Investigating the Benefits of Demand Response Using Variable Speed Heat Pumps

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ABSTRACT

With increased adoption of inverter-based variable speed and cold climate heat pumps (CCHPs) in residential buildings, collectively called variable speed heat pumps (VSHP); policymakers, utilities, and electric grid operators are looking for ways to leverage their ability to modulate the compressor and fan speeds as a means to achieve demand reduction. VSHPs can modulate their heating or cooling capacity in conjunction with the power draw based on ambient conditions to match fluctuating heating and cooling loads in a home. This can potentially be used to ease strains on the electric grid during times of increased demand, such as in peak summer or winter. Currently, the standardized requirements for Demand Response (DR) ready Heating, Ventilation, and Air-Conditioning (HVAC) systems are established by the AHRI 1380 standard. However, VSHPs that offer DR capabilities compliant with this standard are still in early stages of commercialization and there is limited understanding of their operation. Furthermore, the impact on homeowner comfort in relation to the curtailed equipment operation during and after these DR events is an aspect that is not well quantified. In this paper, the authors discuss their recently performed modeling study that compared the potential peak demand reduction that can be achieved by VSHPs over a range of residential building types. The study covered climate zones spanning 4C, 5B, and 6B and the model simulated VSHPs responding to realistic DR event patterns. The paper also addresses a technical and market assessment of VSHPs and provides opportunities and recommendations for improvements in VSHP based DR implementation.

Introduction

Home electrification is increasing the importance of flexible residential loads for grid management. Residential heating and cooling loads are especially relevant because they are weather-sensitive and can coincide with summer and winter peaks. In a conventional DR 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 setpoint until the DR event concludes. Inverter-based VSHPs are a promising DR resource because they can modulate compressor and fan speed rather than simply cycling off. This enables a different DR strategy than conventional thermostat setback: where the system can continue to provide partial heating or cooling while limiting power draw. If VSHP 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 DR 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 effort provides new insights and data on the operation of VSHPs in typical space-conditioning applications where the equipment can serve as a flexible load. The authors connect the emerging AHRI 1380-capable VSHP market with a parametric modeling assessment of practical DR performance. This paper quantifies when VSHP DR provides useful kW shed, when it provides little incremental reduction, and how comfort impacts, indoor temperature offset enforcement, and recovery demand should inform utility program design.

Technology and Market Assessment

Background

Grid operators balance electric supply and demand through generation dispatch, market purchases, storage, and load curtailment. Distributed energy resources (DERs) including batteries, smart thermostats, electric vehicles, water heaters, and HVAC equipment can provide flexible load when they receive and respond to grid or price signals. Figure 1 summarizes the communication sequence for a DR event: a DR provider issues an event, the device receives the signal, equipment controls modify operation, and response status is reported back. A successful event curtails sufficient power to maintain balance on the grid until high demand subsides back to normal operations.

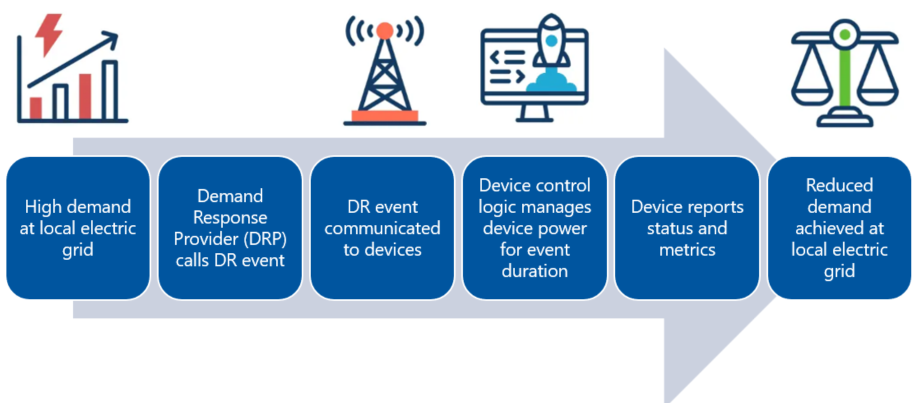

Figure 1 Demand response communication sequence

Communication protocols through the sequence described are a focus area for improved grid management. Interoperability remains a central implementation barrier. OpenADR 2.0b (OpenADR Alliance 2013) or OpenADR 3.0 (OpenADR Alliance 2023) is commonly used for HVAC DR, CTA-2045-B (ANSI/CTA 2021) is common for water heaters, IEEE 2030.5 (IEEE 2023) is used for several DER applications, and many devices still rely on proprietary manufacturer cloud pathways. The resulting fragmentation can complicate aggregation, verification, and brand-agnostic utility program deployment.

