NATIONAL LABORATORY OF THE ROCKIES

ResStock Measure Documentation: HVAC Load Flexibility

Yingli Lou, Rajendra Adhikari, and Andrew Parker

National Laboratory of the Rockies

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List of Acronyms

AC	air conditioner
D3	demand decrease percentage
EIA	U.S. Energy Information Administration
HVAC	heating, ventilation, and air conditioning
RECS	Residential Energy Consumption Survey

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Executive Summary

The goal of this work is to develop energy efficiency, demand flexibility, and other retrofit end-use load shapes (electricity, gas, propane, or fuel oil) that cover a majority of the high-impact, market-ready (or nearly market-ready) measures. "Measures" refers to retrofits that can be applied to buildings during modeling.

An "end-use savings shape" is the difference in energy consumption between a baseline building and a building with an energy efficiency, demand flexibility, or other retrofit measure applied. It results in a time-series profile that is broken down by end use and fuel (electricity or on-site gas, propane, or fuel oil use) at each time step.

ResStock™ is a highly granular, physics-based, bottom-up model that uses multiple data sources, statistical sampling methods, and advanced building energy simulations to estimate the annual subhourly energy consumption of the residential building stock across the United States. The baseline model intends to represent the U.S. residential building stock as it existed in 2018. Technical documentation for the inputs and assumptions in the baseline building stock model is available in Reyna et al. (2025). Calibration and validation of the baseline model results are available in the final technical report of the End-Use Load Profiles project (Wilson et al. 2022).

This documentation focuses on a single end-use savings shape measure: Heating, Ventilation, and Air-Conditioning (HVAC) Load Flexibility.

The HVAC load flexibility measure modifies the heating and cooling thermostat set points before peak periods to preheat or precool the building or during peak periods to shift load away from peak periods. In real deployments of demand flexibility via smart thermostats, the dispatch is typically limited to a handful of days per year to avoid customer fatigue. But the goal of this modeling is to create a dataset that can be analyzed to determine the maximum technical potential load profile impact at any given point in the year, so the **demand flexibility is dispatched nearly every day in the modeled dataset**. Although the profile on any given day is realistic, **the full annual load profiles do not reflect the realistic dispatch of HVAC load flexibility**. Details on the appropriate use of the load profiles can be found in this document.

To keep the logic simple and to generate the most comprehensive result that can support different future analysis, this measure applies to *all* dwelling units with either a heating or a cooling system (approximately 99.7% of the dwelling units modeled in ResStock); however, the heating load analysis in this document is done on only buildings with electric heating. With a 4°F offset during the 4-hour peak periods across all 51 states, this resulted in an average reduction of 57% in peak period heating electricity consumption during the winter months and a 54% reduction in peak period cooling electricity during the summer months.

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ResStock 2025 Release 1 Measure Documentation: HVAC Load Flexibility

Accessing Results

This documentation covers the "HVAC Load Flexibility" measure upgrade methodology and briefly discusses key results. All results can be accessed on the ResStock™ Open Energy Data Initiative "End-Use Load Profiles for the U.S. Building Stock" data lake and on the Data Viewer at resstock.nlr.gov.

Measure Summary

Measure Title	HVAC Load Flexibility
Measure Definition	This upgrade lowers the heating set point and increases the cooling set point during predefined on-peak hours. It can also preheat or precool the dwelling units for 1 to 4 hours, depending on the measure settings.
Applicability	This measure applies to all dwellings with either a heating system or a cooling system that is approximately 99.7% of the building stock.
Not Applicable	This measure does not apply to the dwelling units that have neither a heating system nor a cooling system—approximately 0.3% of the building stock.
Project Configuration File(s)	https://github.com/NatLabRockies/resstock/blob/sdr_2025_Release_1/project_national/sdr_upgrades_amy2018.yml

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1 Technology Summary

Renewable energy is increasingly being adopted for electricity generation. The U.S. Energy Information Administration (EIA) projected that the share of U.S. power generation from renewables will increase from 21% in 2021 to 44% in 2050 (EIA, 2022). This projected increase consists mainly of new wind and solar power, but wind and solar power are inherently variable energy sources, which poses a challenge for grid stability and control compared to fossil fuel-based power generation. For instance, solar power generation fluctuates with the time of day and weather, whereas wind energy is influenced by seasonal and atmospheric conditions. These fluctuations require sophisticated grid management to ensure a stable electricity supply.

