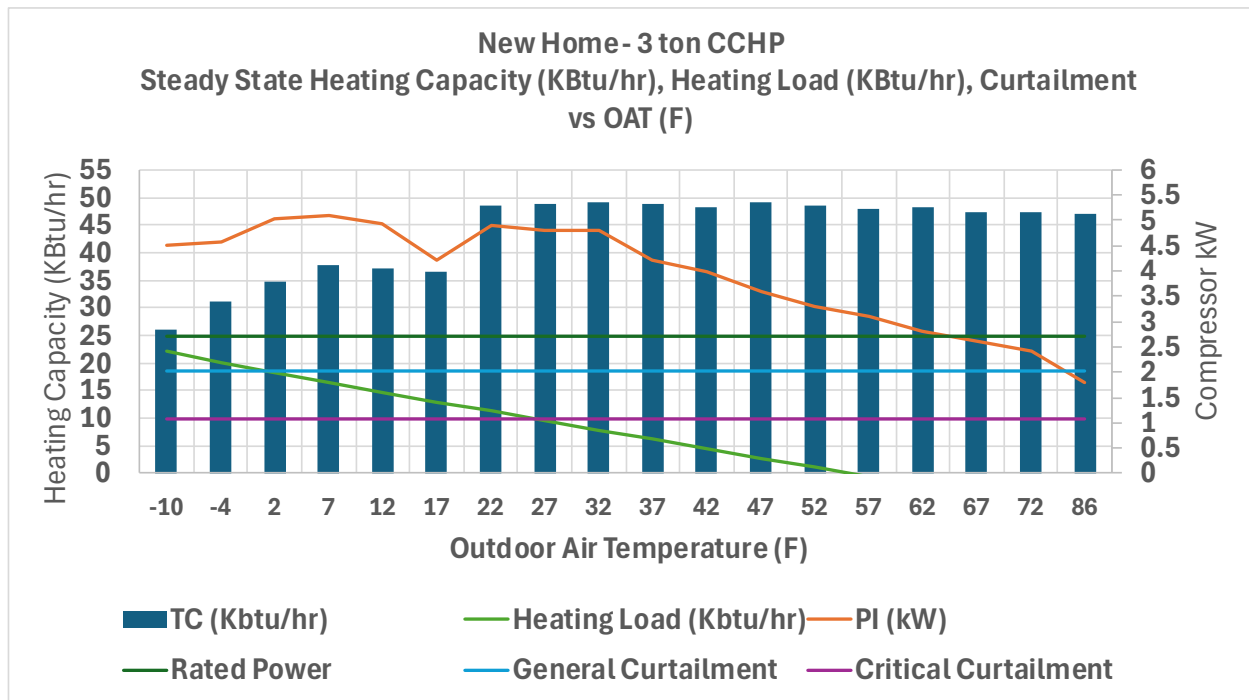


Figure 26 DR potential of modeled CCHP in a new home in Colville, WA

Parametric Modeling Matrix

The parametric modeling analysis was designed to inform utilities and other stakeholders on when and where variable-speed heat pumps (VSHPs) and cold-climate air-source heat pumps (CCHPs) can provide meaningful demand response (DR) through power curtailment while maintaining acceptable thermal comfort.

The simulation matrix was structured to capture the primary drivers of DR effectiveness—ambient conditions at event onset, equipment operating state (part-load vs. near-capacity), and event constraints such as maximum indoor temperature drift (MITO).

Simulations were organized across Pacific Northwest climate zones (4C, 5B, and 6B) and included two residential building vintages to reflect differences in envelope performance and load profiles. Both heating and cooling seasons were evaluated, with the heat pump modulating compressor speed to meet the requested power limit and sustain that limit without exceeding the maximum indoor temperature offset (MITO).

Key parameters varied in the modeling matrix included:

- Climate and location (CZ 4C, 5B, 6B)
- Building vintage (older ~2000; new IECC 2021)
- Heat pump type (VSHP in 4C; CCHP in 5B/6B) and representative performance curves
- Seasonal mode (heating and cooling)
- Outdoor temperature bins (mild, cold/very cold, hot)
- Curtailment level consistent with the AHRI 1380 framework (General $\leq 70\%$ RLP; Critical $\leq 40\%$ RLP; Off/Emergency as applicable)
- MITO values (2°F (1.11°C) to 4°F (2.22°C) offsets from the thermostat setpoint)
- DR event duration (1 to 4 hours)

Results are reported by climate zone and season, emphasizing the interaction between curtailment level, comfort impact, and post-event snapback behavior (recovery demand after the DR event). This type of parametric study can highlight key sweet spots for DR using curtailment that can aid development of adaptive program strategies rather than a single uniform parameter set across all conditions.

Table 8 Metrics varied as part of the parametric modeling study

Climate Zone	Heat Pump	Home Vintage	Outdoor Temperature Bins	Curtailment	MITO Range	DR Event Duration
4C	VSHP	Older	Below Freezing/Very Cold	General	2°F (1.11°C)	1 hour
5B	CCHP	New	Freezing	Critical	3°F (1.67°C)	2 hours
6B			Above Freezing/Mild		4°F (2.22°C)	3 hours
			Hot			4 hours

Modeling Runs in Climate Zone 4C (Seattle/Portland)

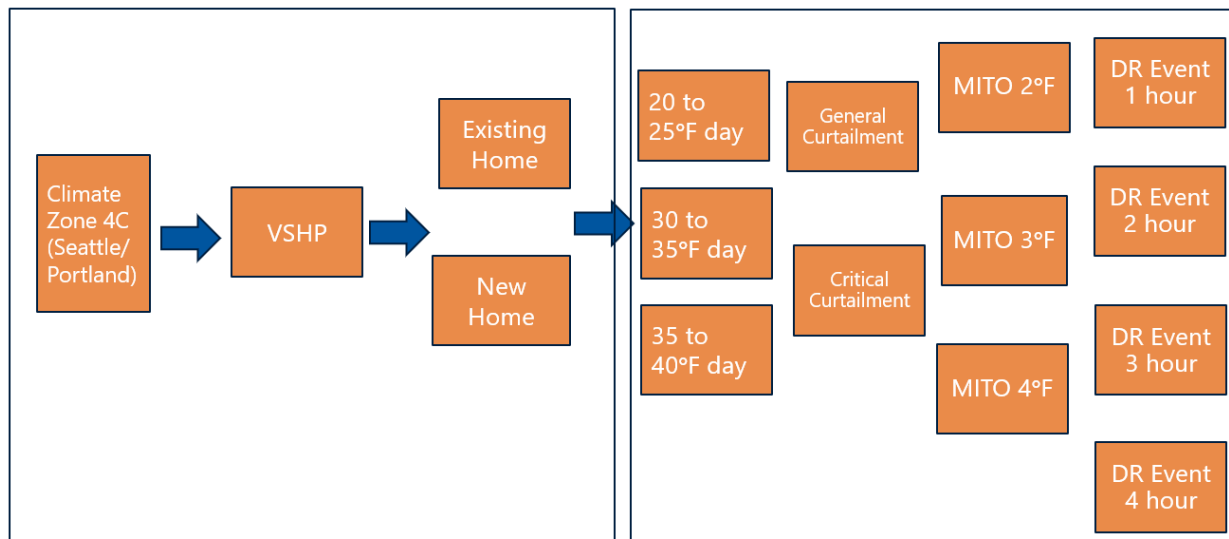


Figure 27 Modeling Runs for Heating in Climate Zone 4C (Seattle/Portland)

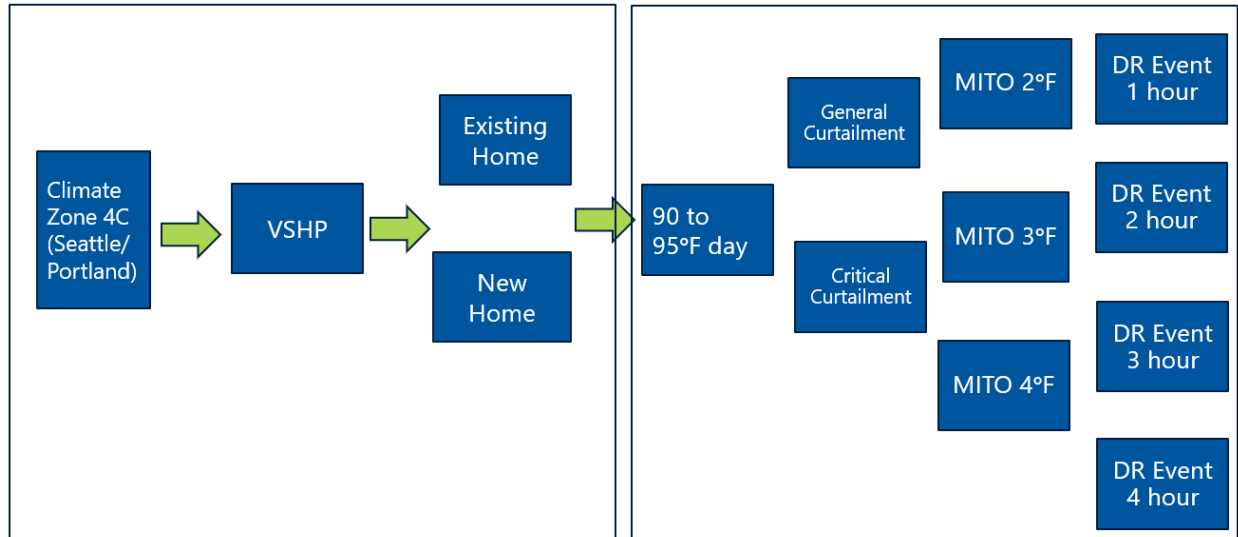


Figure 28 Modeling Runs for Cooling in Climate Zone 4C (Seattle/Portland)

Table 9 Outdoor Air Temperature Bins and Corresponding DR event times chosen

Climate Zone	Outdoor Temperature Bin	DR Event Time Chosen
4C	20 to 25°F (-6.7 to -3.9°C)	February 19 th 5am
	30 to 35°F (-1.1 to 1.7°C)	January 13 th 6pm
	35 to 40°F (1.7 to 4.4°C)	December 8 th 4pm
	90 to 95°F (32.2 to 35°C)	August 10 th 5pm

A similar approach was followed for climate zones 5B and 6B to map different outdoor temperature bins to DR event times.

Modeling Results 4C

Heating

Figure 29 shows the modeled VSHP's compressor power profile under baseline operation and general curtailment on a relatively mild heating day (35–40°F (1.7 to 4.4°C)) in the older home. In this temperature bin, the heat pump is already operating at part-load, with baseline peak kW on the order of ~1.24–1.42 kW, so applying General Curtailment ($\leq 70\%$ RLP) produced essentially no incremental kW reduction because the unit was already below the curtailment cap for much of the period. As a result, thermal comfort was maintained, and post-event "snapback" effects were not prominent in this case.

The dotted green line represents the 70% of the RLP and represents the maximum power draw of the compressor if subject to general curtailment. The dotted red line represents the 40% of the RLP and represents the maximum power draw of the compressor if subject to critical curtailment. The shaded region on the graph represents the operational domain for the compressor with potential reduction in kW if the heat pump were subject to critical curtailment.

In this case, there is minimal operation of the heat pump above the critical curtailment line (compressor power draw goes above the red dotted line at ~5:45pm until ~6:15pm), meaning that there is a very small potential for DR during that time but can only be realized through critical curtailment. General Curtailment (dotted green line) would see no impact on the VSHP kW draw.

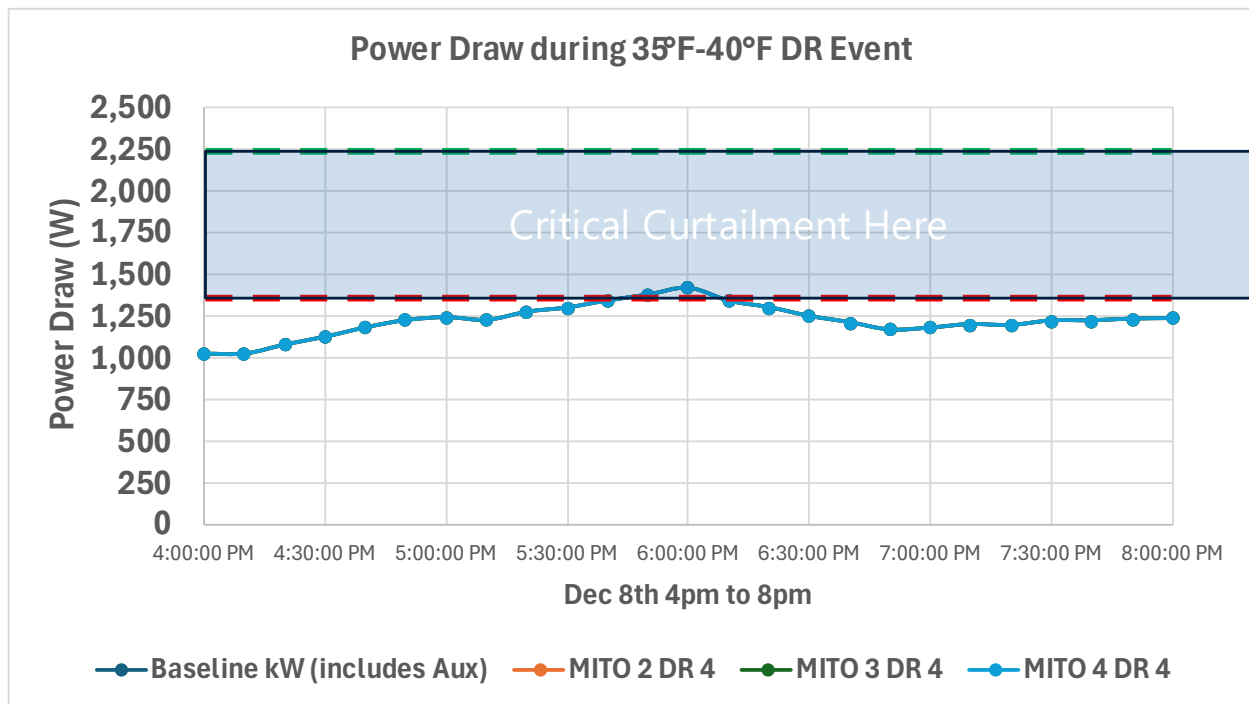


Figure 29 Heating Results – Climate 4C : Older Home 35°F - 40°F (1.7 to 4.4°C) day

- General Curtailment = 2,260 W (70% of RLP)
- Critical Curtailment = 1,290 W (40% of RLP)

Figure 30 expands the (35–40°F (1.7 to 4.4°C)) case by explicitly showing the pre-event, during-event, and post-event behavior, making the recovery dynamics (“snapback”) more visible. In this case, because the heat pump operated below the curtailment thresholds in the DR event, there was no impact on the power demand after the DR event concluded i.e. no snapback effects.