VSHP Capability Assessment

Eight manufacturers with commercially available systems in the North American market participated in the Department of Energy (DOE) CCHP challenge (US DOE 2021). One criteria for meeting the requirements was demonstrating compliance with DR protocols detailed in AHRI standard 1380-2019 (AHRI 2019). The standard is applicable to space conditioning equipment with multi-stage discrete or continuously variable capacity capabilities. Either through communication protocols CTA-2045-A or OpenADR2.0B, DR event requests and event durations were sent to the equipment. All participating manufacturers demonstrated AHRI 1380 capability. As of 2025, several compliant products are commercially available or expected in 2026, supported by the inclusion of AHRI 1380 load-management capability in the 2026 Consortium for Energy Efficiency (CEE) (CEE 2025) air-source heat pump specification.

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 (IECC 2024). 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 are 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).

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 2 2026 CEE air-source heat pump specification includes AHRI 1380 load management

CEE offers equipment specifications for advanced efficiency. New, effective January 1, 2026, is the inclusion of AHRI 1380 compliant load management, with details in Figure 2. 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 65,000 BTU/h, 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 RLP. RLP is separately defined for cooling and heating events (AHRI 2024) at conditions

AFULL for cooling (outdoor 95°F (35°C) and indoor 80°F (26.7°C) dry bulb / 67°F (19.4°C) wet bulb) and H1Nom 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.

Heating RLP definition is especially important. The AHRI heating reference condition, H1Nom occurs at 47°F (8.3°C), which is much milder than many winter peak DR events. At colder temperatures, CCHPs may operate above that rated point to maintain capacity, so a 70% or 40% RLP cap can reduce available capacity sharply and cause MITO to be reached quickly. Conversely, if RLP were defined at a more extreme condition, many milder events could already be below the cap and provide no incremental shed. 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.

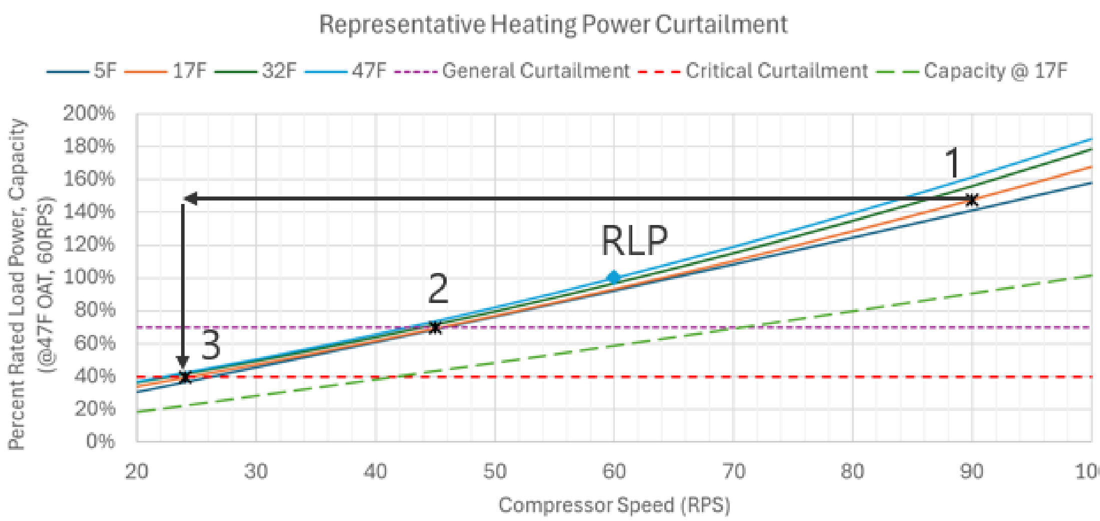

Figure 3 Heating curtailment effectiveness depends on how RLP is defined

Table 1 summarizes an illustrative example of power consumption and capacity relative to the H1Nom rating point, with reference points labeled in Figure 3. Determining a suitable rated load point is critical for the success of VSHP DR programs. Further specifications are also needed for event exit behavior: whether the system immediately returns to the original setpoint, maintains the MITO-adjusted setpoint, ramps up compressor for recovery, or staggers recovery gradually. These choices will directly affect post-event snapback and should be considered by utilities and aggregators when estimating net system benefits.