Flexible loads help balance supply and demand, especially as renewable energy increases. Many utility companies operate demand response programs. These programs range from interruptible service programs targeting large commercial and industrial customers, to rebates given to large customers for voluntary peak hour load reductions, to direct control of water heaters and air-conditioning compressors (Ryan Hledik A. R., 2022). Utilities such as Duke Energy (2024a), Xcel Energy (2024), and Pacific Gas and Electric Company (2024) enable demand response through time-based pricing where electricity rates vary by the time of day. By charging higher rates during peak hours and lower rates at other times, customers are encouraged to shift their usage to off-peak hours.

Residential buildings account for a substantial share of U.S. electricity demand, representing 38% of the total electricity consumption in 2023 (EIA, 2024), making this sector the largest of all sectors. Demand flexibility within the residential building stock is crucial to achieving demand-side load flexibility, which can help balance grid loads. Within the residential sector, most load flexibility potential is found within the heating and cooling end uses because of the inherent thermal energy storage capability of the building's heated or cooled mass.

This measure models the use of smart thermostats to achieve demand flexibility in residential buildings by controlling their heating and cooling systems. This document describes the technology in general, describes how it is modeled in ResStock™, and reviews results at a high level.

1.1 Introduction to Technology

According to Stewart (2023):

> A smart thermostat is an internet-connected device that controls home heating, ventilation, and air-conditioning (HVAC) equipment and can automatically adjust temperature set points to optimize performance and achieve energy savings. Smart thermostat features often include two-way communication, occupancy detection (such as geofencing and occupancy sensors), schedule learning, and seasonal optimization algorithms. Smart thermostats can control most conventional HVAC systems including central air conditioners, heat pumps, and forced air furnaces.

Within the context of demand flexibility programs, the internet-connected feature of a smart thermostat is used by the utility (with customer consent) to remotely adjust the thermostat set points during target times. For example, Xcel Energy deploys Ecobee smart thermostats in their

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demand response program. These thermostats adjust customer home cooling set points by 1°F–4°F for up to 4 hours when there is a risk of an electricity shortage, as determined by Xcel Energy.

1.2 Technical Measure Details

Demand flexibility is commonly categorized into four groups: load shaping, load shifting, load shedding, and load shimmying (Peter Alstone, 2017). In this analysis, we consider load shifting and load shedding. In the following discussion, the peak period, or "on-peak window," is the window of time when the peak is to be reduced. The pre-peak window is the window of time immediately preceding the peak period.

1.2.1 Load Shifting

As defined in (Peter Alstone, 2017), load shifting "represents DR [demand response] that encourages the movement of energy consumption from times of high demand to times when there is a surplus of renewable generation. Shift could smooth net load ramps associated with daily patterns of solar energy generation."

For this analysis, load shifting is accomplished by preheating (for heating days) or precooling (for cooling days) the building prior to the on-peak window (during the pre-peak window). The idea is that the preheating or precooling increases the load prior to the on-peak window, conditions the indoor air, and preconditions the thermal mass and air in the building. Then the building requires less heating or cooling energy to maintain the set point during the on-peak window, reducing the overall load profile during this window. The extent of the load reduction will depend on the building's characteristics, such as the thermal mass, the amount of insulation, the infiltration, the duration of the preconditioning, and the timing of the peak period.

1.2.2 Load Shedding

As defined in (Peter Alstone, 2017), load shedding "describes loads that can be curtailed to provide peak capacity and support the system in emergency or contingency events."

For this analysis, load shedding is accomplished by decreasing the heating set point and increasing the cooling set point of the building during the on-peak window. This allows the temperature to drift beyond the original set point during the on-peak window, trading decreased thermal comfort for reduced peak load. How quickly the temperature drifts to the modified set point will depend on the building's characteristics, such as the thermal mass, the amount of insulation, and the infiltration.

1.2.3 Set Point Change and Magnitude

Different durations of pre-peak load shifting and different set point offsets for load shifting or load shedding can be applied by HVAC load flexibility programs. For a mild impact on residents, a shorter on-peak duration (e.g., 2 hours) with a small set point offset during the on-peak hour (e.g., 2°F) can be used. In contrast, for the maximum load change, a longer pre-peak period (e.g., 4 hours) with larger set point adjustments, such as a low precooling set point (e.g., 60°F) and/or a high on-peak cooling set point (e.g., 80°F), may be applied.

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Table 1 outlines the pre-peak and on-peak durations as well as the set point offsets used in existing smart thermostat programs. Typically, on-peak periods last 1–4 hours, and the set point is adjusted by 1–4°F during peak periods to align with residents' comfort preferences. Load-shifting preheating or precooling strategies are not widely adopted in the current programs surveyed for this analysis. These findings broadly match the findings reported in a 2024 market overview of demand flexibility programs (Sean Murphy, 2024).