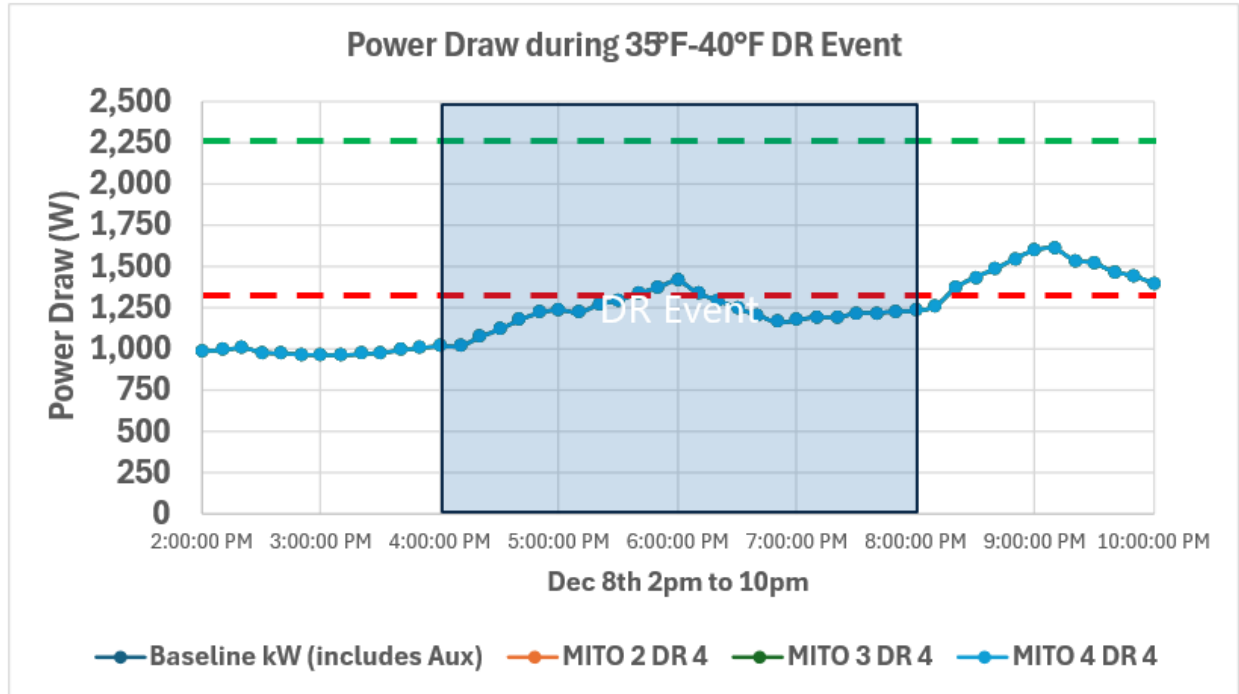


Figure 30 Heating Results – Climate 4C : Older Home 35°F - 40°F (1.7 to 4.4°C) day [Pre and Post DR Event]

Figure 31 shifts to slightly colder outdoor conditions (30–35°F (-1.1 to 1.7°C)), where the modeled VSHP power demand moves closer to the curtailment thresholds. The figure indicates that General Curtailment remains largely ineffective (little to no shed), but Critical Curtailment ($\leq 40\%$ RLP) can create some measurable demand reduction because compressor operation can occasionally exceed the critical limit in this bin. Overall comfort impacts are still relatively modest compared to colder-bin events, reinforcing that meaningful shed at these temperatures generally requires more aggressive curtailment. The shaded region on the graph represents the operational domain for the compressor with potential reduction in kW if the heat pump were subject to critical curtailment.

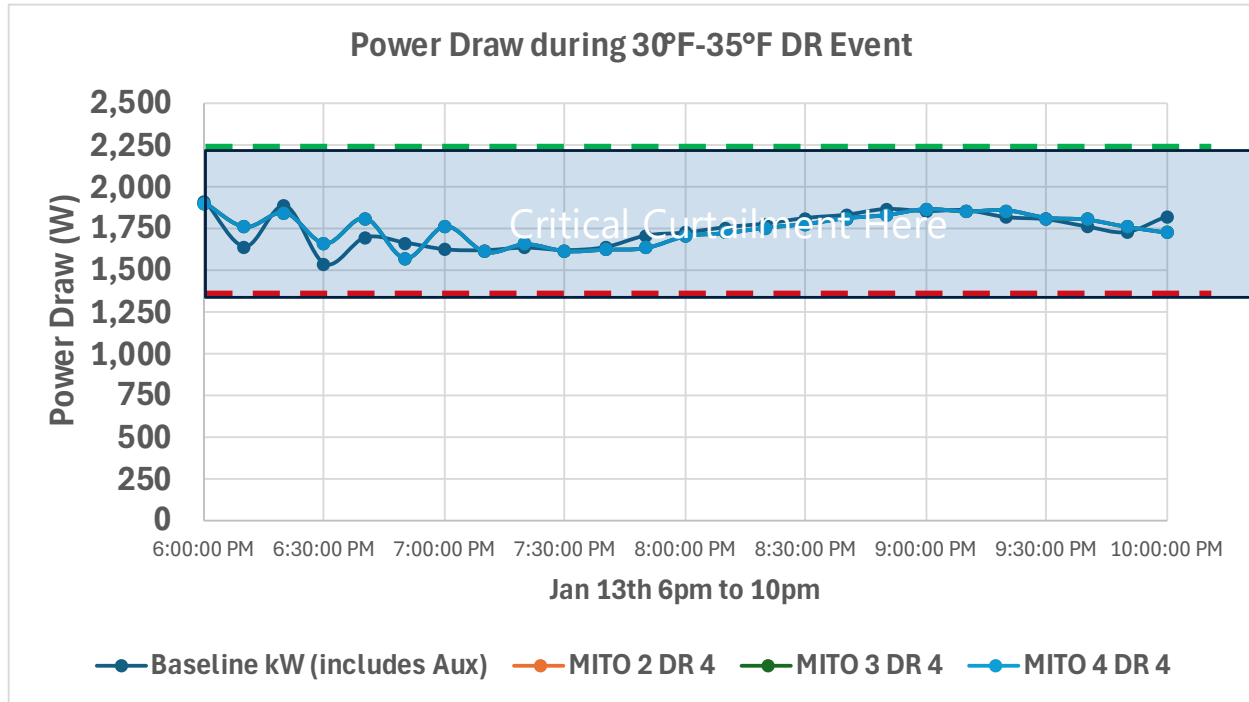


Figure 31 Heating Results – Climate 4C: Older Home 30°F - 35°F (-1.1 to 1.7°C) day

- General Curtailment = 2,260 W (70% of RLP)
- Critical Curtailment = 1,290 W (40% of RLP)

Figure 32 expands the 30–35°F (-1.1 to 1.7°C) case by explicitly showing the pre-event, during-event, and post-event behavior, making the recovery dynamics (“snapback”) more visible. In this case, because the heat pump operated below the curtailment thresholds in the DR event, there was no impact on the power demand after the DR event concluded i.e. no snapback effects.

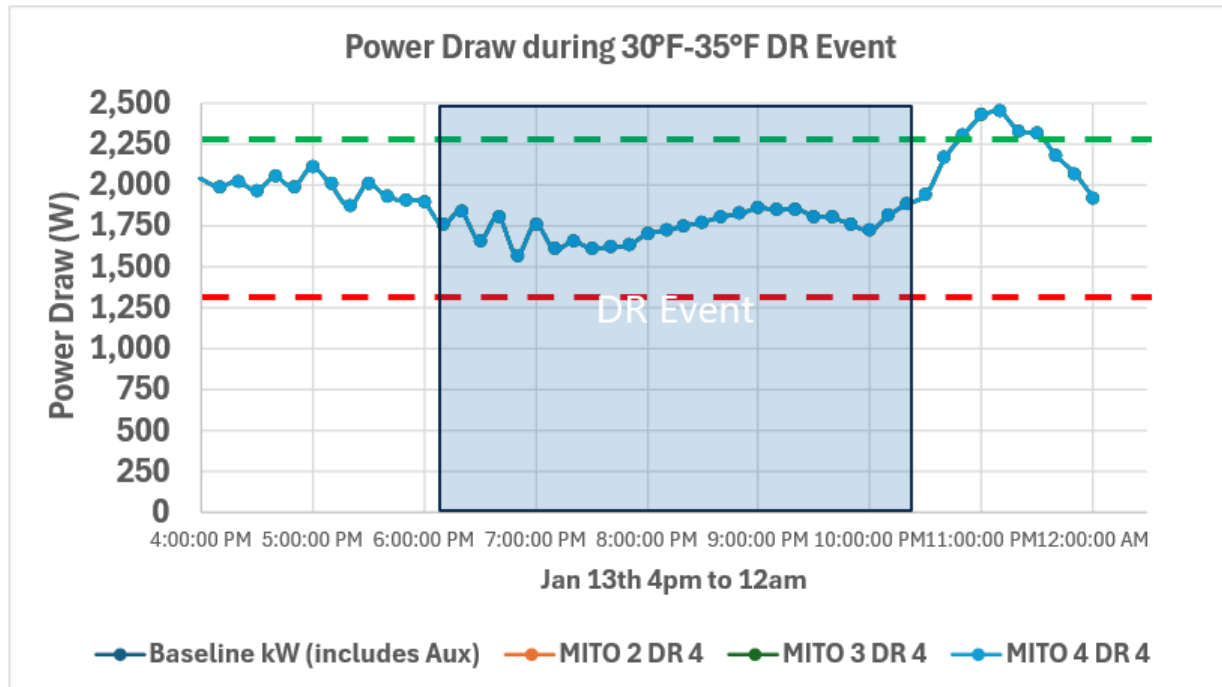


Figure 32 Heating Results – Climate 4C : Older Home 30°F - 35°F (-1.1 to 1.7°C) day [Pre and Post DR Event]

Figure 33 illustrates a colder heating day (20–25°F (-6.7 to -3.9°C)) where the VSHP operates nearer higher output to meet load, making curtailment substantially more consequential. In this bin, General Curtailment reduces modeled baseline peak power from roughly ~4.55–4.79 kW down to ~2.58–2.80 kW, corresponding to an estimated ~1.97–2.16 kW peak reduction. The figure and corresponding data table below also highlights the tradeoff: deeper/longer curtailment increases indoor temperature drift (about ~3.0–4.6°F (1.7°C-2.6°C) drop in this case set) and leads to a notable post-event snapback (roughly ~1.7–3.4 kW, depending on event parameters).

The shaded region with General Curtailment on the graph represents the operational domain for the compressor with potential reduction in kW if the heat pump were subject to general curtailment.

The shaded region with Critical Curtailment on the graph represents the operational domain for the compressor with potential reduction in kW if the heat pump were subject to critical curtailment.

In this case, all 4 scenarios plotted exit curtailment within 1 hour of the DR event because of exceeding MITO. The use case of MITO 4°F (2.2°C) stays the longest within curtailment at around 5:45pm (blue compressor line going above the General Curtailment line of 2,260 W); whereas the smaller MITO ranges exit curtailment within 30 minutes (orange and purple compressor lines).

Once the VSHP has exited curtailment, it is modeled to still stay in the DR event until 9pm (4-hour DR event plotted here). During this time, the indoor thermostat setpoint is setback to the original setpoint minus the MITO i.e. for a MITO of 4°F (2.2°C), the revised setpoint is 68°F (20°C) until the DR event concludes.

Additionally, auxiliary heating is not permitted to be used during the DR event, and this leads to further drop in thermal comfort as the VSHP is sized so that it is operating below its balance point at these ambient conditions. The baseline compressor draw (in dark blue) accounts for auxiliary heating as well to maintain the original setpoint of 72°F (22.2°C).

This approach of revising the indoor setpoint based on the MITO after the VSHP exceeds MITO and curtailment and until the DR event concludes is applied for every simulated scenario.