Table 1 Representative Heating Power Curtailment

Operating Point	Description	Compressor Speed (RPS)	Power % to RLP	Capacity % to RLP
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%

VSHP DR Effectiveness

Figure 4 models the impact on indoor air temperature (IAT) through three simulated DR events for an 82°F (27.8°C) average outdoor air temperature summer day. 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 RLP. The IAT 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, reflected via the gradual drift in IAT relative to setpoint. In other DR methods, either occupant comfort suffers or snapback occurs during the middle or immediately after an event. 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 DR resources represent 6.5% (33.05 GW) of peak demand as of 2023 (FERC 2024) within RTOs/ISOs. The percentage attributed to VSHPs only is significantly lower.

This modeling study additionally explored curtailment during heating and intentionally prohibited auxiliary electric resistance heat during DR events to isolate the load-flexibility capability of the heat pump compressor and avoid inflating curtailment savings. This assumption increased comfort impacts in cold conditions when the heat pump operated below the building balance point, particularly after Maximum Indoor Temperature Offset (MITO) is reached. In practice, utility programs may restrict auxiliary heat during curtailment because resistance heat can erase DR benefits, but most programs could likely allow exceptions for safety, freeze protection, or severe comfort excursions. Therefore, the results should be interpreted as technical curtailment potential under a conservative auxiliary-heat constraint, with field validation needed to determine program-specific backup heat rules.