Table 1. Load Flexibility Scenario Settings in Existing Smart Thermostat Programs

Utility Company	Pre-Peak Duration	On-Peak Duration	Set Point Offset During Pre-Peak	Set Point Offset During On-Peak
Pacific Gas and Electric Company (2024)	-	1–4 hours	-	1–4°F
Xcel (2021)	-	1–6 hours	-	1–4°F
Con Edison (2024)	-	1–4 hours	-	1–4°F
Duke Energy (2024b)	-	1–4 hours	-	1–4°F
Austin Energy (2024)	1–30 minutes	2 hours	2°F	1–4°F
National Grid (2024)	-	1–4 hours	-	1–4°F

The appropriate pre-peak duration and set point offset depend on various factors, including a home's insulation quality, cooling system capacity, and weather conditions. Research suggests that pre-peak durations of 1–4 hours and set point offsets of 2 to 6°F for preheating or precooling are effective strategies (German & Hoeschele, 2014). Table 2 presents the range of common settings for load flexibility based on existing smart thermostat programs and literature.

Table 2. Load Flexibility Dispatch Duration and Set Point Offset Summary

Pre-Peak Duration	Set Point Offset During Pre-Peak	Set Point Offset During On-Peak
1–4 hours	2–6°F	1–4°F

1.2.4 On-Peak Hour Identification

When analyzing the impact of load flexibility, it is necessary to define the target time periods when demand flexibility will be dispatched to reduce load. These time periods are commonly referred to as on-peak hours. On-peak hours can be identified in different ways, depending on the goal. For instance:

- **Reducing system net load:** Grid-wide net load data can be analyzed to identify hours with the highest demand, and demand flexibility can be dispatched to help lower overall system peak power generation requirements.
- **Responding to time-of-use pricing:** Utility rates for individual customers can be analyzed to identify times with the highest electricity prices. This is only applicable for customers with time-of-use rates. Demand flexibility can be dispatched to reduce individual customer utility bills.
- **Minimizing grid operation costs:** Grid-wide operational cost data can be analyzed to identify hours with the highest operational costs, which could be dependent on system

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peak demand, renewable generation, and local or distribution-level peak power. Demand flexibility can be dispatched to help reduce overall system operation costs.

The primary use for the results from this analysis is to feed into a national-scale energy system analysis that extends to 2050. The hypothesis is that demand flexibility will play a more important role further in the future; therefore, for this measure, the goal is to quantify load flexibility's technical potential to reduce net system load in 2050. Cambium is a dataset of load profiles based on assumed changes to the power sector over time (Gagnon, et al., 2024). It provides future load projections and related metrics. The MidCase scenario within Cambium adopts central estimates for key inputs, including technology costs, fuel prices, and demand growth. One important note is that the Cambium data do not consider future changes in load profiles due to wide-scale electrification, such as the addition of electric vehicles or heat pumps. Future work intends to update these load profiles and reassess the peak period definitions.

This project uses 2050 net load data from Cambium's MidCase scenario (Gagnon, et al., 2024) to identify the peak hours for each state, categorized by summer months (June to September), winter months (January to March and December) and intermediate months (April to May and October to November). The definition of seasons as a uniform set of months across all states is imprecise, but given that the modeling is also based on forecasts of the power system in 2050, it was judged to be an acceptable simplification. The identified peak hour is applied consistently as the dispatch time for each day within the corresponding months for each state. On-peak period timing by state is shown in Table 3. The on-peak period is defined as the 4-hour window containing the peak load, not the exact hour of the peak load.

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Table 3.On-Peak Timing by State and Season