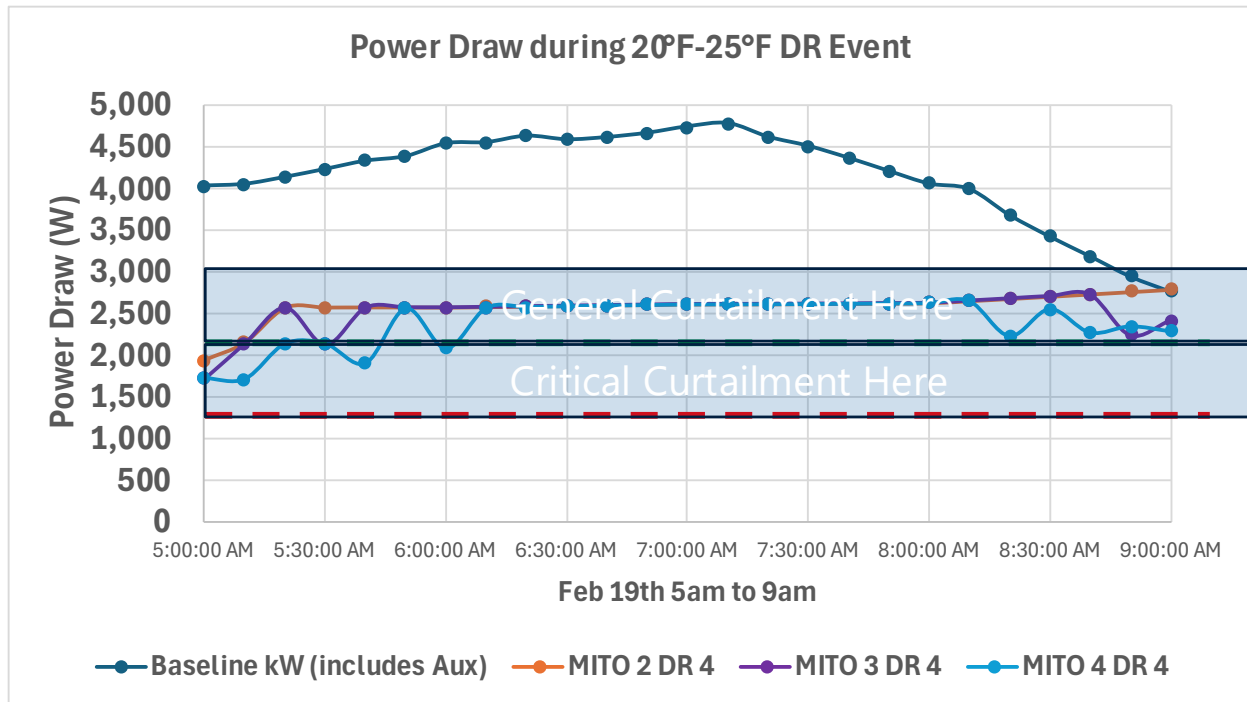


Figure 33 Heating Results – Climate 4C : Older Home 20°F - 25°F (-6.7 to -3.9°C) day

--- General Curtailment = 2,260 W (70% of RLP)

--- Critical Curtailment = 1,290 W (40% of RLP)

MITO offset (°F)	DR Event	Stayed within MITO offset	Peak kW (Baseline)	Peak kW (General Curtailment)	Peak kW reduction	Snapback vs Baseline (kW)	Indoor Temperature Drop from original setpoint (72°F)
2°F	1 hour (5-6)	No	4.55	2.58	1.97	1.73	2.97 (69°F)
	2 hours (5-7)	No	4.75	2.62	2.13	2.34	3.88 (68.1°F)
	3 hours (5-8)	No	4.79	2.63	2.16	2.56	4.1 (67.9°F)
	4 hours (5-9)	No	4.79	2.8	1.99	2.77	4.1 (67.9°F)
3°F	1 hour (5-6)	No	4.55	2.58	1.97	2.15	3.27 (68.7°F)
	2 hours (5-7)	No	4.75	2.62	2.13	2.66	4.04 (68°F)
	3 hours (5-8)	No	4.79	2.63	2.16	2.87	4.25 (67.8°F)
	4 hours (5-9)	No	4.79	2.8	1.99	2.73	4.25 (67.8°F)
4°F	1 hour (5-6)	No	4.55	2.58	1.97	2.57	4.18 (67.8°F)
	2 hours (5-7)	No	4.75	2.62	2.13	3.09	4.33 (67.7°F)
	3 hours (5-8)	No	4.79	2.63	2.16	3.2	4.5 (67.5°F)
	4 hours (5-9)	No	4.79	2.8	1.99	3.38	4.57 (67.4°F)

Figure 34 Heating Results – Climate 4C : Older Home 20°F - 25°F (-6.7 to -3.9°C) day

Figure 35 expands the 20–25°F (-6.7 to -3.9°C) case by explicitly showing the pre-event, during-event, and post-event behavior, making the recovery dynamics (“snapback”) more visible. The figure demonstrates that after the curtailment period ends, power demand can rebound above baseline as the system works to restore thermostat setpoint, and that this rebound risk grows as the event becomes more restrictive (larger MITO and/or longer duration). In other words, Figure 35 visualizes the central operational tradeoff for cold-bin heating DR: useful demand shed during the event versus comfort impacts and elevated recovery demand afterward.

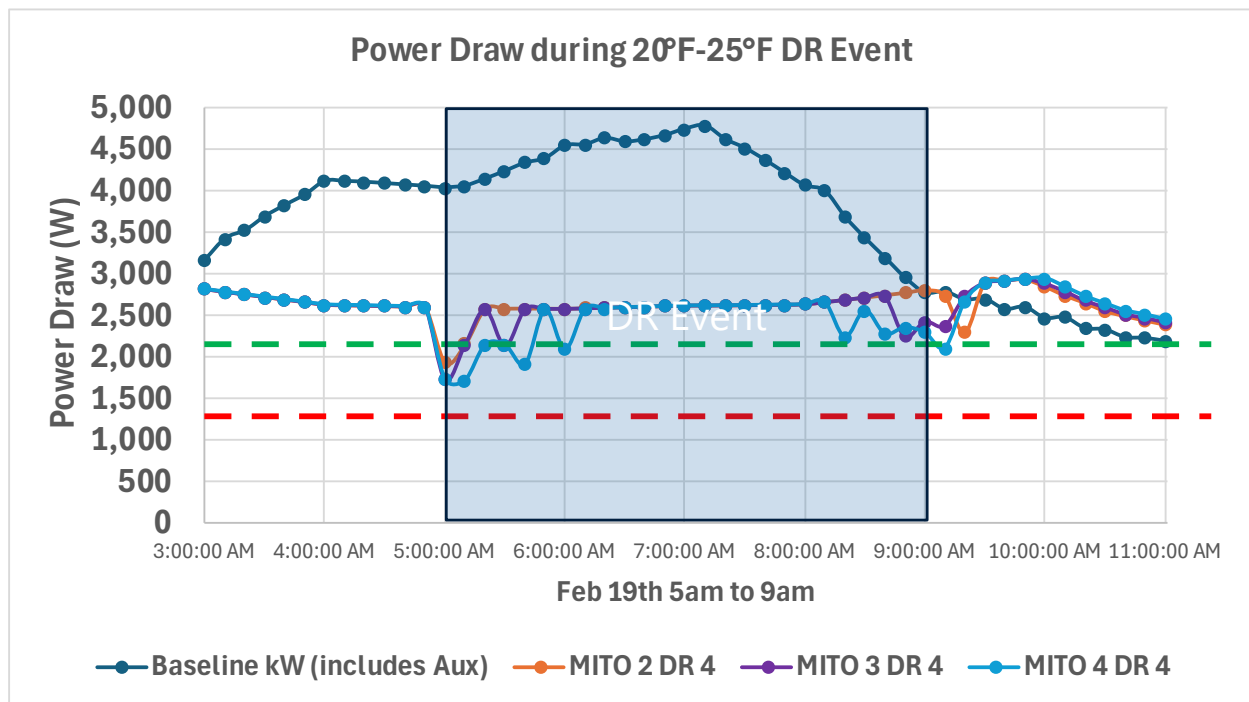


Figure 35 Heating Results – Climate 4C : Older Home 20°F - 25°F (-6.7 to -3.9°C) day [Pre and Post DR Event]

--- · **General Curtailment =
2,260 W (70% of RLP)**

--- · **Critical Curtailment =
1,290 W (40% of RLP)**

Modeling in Climate Zone 4C shows that baseline operating conditions strongly determine curtailment effectiveness. During milder heating conditions (~30°F–40°F (-1.1 to 4.4°C)), the VSHP typically operates at part-load levels already below the General Curtailment threshold (70% of Rated Load Power, RLP). As a result, General Curtailment provides little to no incremental kW reduction in this temperature range. In these bins, Critical Curtailment (40% of RLP) may be required to produce measurable demand reduction, particularly nearer 30°F–35°F (-1.1 to 1.7°C) where operating power can exceed the critical limit.

Under colder heating conditions (~20°F–25°F (-6.7 to -3.9°C)), the VSHP operates closer to higher output to meet load, and General Curtailment yields meaningful demand reduction relative to baseline. However, larger MITO offsets and longer event durations increase indoor temperature drift and can amplify post-event recovery (snapback) demand. These comfort and recovery impacts are also likely to increase the probability of customer opt-outs in real-world program operation.

Programmatic implication for climate zone 4C heating: shorter events (1–2 hours) paired with a smaller MITO (~2°F (1.1°C)) best balance demand reduction and comfort preservation while limiting snapback risk.

Cooling

Figure 36 presents modeled cooling demand response behavior for the older home in Climate Zone 4C on a 90–95°F ((32.2 to 35°C)) day. In this bin, the VSHP is largely operating at part-load (baseline peak approximately ~2.34 kW), such that General Curtailment ($\leq 70\%$ RLP) produces little to no measurable kW reduction because the unit is already operating below the cap for much of the event window. Consequently, indoor comfort impacts remain limited, and the results illustrate that meaningful cooling shed in this climate/house configuration is more likely under hotter-than-TMY conditions or more restrictive curtailment strategies.

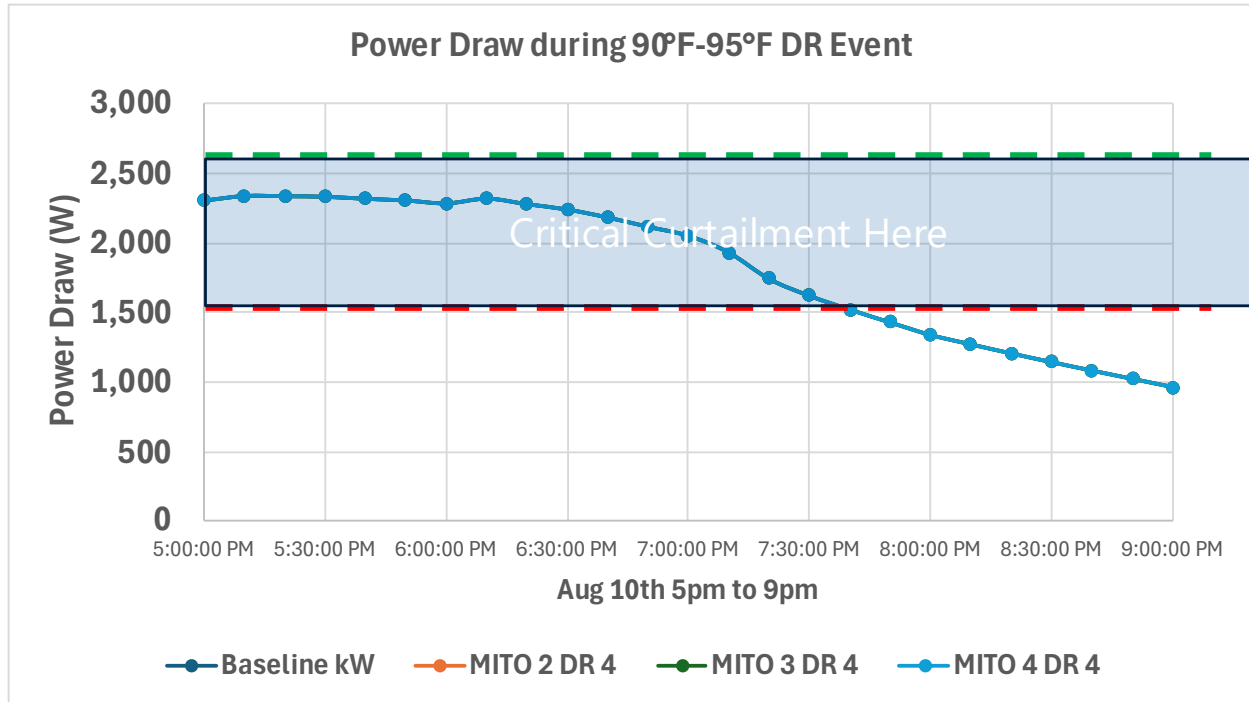


Figure 36 Cooling Results – Climate 4C : Older Home 90°F -95°F (32.2 to 35°C) day

- - - **General Curtailment = 2,650 W (70% of RLP)**
- - - **Critical Curtailment = 1,515 W (40% of RLP)**

Figure 37 expands the 90–95°F ((32.2 to 35°C)) case by explicitly showing the pre-event, during-event, and post-event behavior, making the recovery dynamics (“snapback”) more visible. In this case, because the heat pump operated below the curtailment thresholds in the DR event, there was no impact on the power demand after the DR event concluded i.e. no snapback effects.