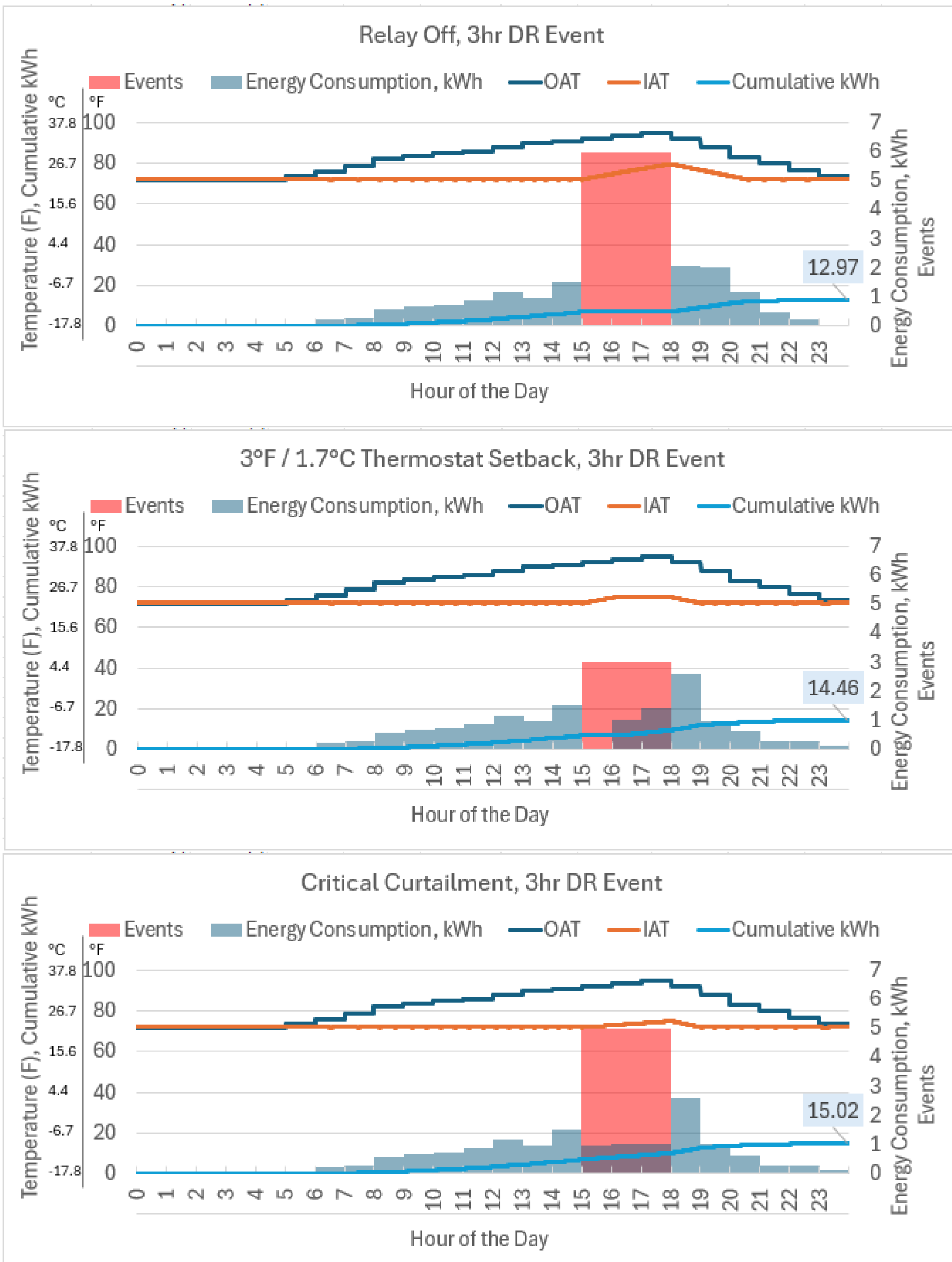

Figure 4 VSHP curtailment reduces demand while slowing indoor temperature drift

Modeling of VSHPs for Demand Flexibility

The authors 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. 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. 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. This was accomplished by developing hourly energy models to simulate the curtailed performance of VSHPs during selected DR event spans in different climates. The modeled hourly simulations were run for multiple building models and climate zones. Table 2 lists the residential building types, and Table 3 lists the cities and associated climate zones covered in this study.

Table 2 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

Table 3 Simulated Cities and Climate Zones

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

The simulations in this study were performed using EnergyPlus 25.1.0 (NLR 2025). 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. The building models used were based on existing, well-established reference buildings representing the existing population of code-compliant buildings (DOE 2024). 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 modified to represent a VSHP and a CCHP, as applicable based on the climate zone being simulated. They were sized based on the Design Day loads and tended to be sized based on the peak design heating loads. Annual simulations of the building energy consumption were performed for the Typical Meteorological Year (TMY3) weather data in each location.

Table 4 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 5 Design Heating Temperatures for the modeled homes

Design Heating Temperatures		
4C	5B	6B
39.6°F (4.2°C)	5.5°F (-14.7°C)	-6°F (-21.1°C)

Table 6 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

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 System (EMS) feature in EnergyPlus provides a way to develop custom control and modeling routines for EnergyPlus models. EMS provides supervisory control to override selected aspects of EnergyPlus modeling. Manufacturer-derived performance relationships linked compressor speed, heating/cooling capacity, and power draw to ambient conditions, enabling the models to estimate kW shed, indoor temperature drift, event persistence, and recovery demand. Validation and uncertainty were addressed by using established DOE prototype building inputs, manufacturer-based VSHP/CCHP performance data, and parametric sweeps of the main drivers of DR performance. Key uncertainties remain; proprietary OEM controls may behave differently than modeled EMS logic; defrost, oil-return, and low-speed operating constraints can vary by product; TMY3 weather may underrepresent peak extremes; and occupant opt-out behavior was not directly modeled. Accordingly, results are best interpreted as scenario-based estimates of technical potential, not guaranteed field performance.

Parametric Modeling Analysis

The parametric modeling analysis 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 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 MITO. 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.

Table 7 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

Across the modeled cases, General Curtailment provided measurable demand reduction only when baseline compressor power was above 70% of RLP for a meaningful portion of the event. Mild heating and cooling temperatures often showed little or no shed because the equipment was already below the cap. Colder heating bins can provide larger shed but increase the likelihood of reaching MITO and producing post-event snapback. This pattern supports adaptive utility event design by temperature bin, season, and equipment/building.