State	Summer		Winter		Intermediate	
	Peak Start	Peak End	Peak Start	Peak End	Peak Start	Peak End
AK	17:00	21:00	17:00	21:00	16:00	20:00
AL	18:00	22:00	18:00	22:00	18:00	22:00
AR	17:00	21:00	17:00	21:00	18:00	22:00
AZ	18:00	22:00	18:00	22:00	17:00	21:00
CA	18:00	22:00	17:00	21:00	17:00	21:00
CO	18:00	22:00	18:00	22:00	16:00	20:00
CT	17:00	21:00	17:00	21:00	17:00	21:00
DE	17:00	21:00	17:00	21:00	17:00	21:00
FL	18:00	22:00	18:00	22:00	18:00	22:00
GA	18:00	22:00	18:00	22:00	18:00	22:00
HI	18:00	22:00	18:00	22:00	18:00	22:00
IA	17:00	21:00	17:00	21:00	17:00	21:00
ID	19:00	23:00	17:00	21:00	18:00	22:00
IL	18:00	22:00	16:00	20:00	16:00	20:00
IN	18:00	22:00	17:00	21:00	17:00	21:00
KS	18:00	22:00	17:00	21:00	17:00	21:00
KY	19:00	23:00	17:00	21:00	17:00	21:00
LA	18:00	22:00	17:00	21:00	18:00	22:00
MA	17:00	21:00	17:00	21:00	17:00	21:00
MD	17:00	21:00	16:00	20:00	17:00	21:00
ME	17:00	21:00	17:00	21:00	16:00	20:00
MI	17:00	21:00	18:00	22:00	17:00	21:00
MN	17:00	21:00	17:00	21:00	16:00	20:00
MO	18:00	22:00	8:00	12:00	16:00	20:00
MS	18:00	22:00	17:00	21:00	18:00	22:00
MT	17:00	21:00	18:00	22:00	19:00	23:00
NC	18:00	22:00	17:00	21:00	17:00	21:00
ND	19:00	23:00	19:00	23:00	18:00	22:00
NE	15:00	19:00	17:00	21:00	16:00	20:00
NH	17:00	21:00	17:00	21:00	17:00	21:00
NJ	17:00	21:00	17:00	21:00	17:00	21:00
NM	18:00	22:00	17:00	21:00	17:00	21:00
NV	18:00	22:00	17:00	21:00	18:00	22:00

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State	Summer		Winter		Intermediate	
	Peak Start	Peak End	Peak Start	Peak End	Peak Start	Peak End
NY	18:00	22:00	17:00	21:00	17:00	21:00
OH	17:00	21:00	17:00	21:00	17:00	21:00
OK	15:00	19:00	4:00	8:00	3:00	7:00
OR	17:00	21:00	17:00	21:00	16:00	20:00
PA	17:00	21:00	17:00	21:00	17:00	21:00
RI	18:00	22:00	17:00	21:00	18:00	22:00
SC	19:00	23:00	18:00	22:00	17:00	21:00
SD	15:00	19:00	16:00	20:00	18:00	22:00
TN	17:00	21:00	17:00	21:00	17:00	21:00
TX	18:00	22:00	17:00	21:00	17:00	21:00
UT	18:00	22:00	17:00	21:00	17:00	21:00
VA	18:00	22:00	16:00	20:00	16:00	20:00
VT	18:00	22:00	18:00	22:00	17:00	21:00
WA	17:00	21:00	17:00	21:00	17:00	21:00
WI	18:00	22:00	17:00	21:00	17:00	21:00
WV	16:00	20:00	17:00	21:00	16:00	20:00
WY	18:00	22:00	8:00	12:00	8:00	12:00

1.2.5 Dispatch Strategy

In historic deployments, thermostat-based demand response is typically only dispatched 15–25 days per year to avoid customer fatigue (Xcel, 2021) (Austin Energy, 2024). But the goal of this modeling is to create a dataset that can be analyzed to determine the maximum technical potential load profile impact at any given point in the year, so the demand flexibility is **dispatched every day in the modeled dataset**. The dispatch strategy is modified for shoulder-season days where heating or cooling load is assumed to be minimal, defined by an average daily temperature greater than 50°F and less than 68°F. On those days, load shifting (done via precooling or preheating) is not dispatched, but load-shedding events are dispatched. The method for choosing this temperature range is described in section 4.2 Initial Sensitivity Analysis. Because of the unrealistically high number of days that demand flexibility is dispatched in this upgrade, the results must be used thoughtfully. One approach is to use daily profiles from the baseline for most days of the year and to splice in daily profiles from the upgrade for days when the intent of the analysis is to dispatch demand flexibility. Similarly, **annualized energy consumption or energy savings metrics should not be used because of the overrepresentation of dispatch**.

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2 ResStock Baseline Approach

The baseline assumption for thermostats in ResStock is a range of heating and cooling set points and setbacks or setups derived from the Residential Energy Consumption Survey (RECS) 2020, which vary based on climate zone, building type, HVAC type, and tenure (U.S. Energy Information Administration, 2023). These set points are assumed to apply year-round. Approximately one-third of dwelling units are assumed to have heating and/or cooling thermostat setbacks or setups, where the set point is changed by the homeowner during part of each day. The distribution of set points in the building stock is shown in Figure 1. ResStock makes no explicit assumption about whether these setbacks or setups are achieved using manual adjustment, a programmable thermostat, or a smart thermostat. In practice, demand response programs typically incentivize or directly pay for customers to install smart thermostats as a condition of program participation.