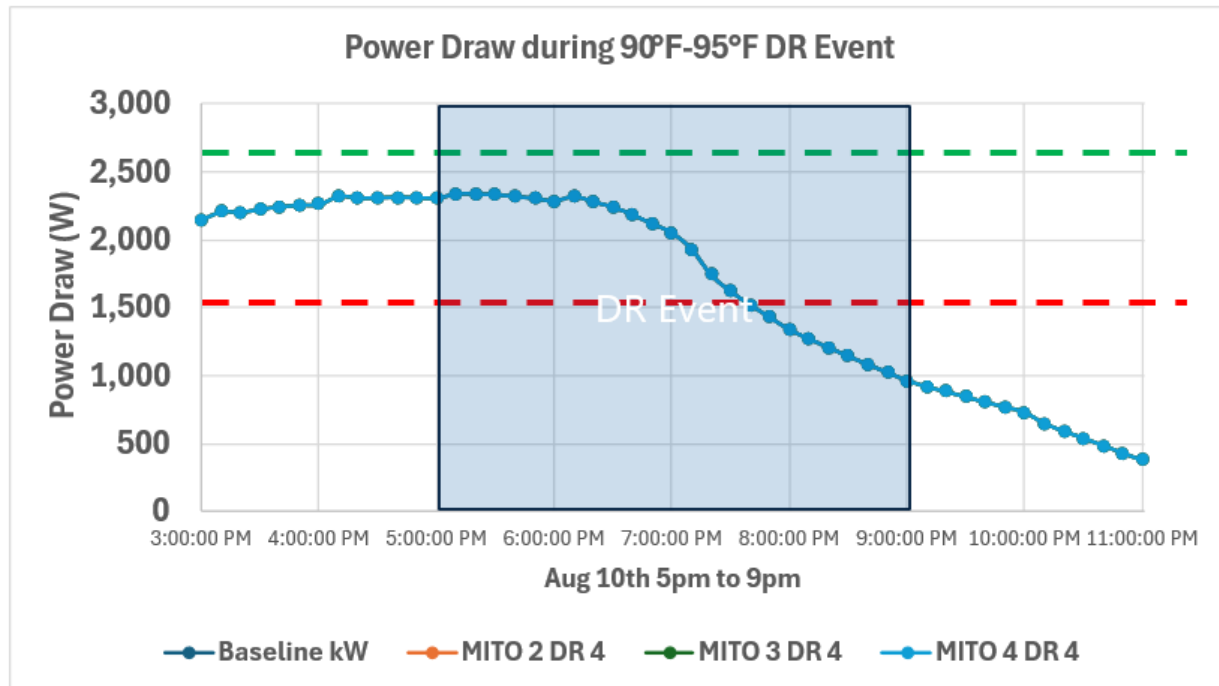


Figure 37 Cooling Results – Climate 4C : Older Home 90°F -95°F (32.2 to 35°C) day [Pre and Post DR Event]

For the modeled climate zone 4C cooling case (Seattle TMY3 peak conditions), the VSHP is primarily sized for heating, and cooling operation at ~90°F–95°F (32.2 to 35°C) generally occurs at part-load conditions below the General Curtailment threshold. Consequently, General Curtailment shows little to no reduction in demand in this bin. Critical Curtailment may yield limited incremental benefit depending on the specific operating point. Meaningful curtailment impacts are more likely on hotter-than-typical days (e.g., >100°F (37.8°C)) or under lower cooling setpoints, which push the equipment closer to higher operating power.

Figures 29–37 collectively show that DR potential is primarily dictated by outdoor temperature at event onset and the VSHP’s baseline operating point in Climate Zone 4C, with substantially different outcomes between mild and cold conditions.

On milder heating days (35–40°F (1.7°C–4.4°C); Figure 29), the VSHP is already at part-load (baseline peak ~1.24–1.42 kW), so General Curtailment ($\leq 70\%$ RLP) provides negligible incremental kW reduction with limited comfort or recovery impacts. As conditions cool to 30–35°F (-1.1 to 1.7°C) (Figure 31), baseline operation moves closer to the curtailment thresholds, and Critical Curtailment ($\leq 40\%$ RLP) becomes the more relevant lever for achieving measurable shed, though impacts remain modest relative to colder bins.

Under colder heating conditions (20–25°F (-6.7 to -3.9°C); Figure 33), the VSHP operates nearer full output and General Curtailment yields substantial peak reduction (baseline ~4.55–4.79 kW reduced to ~2.58–2.80 kW, or ~1.97–2.16 kW shed), but with increased indoor temperature drift (~3.0–4.6°F (1.7°C–2.6°C)) and notable post-event snapback (~1.7–3.4 kW)—tradeoffs made explicit in the pre/during/post profiles in Figure 33.

Finally, the cooling case (Figure 36, 90–95°F(32.2 to 35°C) in the older home) mirrors the mild-heating behavior: the VSHP typically operates at part-load (baseline peak ~2.34 kW), so General Curtailment produces little to no measurable kW reduction, implying that meaningful cooling DR in this region is more likely on hotter-than-typical days or under more aggressive curtailment.

Modeling Results 5B

Heating

Figure 38 shows heating curtailment results for the modeled cold-climate heat pump (CCHP) serving the older home in Climate Zone 5B during a 10–15°F (-12.2°C-(-)9.4°C) day. At these colder conditions, the unit operates closer to the general curtailment boundary, but the modeled results indicate only modest incremental shed under General Curtailment, with peak power reduced from roughly ~2.46–2.48 kW to ~2.31 kW (about ~0.15–0.17 kW reduction). Indoor temperature performance remains near the MITO boundary, suggesting comfort impacts are relatively limited in this case even as available DR magnitude is constrained by baseline operating state.

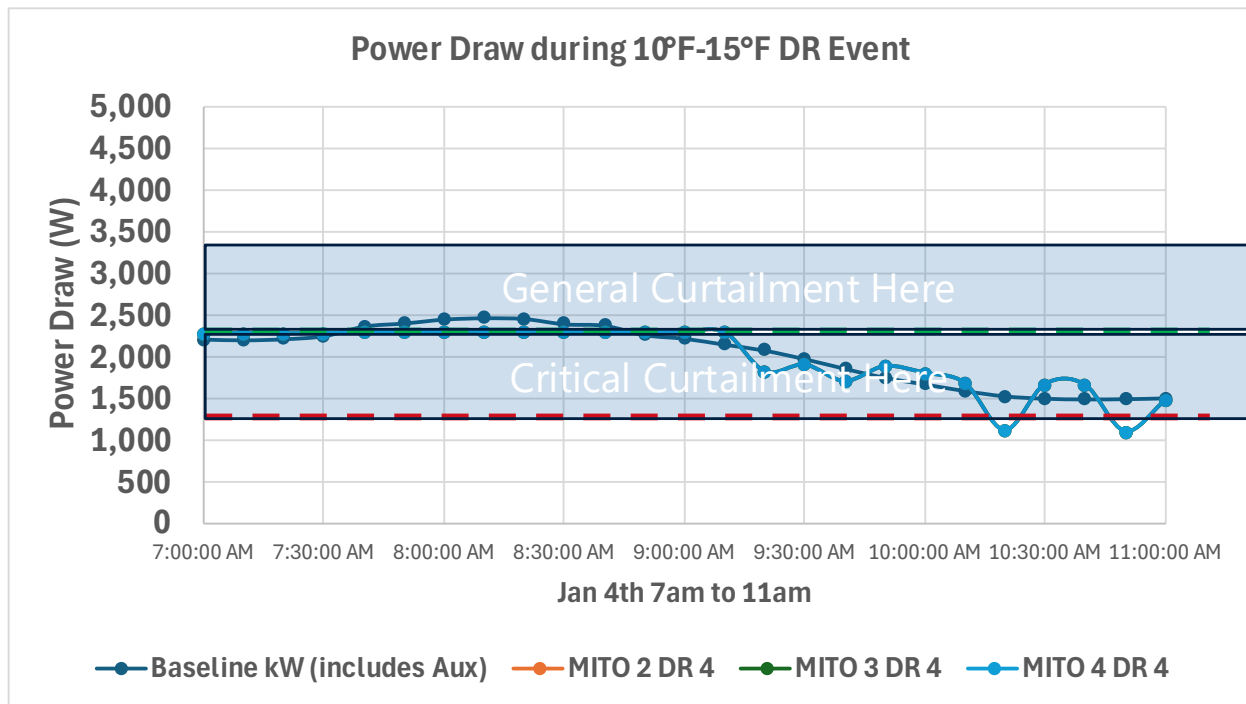


Figure 38 Heating Results – Climate 5B : Older Home 10°F - 15°F (-12.2°C-(-)9.4°C) day

--- **General Curtailment = 1,430 W (70% of RLP)**

--- **Critical Curtailment = 820 W (40% of RLP)**

MITO offset (°F)	DR Event	Stayed within MITO offset	Peak kW (Baseline)	Peak kW (General Curtailment)	Peak kW reduction	Snapback vs Baseline (kW)	Indoor Temperature Drop from original setpoint (72°F)
2°F	1 hour (7-8)	Yes	2.46	2.31	0.154	-	-
	2 hours (7-9)	Yes	2.48	2.31	0.168	-	-
	3 hours (7-10)	Yes	2.48	2.31	0.168	-	-
	4 hours (7-11)	Yes	2.48	2.31	0.168	-	-
3°F	1 hour (7-8)	Yes	2.46	2.31	0.154	-	-
	2 hours (7-9)	Yes	2.48	2.31	0.168	-	-
	3 hours (7-10)	Yes	2.48	2.31	0.168	-	-
	4 hours (7-11)	Yes	2.48	2.31	0.168	-	-
4°F	1 hour (7-8)	Yes	2.46	2.31	0.154	-	-
	2 hours (7-9)	Yes	2.48	2.31	0.168	-	-
	3 hours (7-10)	Yes	2.48	2.31	0.168	-	-
	4 hours (7-11)	Yes	2.48	2.31	0.168	-	-

Figure 39 expands the 5B 10–15°F (-12.2°C-(-)9.4°C) heating case by showing the pre-event, during-event, and post-event profile to highlight persistence and recovery behavior. The plot illustrates that the CCHP tracks the curtailment request during the DR window, and the post-event rebound (“snapback”) is present but relatively modest compared to colder or more constrained scenarios, consistent with the limited amount of curtailment achieved in this temperature bin. Indoor temperature drift remains contained near MITO, emphasizing that in this case the program tradeoff is primarily limited to DR magnitude rather than severe comfort degradation.

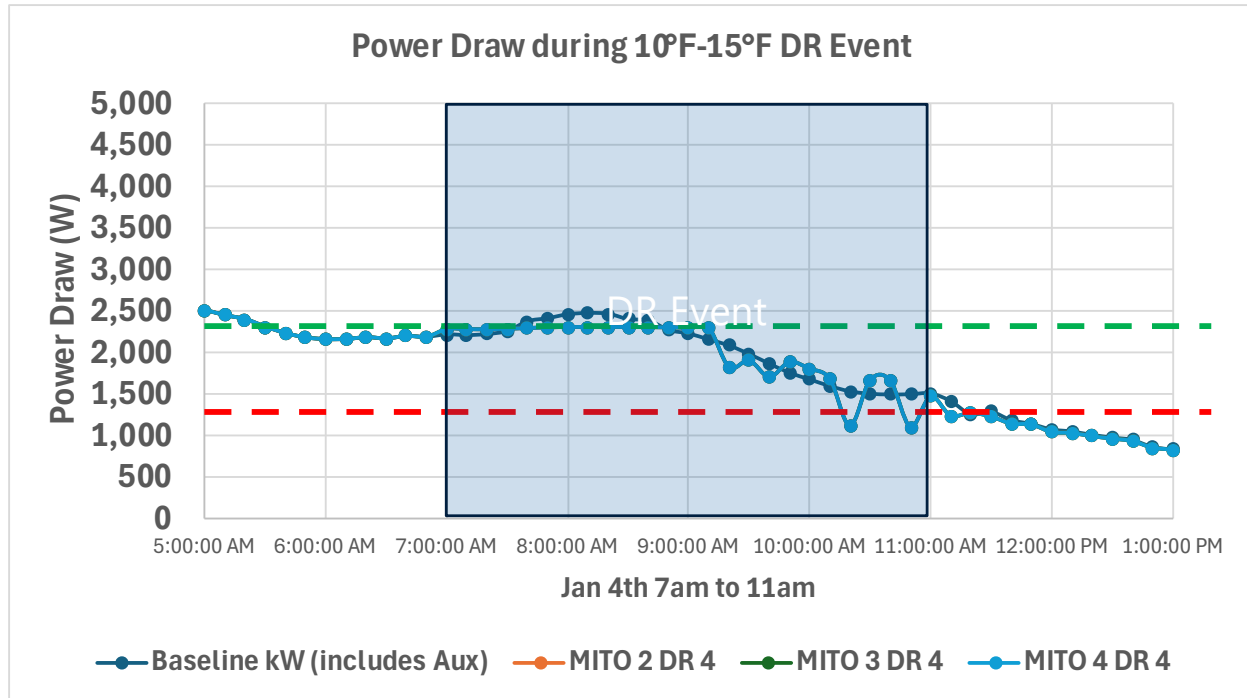


Figure 39 Heating Results – Climate 5B : Older Home 10°F - 15°F (-12.2°C-(-)9.4°C) day [Pre and Post DR Event]

--- General Curtailment =
1,430 W (70% of RLP)

--- Critical Curtailment =
820 W (40% of RLP)

Across modeled heating bins in Climate Zone 5B, General Curtailment is frequently ineffective during mild-to-moderate conditions because the CCHP typically operates at part-load levels below 70% of RLP (especially above freezing and in the ~25°F–40°F (-3.9°C–4.4°C) range). Under those conditions, the system is already operating under the cap, so a General Curtailment request provides minimal incremental DR.