Table 8 Summary of representative modeled DR outcomes

Case	Baseline operating state	Curtailment result	Comfort / snapback implication	Program implication
4C heating, 35-40°F	Part-load; below 70% RLP	Little/no General Curtailment shed	Comfort maintained; no notable snapback	Avoid general events in mild bins or use Critical Curtailment if needed
4C heating, 20-25°F	Higher output; above cap	~1.97–2.16 kW shed	~3.0–4.6°F drift; ~1.7–3.4 kW snapback	Use shorter events and smaller MITO; manage recovery
5B heating, 10-15°F	Near 70% RLP	Modest shed (~0.15–0.17 kW)	Comfort impacts limited	Potential sweet spot may be colder than modeled temperatures
6B heating, 10–15°F	Near/below cap	Minimal General Curtailment savings	Limited drift; persistence constrained	Target very cold temperatures and adaptive duration/MITO
Cooling, 90–100°F	Often part-load due to heating sizing	Little/no General Curtailment shed in older homes	Limited comfort impacts	Cooling DR more likely during >100°F events or Critical Curtailment

Modeling Results Climate Zone 4C

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 19th 5am
	30 to 35°F (-1.1 to 1.7°C)	January 13th 6pm
	35 to 40°F (1.7 to 4.4°C)	December 8th 4pm
	90 to 95°F (32.2 to 35°C)	August 10th 5pm

Figure 5 shows a mild 4C heating case (35-40°F) in which baseline compressor power is already below the General Curtailment cap. General Curtailment therefore produces little or no incremental shed, while comfort and post-event recovery are largely unaffected. Critical Curtailment would be needed for measurable reduction in limited periods when the unit exceeds the 40% RLP threshold. 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.

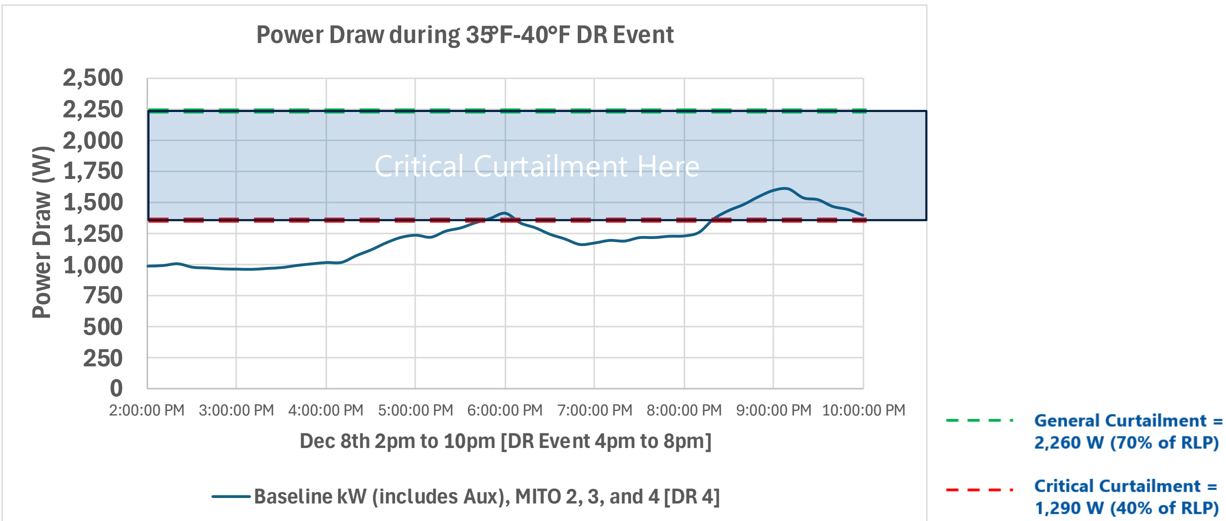

Figure 5 Mild 4C heating: General Curtailment provides little shed because baseline power is already below the cap

Figure 6 shows the representative cold 4C heating case (20-25°F). Baseline peak power of approximately 4.55-4.79 kW is reduced to approximately 2.58-2.80 kW under General Curtailment, or about 1.97-2.16 kW of peak reduction. The benefit is accompanied by faster approach to MITO: all plotted scenarios exit curtailment within roughly 1 hour, with smaller MITO values exiting sooner. Once the VSHP has exited curtailment, it was 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 was applied for every simulated scenario.