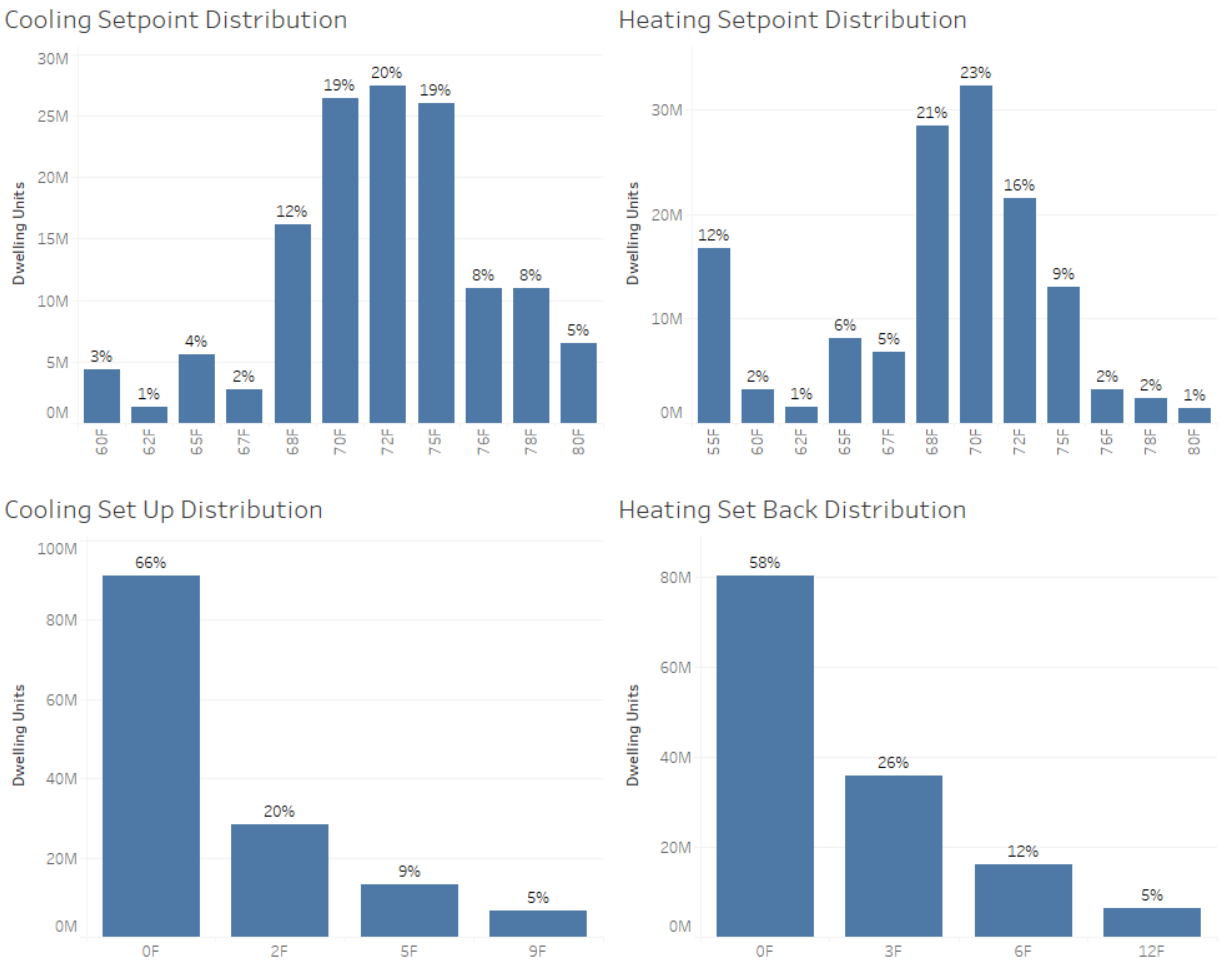

Figure 1. Distributions of thermostat set points, setups, and setbacks[1]

[1] In the heating set point distribution plot, the 55°F set points are for vacant units, and the set point is set to avoid pipes freezing.

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3 Modeling Approach

3.1 Applicability

The goal of demand flexibility is to change the electric or gas load profile of the building in a meaningful way; therefore, this measure is applicable to all dwelling units with either a cooling system or a heating system. Although the measure shifts the load profile of the dwelling units with nonelectric heating during heating season, the change to the electric load profile is minimal because it only changes the fan or pump electricity consumption. For this reason, the heating load analysis in this document is focused on buildings with electric heating only. Table 4 summarizes the breakout of the building stock to which the measure applies and what is included in heating and cooling load analysis.