Critical Curtailment may be needed to observe measurable demand reduction in moderate bins (e.g., around 30°F–35°F (-1.1 to 1.7°C)). At colder conditions (~10°F–15°F (-12.2°C-(-)9.4°C)), the modeled CCHP often operates near ~70% of RLP to maintain the thermostat setpoint, which limits the additional reduction achievable through General Curtailment. Comfort impacts were generally limited in these bins, with indoor temperatures remaining close to the MITO boundary.

Programmatic implication for 5B heating: for modern CCHPs that maintain strong low-ambient capacity and are commonly sized for heating design loads, a potential sweet spot for General Curtailment may occur during very cold conditions (~0°F–10°F (-17.8°C-(-)12.2°C)), where operating power is high enough for curtailment to matter but not so extreme that comfort is rapidly compromised.

Cooling

Figure 40 presents cooling results for the older home in Climate Zone 5B on a 95–100°F (35°C–37.8°C) day. The modeled CCHP is generally operating at part-load, with demand frequently below the General Curtailment cap, leading to little or no kW reduction during a general curtailment event. The figure reinforces that, for this equipment sizing and load profile, cooling DR effectiveness improves when ambient conditions are more extreme (e.g., >100°F(37.8°C)) or when operating points push the unit closer to higher compressor power levels.

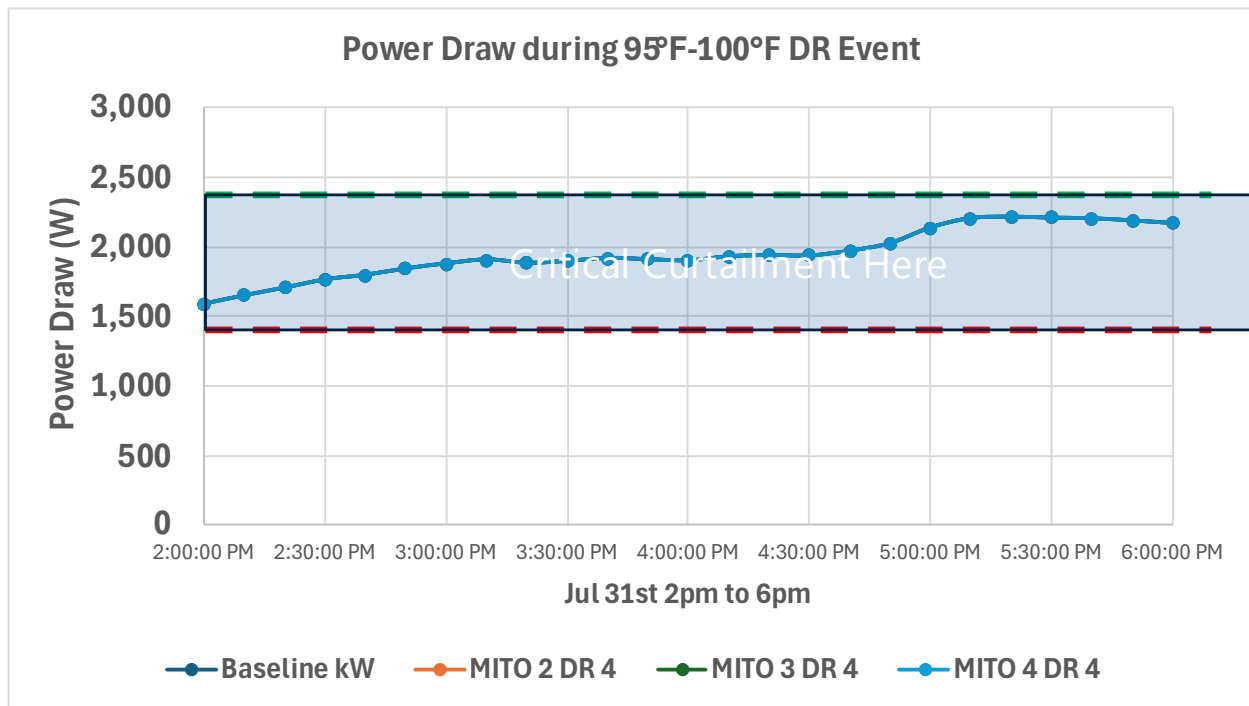


Figure 40 Cooling Results – Climate 5B : Older Home 95°F -100°F (35°C-37.8°C) day

- General Curtailment = 1,770 W (70% of RLP)
- Critical Curtailment = 1,010 W (40% of RLP)

In the modeled 5B cooling bin (~95°F–100°F (35°C–37.8°C)), the CCHP—sized primarily for heating—generally operates at part-load conditions below 70% of RLP, resulting in little to no kW reduction under General Curtailment. Hotter-than-typical conditions (e.g., >100°F (37.8°C)) would be more likely to push the system toward higher power operation and increase the effectiveness of curtailment.

Modeling Results 6B

Heating

Figure 41 shows heating curtailment behavior for a CCHP in the new home in Climate Zone 6B during a 10–15°F (-12.2°C-(-)9.4°C) day. Results indicate minimal kW savings under General Curtailment, reflecting that baseline operation at event onset is not sufficiently above the curtailment cap to enable substantial shed (i.e., the unit is already near or below the relevant limit for portions of the event). Indoor temperature drift remains limited and tends to stay near the MITO boundary, suggesting that in this modeled case the primary constraint is available for demand reduction, not comfort feasibility.

In this case, all 4 scenarios plotted exit curtailment within 2 hours of the DR event because of exceeding MITO. The use case of MITO 4°F (2.2°C) stays the longest within curtailment at around 9:45am (blue compressor line going above the General Curtailment line of 2,620 W); whereas the smaller MITO ranges exit curtailment within 1 hour (orange and purple compressor lines).

Once the VSHP has exited curtailment, it is modeled to still stay in the DR event until 12pm (4-hour DR event plotted here). During this time, the indoor thermostat setpoint is setback to the original setpoint minus the MITO i.e. for a MITO of 4°F (2.2°C), the revised setpoint is 68°F (20°C) until the DR event concludes.

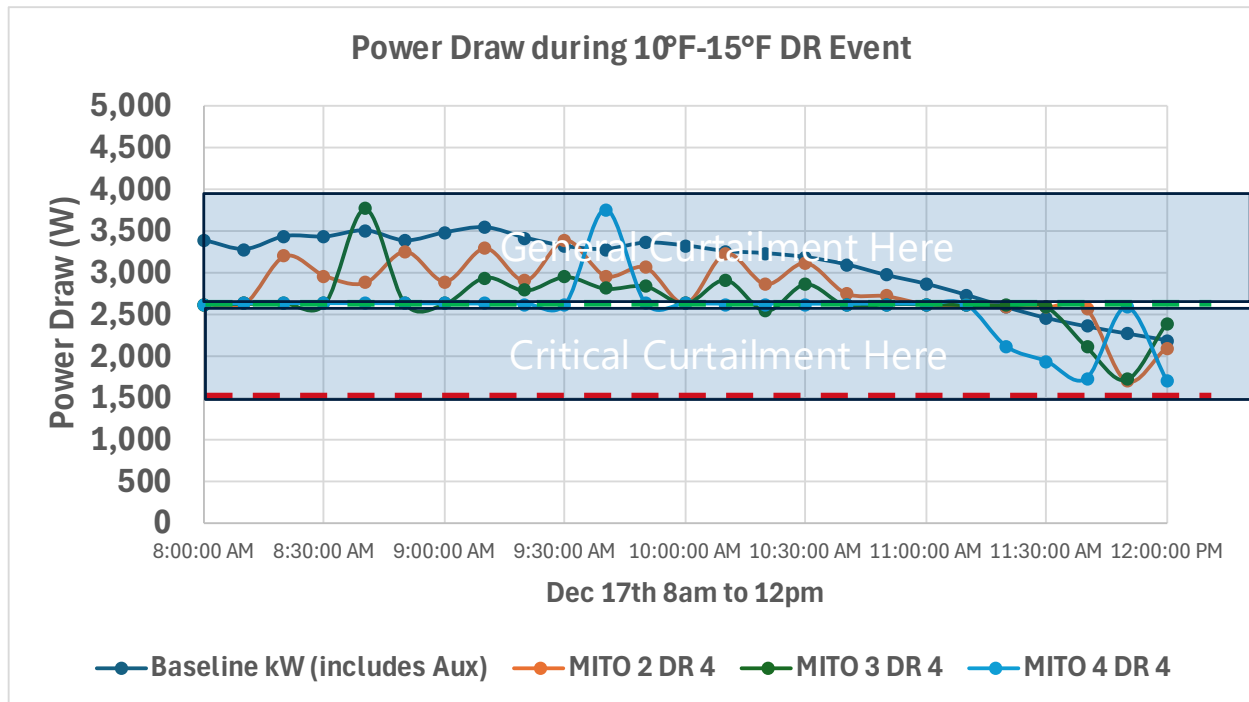


Figure 41 Heating Results – Climate 6B : New Home 10°F - 15°F (-12.2°C-(-)9.4°C) day

--- General Curtailment =
2,620 W (70% of RLP)

--- Critical Curtailment =
1,500 W (40% of RLP)

MITO offset (°F)	DR Event	Stayed within MITO offset	Peak kW (Baseline)	Peak kW (General Curtailment)	Peak kW reduction	Snapback vs Baseline (kW)	Indoor Temperature Drop from original setpoint (72°F)
2°F	1 hour (8-9)	No	3.51	3.26	0.25	2.07	2.19 (69.8°F)
	2 hours (8-10)	No	3.55	3.39	0.15	1.62	2.51 (69.5°F)
	3 hours (8-11)	No	3.55	3.39	0.15	0.54	2.51 (69.5°F)
	4 hours (8-12)	No	3.55	3.39	0.15	1.27	2.51 (69.5°F)
3°F	1 hour (8-9)	No	3.51	3.77	(0.25)	2.84	2.97 (69°F)
	2 hours (8-10)	No	3.55	3.77	(0.22)	2.76	3.20 (68.8°F)
	3 hours (8-11)	No	3.55	3.77	(0.22)	1.81	3.20 (68.8°F)
	4 hours (8-12)	No	3.55	3.77	(0.22)	1.98	3.20 (68.8°F)
4°F	1 hour (8-9)	Yes	3.51	2.64	0.87	2.87	3.35 (68.6°F)
	2 hours (8-10)	No	3.55	3.77	(0.22)	3.05	3.94 (68.1°F)
	3 hours (8-11)	No	3.55	3.77	(0.22)	1.95	3.20 (68.8°F)
	4 hours (8-12)	No	3.55	3.77	(0.22)	2.49	3.20 (68.8°F)

Figure 42 provides the corresponding pre/post event view for the Climate Zone 6B new-home heating scenario, illustrating how load and indoor temperature evolve through the DR window and recovery period. The figure shows that curtailment yields limited incremental reduction and that the post-event snapback is comparatively large, consistent with the large temperature drift during the event. Overall, the plot emphasizes that for this bin and building vintage, event performance is dominated by part-load/near-cap operation and therefore offers constrained DR value unless event strategy or operating conditions change.

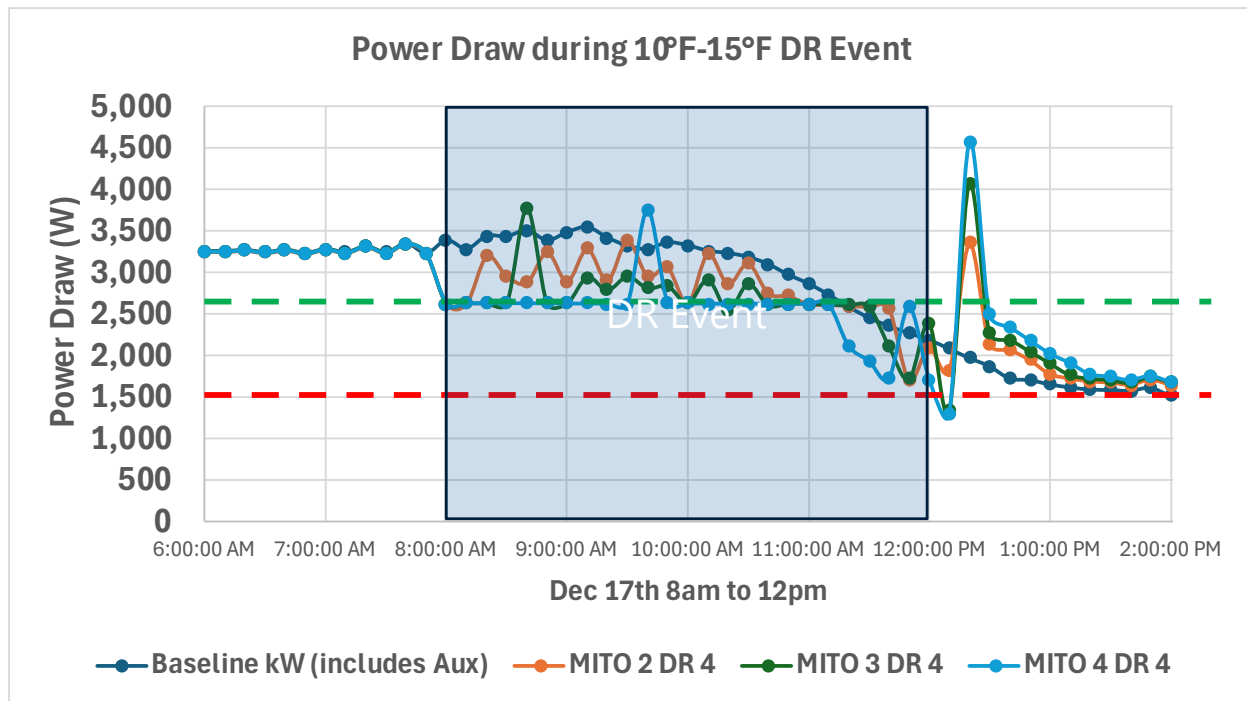


Figure 42 Heating Results – Climate 6B : New Home 10°F - 15°F day (-12.2°C-(-)9.4°C) [Pre and Post DR Event]

- General Curtailment = 2,620 W (70% of RLP)
- Critical Curtailment = 1,500 W (40% of RLP)

Climate Zone 6B results highlight the part-load limitation for curtailment-based DR. During mild-to-moderate heating conditions (~25°F–40°F (-3.9°C–4.4°C)), the CCHP operates well below the General Curtailment threshold and often below the Critical threshold as well, yielding little to no incremental demand reduction under either curtailment level.