Figure 6 and Table 10 also highlight 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 lead to a notable post-event snapback (roughly ~1.7-3.4 kW, depending on event parameters).

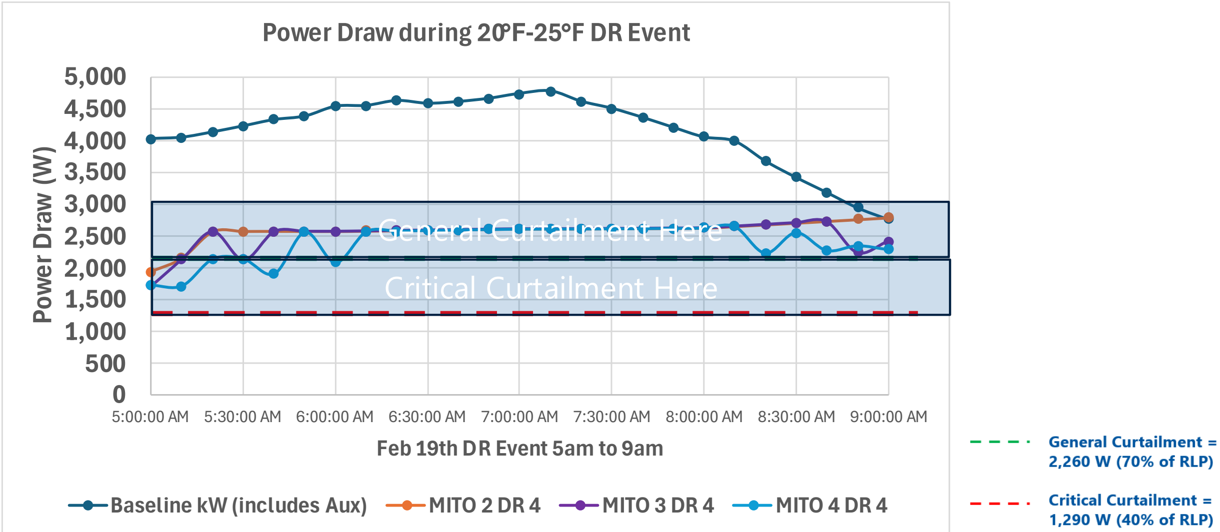

Figure 6 Cold 4C heating: General Curtailment provides meaningful shed but reaches MITO quickly

Table 10 Cold 4C heating: comfort drift increases with deeper or longer curtailment

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 7 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. It 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). The figure visualizes the central operational tradeoff for cold-bin heating DR: useful demand shed during the event versus comfort impacts and elevated recovery demand afterward.