Table 4. Summarized Applicability Logic for HVAC Load Flexibility

HVAC Cooling Type	Heating Fuel	Stock Saturation (%)	Measure Is Applicable	Included in Heating Load Analysis	Included in Cooling Load Analysis
Central AC	Electricity	14.4	Yes	Yes	Yes
	Fuel oil	1.9	Yes	No	Yes
	Natural gas	32.7	Yes	No	Yes
	None	0.2	Yes	No	Yes
	Other fuel	0.1	Yes	No	Yes
	Propane	3.2	Yes	No	Yes
	Wood	0.5	Yes	No	Yes
Ducted heat pump	Electricity	15.7	Yes	Yes	Yes
Non-ducted heat pump	Electricity	1.0	Yes	Yes	Yes
Room AC	Electricity	6.0	Yes	Yes	Yes
	Fuel oil	2.1	Yes	No	Yes
	Natural gas	9.8	Yes	No	Yes
	None	0.2	Yes	No	Yes
	Other fuel	0.2	Yes	No	Yes
	Propane	0.9	Yes	No	Yes
	Wood	0.6	Yes	No	Yes
None	Electricity	3.1	Yes	Yes	No
	Fuel oil	0.7	Yes	No	No
	Natural gas	5.3	Yes	No	No
	Other fuel	0.1	Yes	No	No
	Propane	0.4	Yes	No	No
	Wood	0.4	Yes	No	No
	None	0.3	No	No	No

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3.2 ResStock Workflow

Figure 2 illustrates the modeling approach used to integrate a load flexibility measure into ResStock. This measure modifies the existing building energy model thermostat set point schedules during the pre-peak and on-peak periods only. For times outside of the event, the existing thermostat schedules in the model are unchanged. If the baseline thermostat set point schedules indicate that the dwelling unit is already in a setback or a setup state, the demand flexibility thermostat change still applies.

The load flexibility scenario (which includes the pre-peak duration and the set point offset values) serves as input for the measure, allowing customized controls. The input values used for this measure are explained in section 3.3 Input Variables.