At colder conditions (~10°F–15°F (-12.2°C-(-)9.4°C)), the modeling indicates minimal kW savings under General Curtailment and limited comfort degradation, with indoor temperatures generally staying close to the MITO boundary. Meaningful DR potential is more likely during very cold conditions (<10°F (-12.2°C)) when the heat pump operates nearer higher output levels, and a curtailment cap can produce measurable shed.

Programmatic implication for 6B heating: when events are called in colder bins, a shorter event duration (~1 hour) paired with a larger allowable MITO (~4°F (2.2°C)) may better preserve event persistence while still enabling measurable shed in the most promising conditions.

Cooling

Figure 43 presents cooling results for the older home in Climate Zone 6B at 95–100°F (35°C–37.8°C). Similar to other Pacific Northwest cooling bins, the modeled CCHP often operates at part-

load with baseline demand below the General Curtailment threshold, yielding negligible kW reduction under general curtailment. The figure suggests that Critical Curtailment may provide limited additional benefit depending on the operating point, but the overall implication is that cooling DR in this bin is most effective under hotter conditions or when the system is driven closer to higher cooling loads (e.g., lower setpoints or extreme heat days).

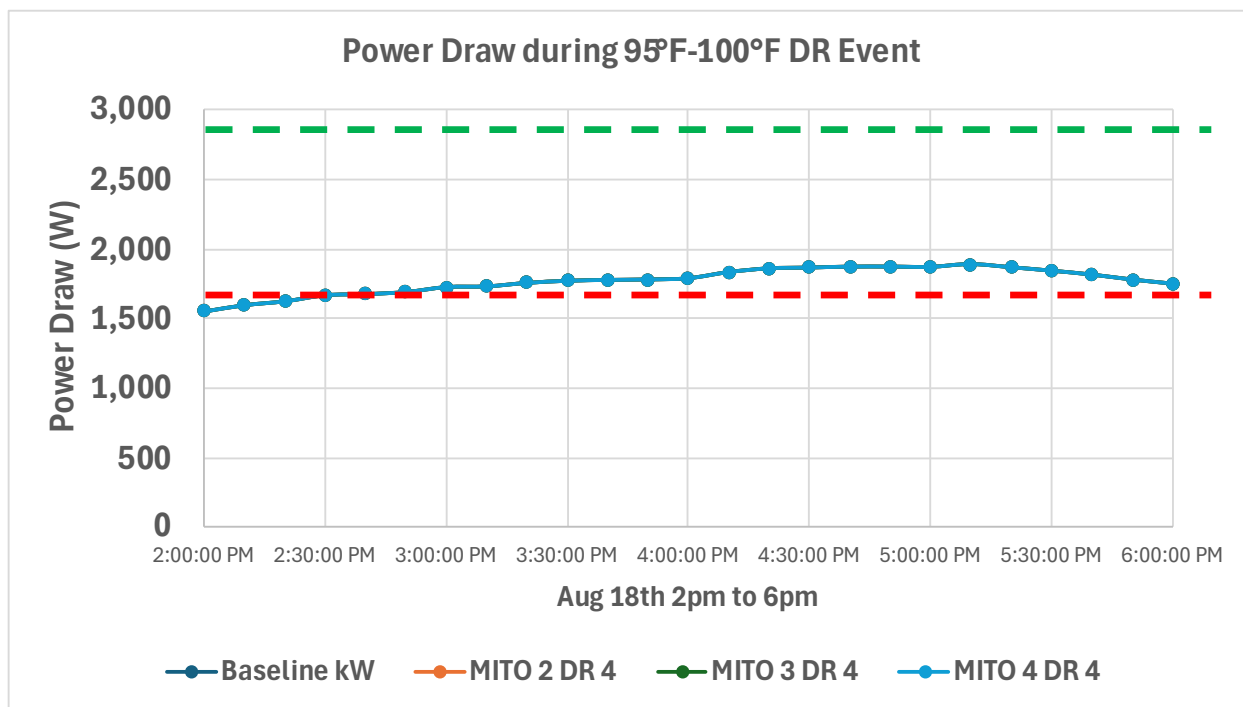


Figure 43 Cooling Results – Climate 6B : Older Home 95°F -100°F (35°C-37.8°C) day

--- General Curtailment =
2,810 W (70% of RLP)

--- Critical Curtailment =
1,610 W (40% of RLP)

In the modeled cooling bin (~95°F–100°F (35°C–37.8°C)), the CCHP operates at part-load levels below 70% of RLP, so General Curtailment produces little to no kW reduction. Critical Curtailment may provide limited benefits depending on the operating point. Higher cooling DR potential is more likely under hotter-than-typical conditions (>100°F (37.8°C)) or with alternative equipment/control characteristics that operate closer to higher loads in cooling mode.

Taken together, Figures 38–43 show that baseline operating state (part-load vs. near-capacity) is the dominant driver of curtailment effectiveness across both seasons and climate zones, and that many modeled hours in the Pacific Northwest fall into bins where systems are already operating below the General Curtailment cap. In cooling (Figures 37, 40, and 43), the modeled units—often sized primarily for heating—tend to run at part-load in the 90–100°F (32.2°C–37.8°C) bins, so

General Curtailment produces little or no incremental kW reduction, implying that meaningful cooling DR is more likely on hotter-than-typical days or under more aggressive control limits.

In heating, the contrast across bins and zones is clearer: Climate Zone 5B at 10–15°F (-12.2°C-(-)9.4°C) (Figures 38–39) demonstrates only modest shed with relatively contained comfort impacts and modest recovery behavior, while Climate Zone 6B (Figures 41–42) similarly indicates limited additional reduction and relatively small snapback in the modeled 10–15°F (-12.2°C-(-)9.4°C) case—again reflecting conditions where the equipment is not substantially above the curtailment threshold at event onset. Overall, these figures reinforce the programmatic implication that static, one-size-fits-all events will yield inconsistent outcomes, and that utilities are likely to need adaptive event strategies (by temperature bin, season, and building/equipment context) to reliably balance achievable shed against comfort and recovery (“snapback”) risk.

DISCUSSION

This project combined a technology and market assessment with a parametric EnergyPlus modeling effort to assess the practical demand flexibility potential of VSHPs, including CCHPs, under the current AHRI 1380 framework.

Across both efforts, a consistent theme emerged: the achievable DR from VSHP power curtailment can be meaningful but is currently in a stage of infancy. Market readiness is advancing—with several OEMs already demonstrating AHRI 1380 capability—but the overall ecosystem (standards, communications, program design, and value proposition) remains early-stage and fragmented.

From the modeling, the dominant driver of DR effectiveness is the operating conditions at the onset of the event. In many mild-to-moderate outdoor temperature bins, VSHPs/CCHPs naturally operate at part-loads below the general curtailment threshold (70% of rated load power, RLP), so a general curtailment event provides little to no incremental kW reduction. Meaningful demand reductions generally require either (a) colder/hotter conditions that push the system closer to full output, or (b) a more aggressive curtailment level (critical curtailment at 40% RLP).

The modeling also highlights the central trade-off utilities must manage i.e., deeper and longer curtailments increase the likelihood of reaching the maximum indoor temperature offset (MITO), causing comfort impacts and/or DR event exits, and can increase post-event ‘snapback’ demand. These effects point to the need for DR program parameters that are adaptive—by climate, season, building vintage, and forecasted conditions—rather than one-size-fits-all event settings.

Finally, the market assessment suggests that widespread adoption will depend on an end-to-end solution that aligns OEM controls, aggregators/DERMS capabilities, and utility program requirements while keeping the end-user experience and incentives front-and-center. Near-term progress will therefore require coordinated standard development (including broader stakeholder representation), targeted validation (lab/field), and value assessment to clarify benefits for utilities, customers, and manufacturers.

Key Outcomes and Lessons Learned

Overall, the modeling indicates that VSHP-based DR potential is strongly dependent on outdoor temperature, equipment sizing, and event parameters (curtailment level, MITO, and duration). As a result, AHRI 1380-style events can range from providing substantial kW reductions in select conditions to providing little or no reduction when systems are already operating below the requested power limit.

Heating – moderate outdoor temperatures (30°F (-1.1°C) and above)

- In all modeled climate zones, VSHPs/CCHPs frequently operated below 70% of RLP at these conditions, resulting in little to no incremental kW reduction during General Curtailment. (e.g., Seattle heating at 35–40°F (1.7 to 4.4°C): baseline peak ~1.24–1.42 kW (older home) and ~0.64–1.10 kW (new home), with no measurable kW reduction under curtailment).
- Critical Curtailment may be required to realize meaningful demand reductions during above-freezing events.

Heating – colder outdoor temperatures (25°F (-3.9°C) and below)

- Climate Zone 4C (Seattle/Portland): General Curtailment on colder (20–25°F (-6.7 to -3.9°C)) days produced significant kW reductions relative to baseline. (e.g., Seattle 20–25°F (-6.7 to -3.9°C) heating: baseline peak ~4.55–4.79 kW (older home) reduced to ~2.58–2.80 kW under General Curtailment, a ~1.97–2.16 kW reduction).
- However, larger MITO values and longer events increased comfort impacts and post-event snapback demand; shorter events (1–2 hours) with smaller MITO (2°F (1.1°C)) best balanced DR and comfort in these conditions. In those same Seattle 20–25°F cases, indoor temperature dropped ~3.0–4.6°F (1.7°C–2.6°C) and snapback ranged ~1.7–3.4 kW, increasing with longer events and larger MITO.
- Climate Zones 5B and 6B (Bend/Colville): General Curtailment showed potential for kW savings in colder bins, but at around 10°F (-12.2°C) the CCHP often operated near ~70% RLP, limiting the available reduction. (e.g., Bend 10–15°F (-12.2°C–(-)9.4°C) heating: baseline peak ~2.46–2.48 kW reduced to ~2.31 kW under General Curtailment, only ~0.15–0.17 kW reduction).
- Because state-of-the-art CCHPs maintain capacity at very low ambient temperatures (e.g., ~5°F (-15°C)) and are commonly sized to meet heating loads at design conditions, the modeling suggests a 'sweet spot' for General Curtailment may occur between ~0°F (-17.8°C) and 10°F (-12.2°C) in colder climates.

Cooling – moderate hot days in the Pacific Northwest (90–100°F (32.2°C–37.8°C))

- In older homes, General Curtailment often had little or no impact on kW because systems sized for heating tended to operate at part-load during these cooling conditions. (e.g., Seattle 90–95°F (32.2 to 35°C) cooling in an older home: baseline peak ~2.34 kW with no measurable reduction under curtailment).
- In new homes, some kW reduction potential emerged because modeled heating and cooling loads were more comparable; systems operated closer to 60–80% of RLP, making curtailment more consequential. (e.g., Seattle 90–95°F (32.2 to 35°C) cooling in a new home: baseline peak ~2.13 kW reduced to ~1.68 kW under General Curtailment, ~0.45 kW reduction, with ~1.62°F (0.9°C) indoor temperature increase).
- For new homes, Critical Curtailment was consistently more impactful than General Curtailment; longer events (3–4 hours) and larger MITO (4°F (2.2°C)) were generally feasible with limited comfort impacts in the modeled cooling bins.
- Across vintages, hotter conditions (>100°F (37.8°C)) are more likely to produce measurable demand reductions, but these extremes are not well represented in a typical (TMY3) weather year. For context, modeled general/critical curtailment limits in Seattle were approximately 1.43/0.82 kW (new home) and 2.26/1.29 kW (older home), illustrating why many mild-hour operating points fall below the 70% RLP threshold.

Comfort and snapback behavior

- Increasing MITO and/or extending DR event duration increases the magnitude of indoor temperature drift and can elevate post-event snapback demand. Shorter events and smaller offsets reduce these risks but also cap achievable DR.

Implementation considerations

- The modeling intentionally disabled auxiliary heating during DR events to isolate VSHP/CCHP curtailment behavior; real-world installations with auxiliary/backup heat and diverse thermostat schedules may respond differently and should be validated.

Additional Testing and Research Needs

The Phase 1 results highlight several near-term and longer-term research needs to translate modeled potential into reliable, scalable demand response programs.

A. Validation – laboratory and field testing

- Conduct near-term laboratory testing to validate AHRI 1380 DR-capable performance maps and confirm curtailment response across representative operating points (including low-speed operation, defrost/oil management behaviors, and DR event exit behavior).
- Execute end-to-end DR tests from event initiation (utility/aggregator VTN) through OEM cloud/VEN to device, including acknowledgements, latency, reporting, and fail-safe behaviors.
- Plan longer-term, larger-scale field demonstrations to quantify kW reduction, persistence, customer comfort/satisfaction, opt-out rates, and adoption barriers under real program conditions.