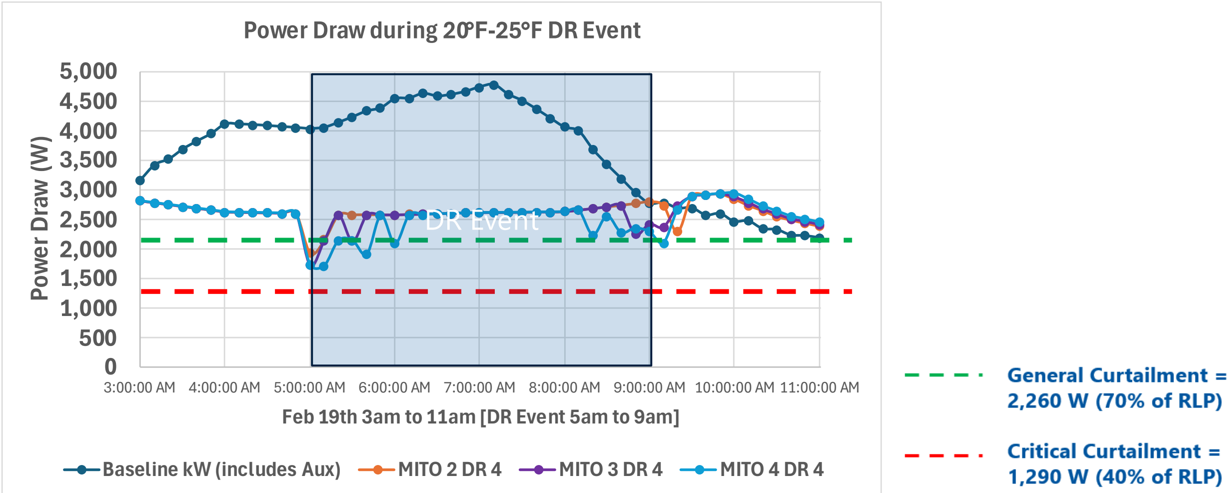

Figure 7 Cold 4C heating: post-event recovery demand creates snapback risk

Modeling in Climate Zone 4C showed 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 temperature 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.

Heating Results Climate Zone 5B

Table 11 shows a 5B heating case (10-15°F) where the CCHP operates near the General Curtailment boundary. Modeled peak power falls from approximately 2.46-2.48 kW to about 2.31 kW, or only 0.15-0.17 kW of reduction. Comfort impacts are limited, but the available DR magnitude is constrained by the baseline operating state.

Table 11 Cold 5B heating: CCHP operation near the 70% RLP boundary limits incremental shed

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	-	-

Heating Results Climate Zone 6B

Table 12 shows a 6B heating case (10-15°F) with minimal General Curtailment savings because baseline operation is not sufficiently above the cap for sustained shed. The result reinforces that, for modern CCHPs sized for heating design loads, the most promising General Curtailment conditions may occur in very cold temperatures where operating power is high enough for curtailment to matter without immediately compromising comfort.

Table 12 Cold 6B heating: part-load operation limits General Curtailment savings

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	2.97 (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)

Conclusions and Recommendations

Key Takeaways from the Market Assessment:

VSHP-based DR is technically promising but still early in commercialization. Manufacturers have demonstrated AHRI 1380 response capability, and CEE specification changes may increase product uptake. The most actionable market need is an end-to-end implementation pathway that aligns OEM controls, communication protocols, aggregators/DERMS, utility dispatch requirements, customer incentives, and measurement/reporting.

Key Outcomes and Lessons Learned from Modeling:

The modeling shows that VSHP-based DR potential depends primarily on outdoor temperature, equipment sizing, baseline power relative to RLP, MITO, and event duration. Static events will yield inconsistent results: some conditions provide meaningful kW shed, while many mild or moderate bins provide little or no incremental reduction because equipment is already operating below the requested cap.

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 1-2-hour events with smaller MITO values near 2°F (1.1°C) best balanced DR and comfort in these conditions. At portfolio scale, unmanaged snapback could reduce or reverse peak-reduction benefits if many homes recover simultaneously. Utilities and aggregators should therefore apply diversity assumptions and consider gradual recovery, staged setpoint return, randomized delays, or staggered event release.
- Climate Zones 5B and 6B (Bend/Colville): General Curtailment showed potential for kW savings at colder temperatures, 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).
- 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.

Recommendations for Future Work

Customer behavior is a key uncertainty. Participants may tolerate a single mild event but opt out more frequently during repeated events, longer events, larger offsets, or cold-weather events where comfort impacts are more noticeable. Field demonstrations should track opt-out timing, repeated-event fatigue, customer satisfaction, and differences in comfort preferences across households.

1. Standards and interoperability

- Support development of more harmonized DR standards to reduce fragmentation across residential HVAC, commercial HVAC, water heating, and other DER applications.
- Prioritize clarification in AHRI 1380 for: (a) the definition of 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/sampling rate).

2. Utility program design and customer experience

- Develop DR program rules that adapt by season, climate zone, equipment type, baseline operating condition, event duration, and MITO.
- Evaluate event exit strategies to mitigate secondary peaks and snapback demand, including ramped recovery, staggered event end times, staged setpoint return, and randomized recovery delays across aggregated populations.

3. 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 field demonstrations to quantify real-world kW reduction, persistence, customer comfort/satisfaction, repeated-event opt-out behavior, communication reliability, and adoption barriers across utilities and climates.

Acknowledgments

This paper is based on research work performed by GTI Energy for the Northwest Energy Efficiency Alliance under Contract 53228/GTI Energy project number 23811.

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