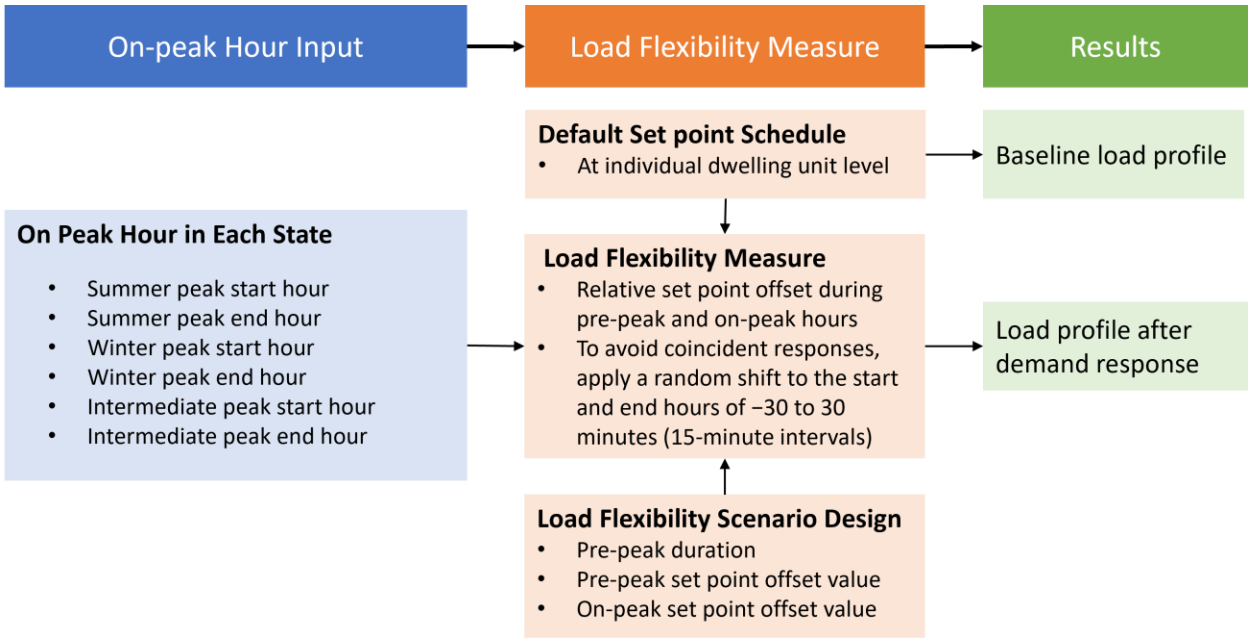

Figure 2. Modeling approach for running a load flexibility measure in ResStock

Values for on-peak hours for summer months, winter months, and intermediate months are provided at the state level in an input file. The load flexibility measure first retrieves the heating and cooling set point schedules specific to each individual dwelling unit. It then modifies these schedules by adjusting the set points by an offset during the designated pre-peak and on-peak periods. This approach ensures that each unit's load flexibility aligns with its original comfort settings while providing targeted adjustments to reduce energy use during peak demand times. A minimum heating set point of 55°F and a maximum cooling set point of 82°F ensure that extreme discomfort is avoided. If the set point change would cause a heating set point higher than the original cooling set point or a cooling set point lower than the original heating set point, the set point adjustment is limited to avoid this condition. These thresholds and exceptions were chosen based on engineering judgment and only apply to a small percentage of dwelling units.

To prevent the creation of a new peak caused by the coincident return to normal set point temperatures, the load flexibility measure introduces a random shift to each dwelling unit's demand response start and stop time. The maximum allowable shift is defined in the scenario

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design, allowing each unit to randomly adjust its response start time within this range. For example, with a maximum random shift of 30 minutes and a 15-minute simulation time step, the potential random shift values are -30 minutes, -15 minutes, 0 minutes, 15 minutes, and 30 minutes.

3.3 Input Variables

There are two types of input variables: input variables for load flexibility scenario design and on-peak hour inputs. On-peak hour inputs are provided as a json file to indicate the peak hour start and end time at the state level. Table 5 presents a list of input variables and settings used for this analysis. These were based on the utility programs outlined in the technology overview in consultation with the demand flexibility modelers using the outputs of this analysis.

Table 5. Input Variables for HVAC Load Flexibility

Variable Name	Description	Value
loadflex_peak_offset	Set point offset value during the peak period in degrees Fahrenheit. The set point is increased for cooling, and it is decreased for heating.	2–4°F
loadflex_pre_peak_duration_hours	Duration of the pre-peak period in hours	1–4 hours
loadflex_pre_peak_offset	Set point offset value during the pre-peak period in degrees Fahrenheit. The set point is decreased for cooling, and it is increased for heating.	2–4°F
loadflex_random_shift_minutes	Maximum minutes to randomly shift the peak period. If the minutes are less than the time step, they will be assumed to be 0.	30 minutes
peak_start_time	The time (local time) the peak period starts	Varies by state and season; see Table 3

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4 Results

4.1 Single-Building Examples

We performed an initial ResStock test run to validate the operation of the load flexibility measures. This was a test run performed before the final input values were established, which is why some values differ from the final selection. The test run was performed using 50 models spread across the nation with two scenarios (also called upgrades):

- **Upgrade 1: load shifting plus load shedding**—a pre-peak duration of 2 hours, a peak duration of 1 hour, and an offset of 2°F during both the pre-peak and on-peak period
- **Upgrade 2: load shedding only**—no pre-peak load shifting, a peak duration of 1 hour, and an offset of 2°F during the on-peak period.

Figure 3 shows the time-series thermostat set point for a dwelling unit in Delaware. Note that this dwelling unit has a temperature setback during the night. We can see that for upgrade 1, there is both a pre-peak and peak offset, with the peak period being 18:00 to 19:00. For upgrade 2, there is no pre-peak offset. Both show the expected temperature offset of 2°F.