B. Expanded modeling and sensitivity analyses

- Extend simulations to extreme heating (<10°F (-12.2°C)) and cooling (>100°F (37.8°C)) conditions and to bins closer to design temperatures (99–99.6%) that are not well represented in TMY3 weather files.
- Evaluate sensitivity to heat pump sizing practices (oversizing factors, balance points, and cooling-driven sizing in milder climates) and quantify how mis-sizing affects available shed and comfort outcomes.
- Assess the effect of alternate thermostat setpoints, event timing, and strategies such as pre-heating/pre-cooling on net load shape (including the risk of secondary peaks and snapback).
- Model non-cold-climate VSHPs operating in cold climates (5B/6B) to understand DR potential and comfort implications when capacity is limited at low ambient conditions.

C. Program, economic, and customer research

- Perform an economic and financial value assessment for utilities, customers, aggregators, and manufacturers (including scenarios with dual-fuel backup) to clarify program ROI and customer incentives needed for participation.
- Characterize customer experience thresholds (temperature drift, duration, event frequency) that drive opt-outs and translate these findings into practical MITO and duration guidance by climate and season.

D. Standards, interoperability, and reporting

- Continue engagement in AHRI 1380 development, emphasizing broader stakeholder input (utilities, grid operators, aggregators/DR providers) and clearer definitions for MITO handling, event exit behavior, and reporting requirements.
- Assess pathways toward more harmonious DR standards and clearer guidance on communication protocol adoption to reduce fragmentation and accelerate manufacturer and aggregator investment.

GLOSSARY

The following list of acronyms, abbreviations, and terms are applicable for this report:

Acronym or Term	Definition
A/C	Air Conditioner
ACEEE	American Council for and Energy Efficient Economy
ACCA	Air Conditioning Contractors of America
Aggregator	Market participant that optimizes the use of DER. They act as intermediaries between electricity producers, consumers, and energy markets, helping to balance supply and demand and enhance grid resilience and flexibility
AHRI	Air Conditioning, Heating, and Refrigeration Institute
ANSI	American National Standards Institute
API	Application Programming Interface
ASHP	Air Source Heat Pump
ASHRAE	American Society of Heating Refrigeration & Air Conditioning Engineers
BTU/h	British Thermal Units per Hour
COP	Coefficient of Performance
CCHP	Cold Climate Heat Pump
CEE	Consortium for Energy Efficiency
CTA	Consumer Technology Association
°C	Degrees Celsius
°F	Degrees Fahrenheit
DR	Demand Response
DRP	Demand Response Provider
DOE	Department of Energy
DERMS	Distributed Energy Resource Management System
DER	Distributed Energy Resources
EPRI	Electric Power Research Institute
GW	Gigawatt
HP	Heat Pump
HVAC	Heating, Ventilation and Air Conditioning
HCA	Home Connectivity Alliance
HEMS	Home Energy Management System
ISO	Independent System Operator
IAT	Indoor Air Temperature
IEEE	Institute of Electrical and Electronics Engineers
IECC	International Energy Conservation Code
kBTU	Thousand British Thermal Units
kW	Kilowatt
MITO	Maximum Indoor Temperature Offset
MW	Megawatt

Acronym or Term	Definition
NLR	National Laboratory of the Rockies
NREL	National Renewable Energy Laboratory
OAT	Outdoor Air Temperature
ORNL	Oak Ridge National Laboratory
OpenADR	Open Automated Demand Response
PNNL	Pacific Northwest National Laboratory
PV	Photovoltaic
RLP	Rated Load Power
RTO	Regional Transmission Organization
SOAP Web Protocol	Simple Object Access Protocol
Turndown Ratio	Ratio of inverter compressor capacity at maximum and minimum
VSHP	Variable Speed Heat Pump
VEN	Virtual End Node
VTN	Virtual Top Node
RESTful Web Protocol	Representational State Transfer

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APPENDICES

APPENDIX A: AHRI STANDARD 210/240-2024

Table 7. Required Tests ¹								
Test Name	Single Stage System	Single Stage Outdoor Unit with VAV/MIB	Variable Capacity Certified, Single-capacity System	Two-stage System ⁸	Two-stage Northern Heat Pump	Variable Capacity Certified, Two-capacity System	Variable Capacity System	Triple-capacity Northern Heat Pumps
Cooling Mode²								
A _{Full}	R	R	R	R	R	R	R	R
A _{Low}	—	R	—	—	—	—	—	—
B _{Full}	R	R	R	R	R	R	R	R
B _{Low}	—	R	—	R	—	R	R	R
C _{Full}	O ³	—	O ³	O ³	O ³	O ³	—	O ³
C _{Low}	—	O	—	O ³	—	O ³	—	O ³
D _{Full}	O ³	—	O ³	O ³	O ³	O ³	—	O ³
D _{Low}	—	O	—	O ³	—	O ³	—	O ³
E _{Int}	—	—	—	—	—	—	R	—
F _{Low}	—	—	—	R	—	R	R	R
G _{Low}	—	—	—	—	—	—	O ³	—
I _{Low}	—	—	—	—	—	—	O ³	—
Heating Mode⁴								
H0 _{Low}	—	—	—	R	R	R	R	R
H1 _{Full}	R	R	O	R	R	O	O	R
H1 _{Low}	—	R	—	R	R	R	R	R
H1C _{Full}	O ⁵	—	O ⁵	O ⁵	O ⁵	—	—	O ⁵
H1C _{Low}	—	O ⁵	—	O ⁵	O ⁵	O ⁵	O ⁵	O ⁵
H1 _{Nom}	—	—	R	—	—	R	R	—
H2 _{Boost}	—	—	—	—	—	—	—	O
H2 _{Full}	R	R	R	R	R	O	O	R
H2 _{Low}	—	O ⁶	—	O ⁶	O ⁶	O ⁶	—	O ⁶
H2 _{Int}	—	—	—	—	—	—	R	—
H3 _{Full}	R	R	R	R	R	R	R	R
H3 _{Low}	—	R	—	R ⁷	R ⁷	R	—	R ⁷
H3 _{Boost}	—	—	—	—	—	—	—	R
H3C _{Boost}	—	—	—	—	—	—	—	O
H4 _{Full}	O ⁹	O ⁹	O ⁹	O ⁹	O ⁹	O ⁹	O ⁹	—
H4 _{Boost}	—	—	—	—	—	—	—	R
Notes:								
1. “R” means Required, “O” means Optional, and a blank cell indicates test is not applicable for the given product type.								
2. Required for any unit that has a cooling mode function.								
3. Refer to Section 6.1.3.1. Required for systems having a <i>mandatory constant circulation system</i>								
4. Required for any unit that has a heating mode function.								
5. Refer to Section 6.1.3.2. Required for systems having a <i>mandatory constant circulation system</i>								
6. Refer to Section 6.1.3.4.								
7. Not required if the <i>heat pump</i> locks out low capacity at outdoor temperatures less than 37.0°F.								
8. <i>Two-stage system</i> tests apply for <i>MIB</i> .								
9. Required for all systems certified as <i>cold climate heat pump</i> .								

Table 8. Test Conditions ^{1, 13, 14}				
Test Name	Air Entering Outdoor Unit ² (°F)	Air Entering Indoor Unit ² (°F)	Compressor Capacity ³	Indoor Airflow ⁴
Cooling Mode				
A _{Full}	95.0 / 75.0 ^{5,6}	80.0 / 67.0	Full _C ¹²	Full _C ¹²
A _{Low}	95.0 / 75.0 ^{5,6}	80.0 / 67.0	Full _C ^{12,16}	Low _C
B _{Full}	82.0 / 65.0 ^{5,6}	80.0 / 67.0	Full _C	Full _C
B _{Low}	82.0 / 65.0 ^{5,6}	80.0 / 67.0	Low _C ¹⁶	Low _C
C _{Full}	82.0 / 58.0 ^{5,6}	80.0 / 57.0 ⁷	Full _C	Full _C
C _{Low}	82.0 / 58.0 ^{5,6}	80.0 / 57.0 ⁷	Low _C ¹⁶	Low _C
D _{Full}	82.0 / 58.0 ^{5,6}	80.0 / 57.0 ⁷	Full _C	Full _C ⁸
D _{Low}	82.0 / 58.0 ^{5,6}	80.0 / 57.0 ⁷	Low _C ¹⁶	Low _C ⁸
E _{Int}	87.0 / 69.0 ^{5,6}	80.0 / 67.0	Int _C	Int _C
F _{Low}	67.0 / 53.5 ^{5,6}	80.0 / 67.0	Low _C ¹⁶	Low _C
G _{Low}	67.0 / 58.0 ^{5,6}	80.0 / 57.0 ⁷	Low _C ¹⁶	Low _C
I _{Low}	67.0 / 58.0 ^{5,6}	80.0 / 57.0 ⁷	Low _C ¹⁶	Low _C ⁸
Heating Mode				
H0 _{Low}	62.0 / 56.5	70.0 / 60.0 ⁹	Low _H ^{16,21}	Low _H
H0C _{Low}	62.0 / 56.5	70.0 / 60.0 ⁹	Low _H ^{16,21}	Low _H
H1 _{Full}	47.0 / 43.0	70.0 / 60.0 ⁹	Full _H ¹⁹	Full _H
H1 _{Low}	47.0 / 43.0	70.0 / 60.0 ⁹	Low _H ^{16,21}	Low _H
H1C _{Full}	47.0 / 43.0	70.0 / 60.0 ⁹	Full _H	Full _H ⁸
H1C _{Low}	47.0 / 43.0	70.0 / 60.0 ⁹	Low _H ^{16,21}	Low _H ⁸
H1 _{Nom}	47.0 / 43.0	70.0 / 60.0 ⁹	Nom _H ¹⁵	Nom _H ¹⁰
H2 _{Boost}	35.0 / 33.0	70.0 / 60.0 ⁹	Boost _H	Full _H
H2 _{Full}	35.0 / 33.0	70.0 / 60.0 ⁹	Full _H ¹⁹	Full _H
H2 _{Low}	35.0 / 33.0	70.0 / 60.0 ⁹	Low _H ^{16,21}	Low _H
H2 _{Int}	35.0 / 33.0	70.0 / 60.0 ⁹	Int _H	Int _H
H3 _{Full}	17.0 / 15.0	70.0 / 60.0 ⁹	Full _H ¹⁹	Full _H
H3 _{Low}	17.0 / 15.0	70.0 / 60.0 ⁹	Low _H ^{16,21}	Low _H
H3 _{Boost}	17.0 / 15.0	70.0 / 60.0 ⁹	Boost _H	Full _H
H3C _{Boost}	17.0 / 15.0	70.0 / 60.0 ⁹	Boost _H	Full _H
H4 _{Full}	5.0 / 4.0 ¹¹	70.0 / 60.0 ⁹	Full _H ¹⁸	Full _H
H4 _{Boost}	5.0 / 4.0 ¹¹	70.0 / 60.0 ⁹	Boost _H	Full _H
Notes:				
1. Test condition tolerances are defined within ASHRAE Standard 37, ASHRAE Standard 116 Table 3b for cyclic tests, and Section 8.7 of this standard.				
2. Values listed are dry-bulb temperature / wet-bulb temperature, °F.				
3. Refer to Section 3 for definition of “Full”, “Low”, “Int” and “Boost” for each compressor type.				
4. Refer Section 6.1.5 for airflow details.				
5. Wet-bulb temperature specification required only if unit rejects condensate to outdoor coil.				
6. For single package units that do not reject condensate to the outdoor coil, where all or part of the equipment is located in the outdoor room, adjust the outdoor wet-bulb temperature such that the dew point is 60.5 ± 3.0°F.				
7. The entering air must have a low enough moisture content so no condensate forms on the indoor coil (It is recommended that an indoor wet-bulb temperature of 57.0°F or less be used.)				
8. For cyclic tests, use the same airflow as steady state test which is defined as the same static pressure difference or velocity pressures across the nozzle(s) during the ON period.				
9. Maximum value for all tests. If outdoor air enthalpy method is used for single package heat pumps, then the indoor wet-bulb temperature shall be adjusted to match as close as reasonably possible to the dew point of the outdoor entering air.				
10. Refer to Section 6.1.5.8.				
11. 4.0 Maximum.				
12. For two-stage northern heat pump, Full _C means operating compressor and airflow at low stage.				
13. For three-stage northern heat pump, Full _C means operating compressor and airflow at middle stage, Low _C means compressor and airflow at low stage. Note: Tests D _{Full} , D _{Low} , I _{Low} , H1C _{Full} , and H1C _{Low} are cyclic in nature. Some heating tests, particularly H2 _{Full} and H2 _{Low} will be transient in nature. All other tests are steady state tests.				

14. For *single package units* that do not reject condensate to the *outdoor coil*, where all or part of the equipment is located in the outdoor room, outdoor wet-bulb temperature must be less than 58°F.
15. Maximum speed that the *system controls* would operate the compressor in normal operation in 47°F ambient temperature.
16. For all *low stage* tests of *MIB* with *single stage systems*, compressor capacity is *full stage*.
18. Maximum speed that the *system controls* would operate the compressor in normal operation in 5°F ambient temperature.
19. The compressor shall operate for the $H1_{Full}$ and $H3_{Full}$ tests at the same heating full speed, measured by RPM or power input frequency (Hz), as the maximum speed at which the *system controls* would operate the compressor in normal operation in 17 °F ambient temperature. The $H1_{Full}$ test is not needed if the $H1_{Nom}$ test uses this same compressor speed.
20. The compressor shall operate for the $H1_{Nom}$ test at the maximum speed at which the *system controls* would operate the compressor in normal operation in 47 °F ambient temperature. Additionally, for a cooling/heating *heat pump*, the compressor shall operate for the $H1_{Nom}$ test at a speed, measured by RPM or power input frequency (Hz), no lower than the speed used in the A_{Full} test if the tested $H1_{Nom}$ heating capacity is less than the tested A_{Full} cooling capacity.
21. The compressor shall operate at the same heating minimum speed, measured by RPM or power input frequency (Hz), for the $H0_{Low}$, $H1C_{Low}$, and $H1_{Low}$ tests.

APPENDIX B: BUILDING MODEL ASSUMPTIONS

The building models used to perform the parametric energy modeling for the VSHPs for this analysis were developed using a EnergyPlus v25.1 and the DOE Building Prototypes. The primary building characteristics are summarized in Table 10 and Table 11.

- Climate Zone 4C: A home with 2,377 sq.ft. conditioned area, paired with VSHPs.
- Climate Zone 5B and 6B: A home with 2,377 sq.ft. conditioned area, paired with CCHPs.

Table 10 and Table 11 summarizes some representative building envelope assumptions. Where not prescribed in IECC codes, default assumptions of the Building America House Simulation Protocols were used⁴.

Table 10: Building Modeling Assumptions used for IECC 2021 single family home model

Category Name	Climate Zone 4C	Climate Zone 5B	Climate Zone 4C
Walls			
Wood Stud	R-20 Fiberglass Batt, 2x4, 16" o.c.		
Wall Sheathing	R-5 XPS		
Exterior Finish	Vinyl, Light		
Interzonal Walls	R-13, 2x4, 16" o.c.		R-15, 2x4, 16" o.c.
Ceilings/Roofs			
Unfinished Attic	Ceiling R-60 Cellulose, Vented		
Roof Material	Asphalt Shingles, Medium		
Radiant Barrier	None		
Foundation/Floors			
Foundation	Vented Crawlspace		
Carpet	40% Carpet		
Thermal Mass			
Floor	Wood Surface		
Exterior Wall	1/2 in. Drywall		
Partition Wall	1/2 in. Drywall		
Ceiling	1/2 in. Drywall		
Windows & Doors			
Window Areas	F15 B15 L15 R15		

⁴ Wilson, E., Horowitz, S., Building America Housing Simulation Protocols, NREL/TP-5500-60988

(Fraction of Exterior Facade)	
Windows	SHGC 0.30
Interior Shading Fraction	Summer = 0.7, Winter = 0.7
Door Area	20 ft ²
Doors	Steel
Eaves	2 ft
Overhangs	None
Airflow	
Air Leakage	3 ACH50
Mechanical Ventilation	Whole-house mechanical ventilation fans
Natural Ventilation	Year-Round, 3 days/wk
Space Conditioning	
Heating Set Point	72°F (22.2°C) (no setback schedule)
Cooling Set Point	75°F (23.9°C) (no setback schedule)

Table 11 Building Modeling Assumptions used for 2000 vintage single family home model

Category Name	Climate Zone 4C	Climate Zone 5B	Climate Zone 6B
Walls			
Wood Stud	R-13 Fiberglass Batt, 2x4, 16" o.c.	R-18 Fiberglass Batt, 2x4, 16" o.c.	R-21 Fiberglass Batt, 2x6, 24" o.c.
Wall Sheathing	OSB		
Exterior Finish	Vinyl, Light		
Interzonal Walls	Uninsulated, 2x4, 16 in o.c.		
Ceilings/Roofs			
Unfinished Attic	Ceiling R-38 Cellulose, Vented	Ceiling R-38 Cellulose, Vented	Ceiling R-49 Cellulose, Vented
Roof Material	Asphalt Shingles, Medium		
Radiant Barrier	None		

Foundation/Floors			
Foundation	Vented Crawlspace		
Carpet	40% Carpet		
Thermal Mass			
Floor	Wood Surface		
Exterior Wall	1/2 in. Drywall		
Partition Wall	1/2 in. Drywall		
Ceiling	1/2 in. Drywall		
Windows & Doors			
Window Areas (Fraction of Exterior Facade)	F15 B15 L15 R15		
Windows	SHGC 0.45	SHGC 0.35	SHGC 0.35
Interior Shading Fraction	Summer = 0.7, Winter = 0.7		
Door Area	20 ft ²		
Doors	Steel		
Eaves	2 ft		
Overhangs	None		
Airflow			
Air Leakage	8 ACH50		
Mechanical Ventilation	None		
Natural Ventilation	Year-Round, 3 days/wk		
Space Conditioning			
Heating Set Point	72°F (22.2°C) (no setback schedule)		
Cooling Set Point	75°F (23.9°C) (no setback schedule)		

APPENDIX C: MODELED SCENARIOS

Climate Zone 5B

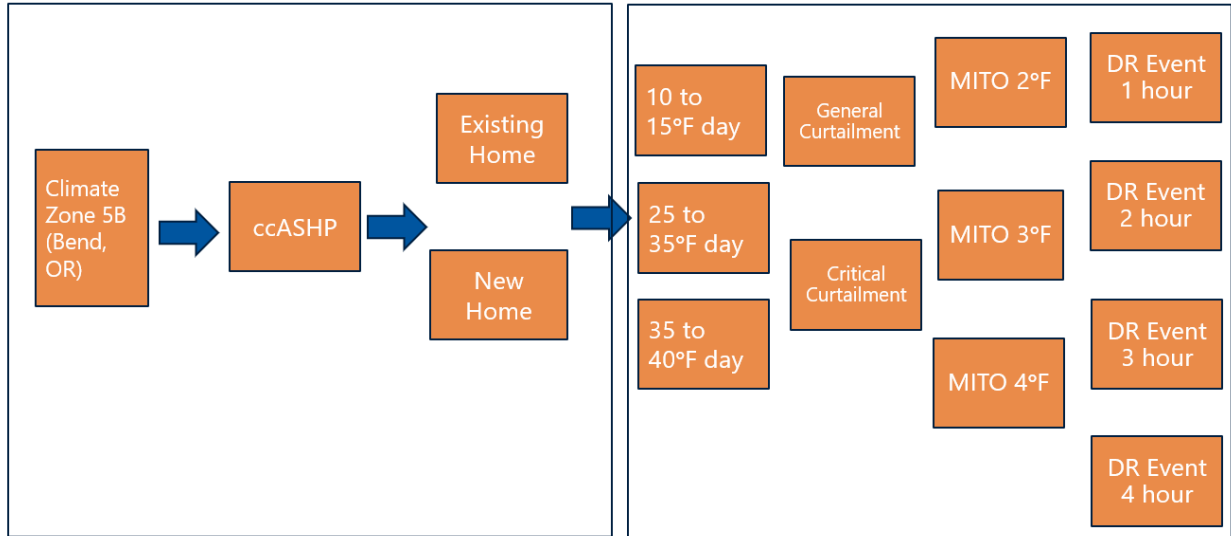


Figure 44 Modeling Runs for Heating in Climate Zone 5B

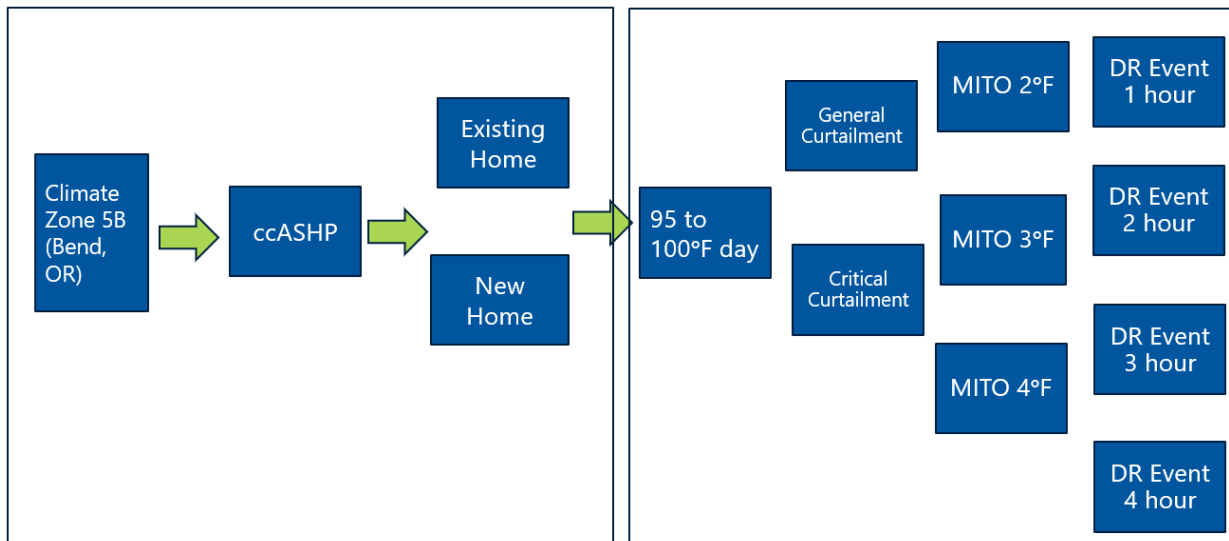


Figure 45 Modeling Runs for Cooling in Climate Zone 5B

Climate Zone 6B

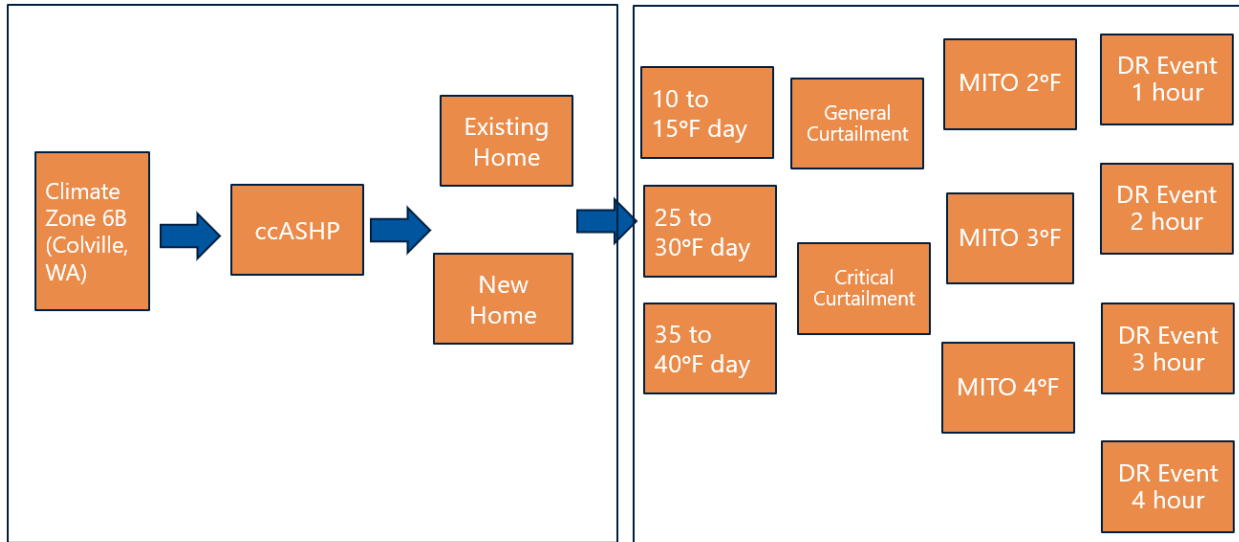


Figure 46 Modeling Runs for Heating in Climate Zone 6B

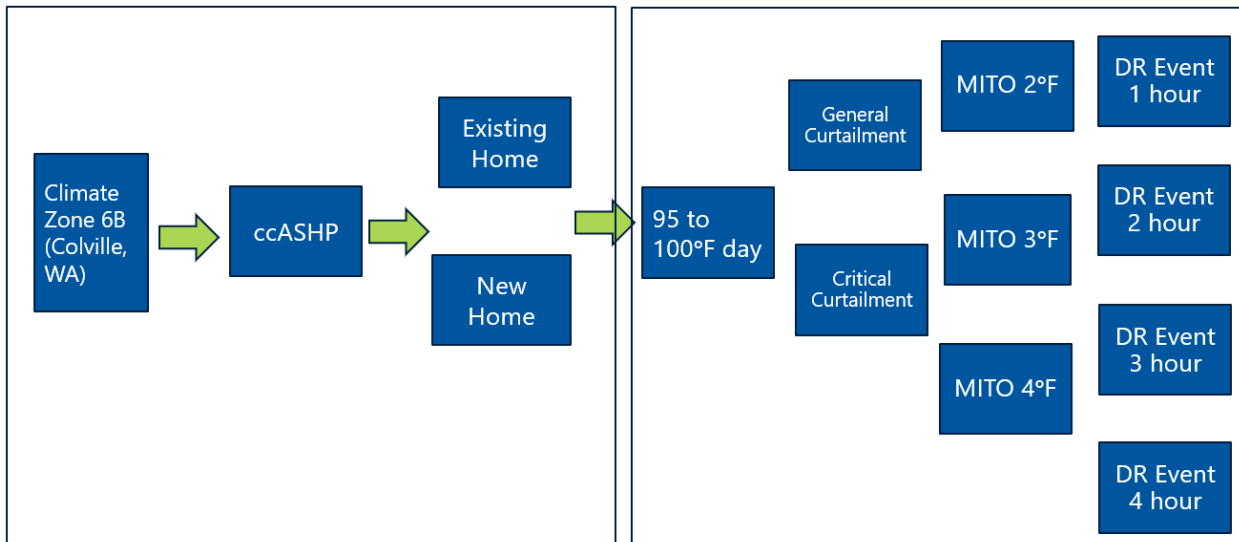


Figure 47 Modeling Runs for Cooling in Climate Zone 6B



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