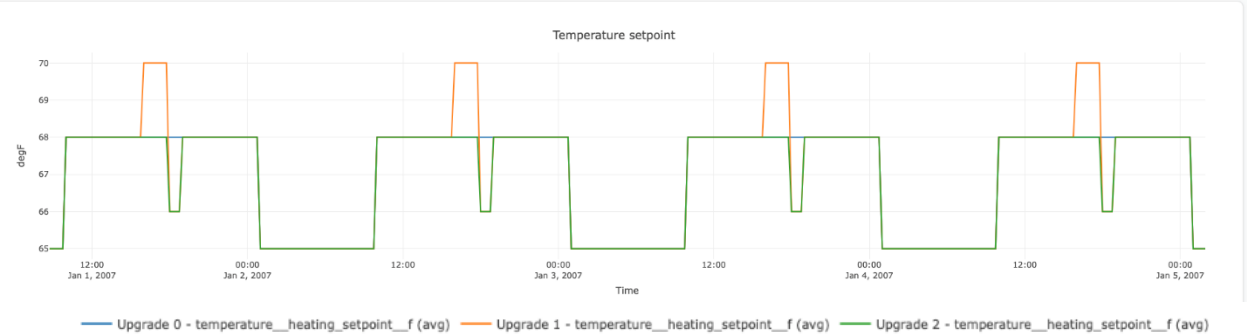

Figure 3. Verification of set point changes

Figure 4 shows the time-series conditioned space temperature changes. The results show that the indoor temperature quickly tracks the set point changes, especially during preheating. This hints that the preheating duration can be significantly shortened, at least for this building. See Section 4.6 on the known limitations for a discussion on the thermal capacitance of the models in ResStock, which also has a bearing on this observation.

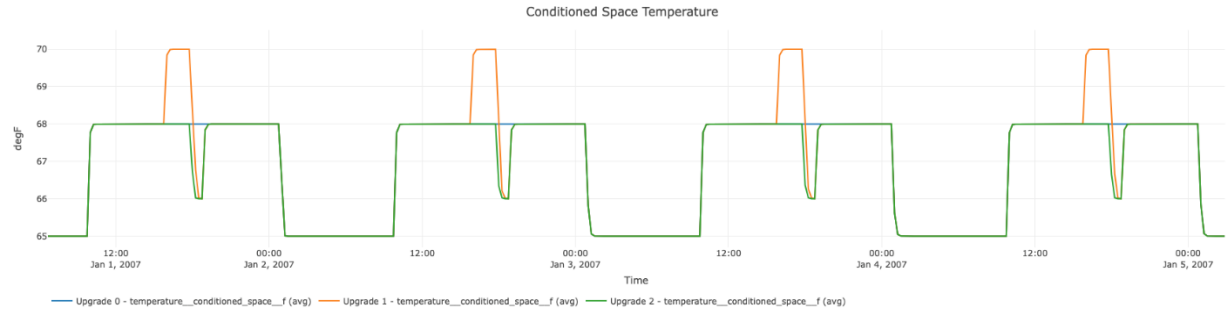

Figure 4. Verification of conditioned space temperature changes

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Figure 5 shows the time-series heating energy consumption. For upgrade 1, the results show additional energy consumption for preheating before the peak period and lower energy consumption during the peak period. There is also an occasional rebound after the peak period ends at 19:00. For upgrade 2, the energy consumption starts deviating from the baseline only at the beginning of the peak period. Although it consumes less energy than the baseline during the peak, it consumes slightly more than upgrade 1 because it does not have preheating.

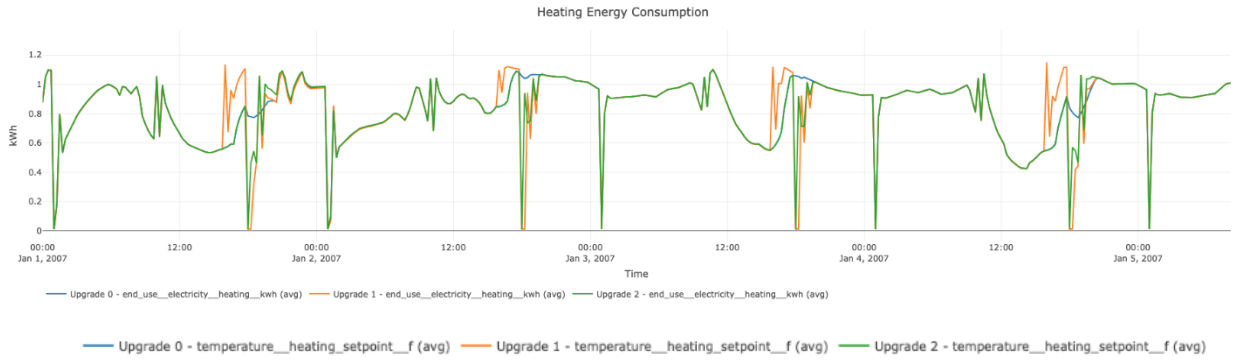

Figure 5. Verification of conditioned space temperature changes

Figure 6 shows the daily total heating energy consumption for the same period as the time-series data in Figure 5. The jaggedness of the heating consumption profile was not investigated because of scope limitations. Although the daily consumption values are all very close, upgrade 2 is usually the lowest (though not always) due to the lack of preheating and the offset during the peak. Interestingly, upgrade 1 is also frequently lower than the baseline despite the preheating period, which is twice as long as the peak period, and the equal offset in the other direction.

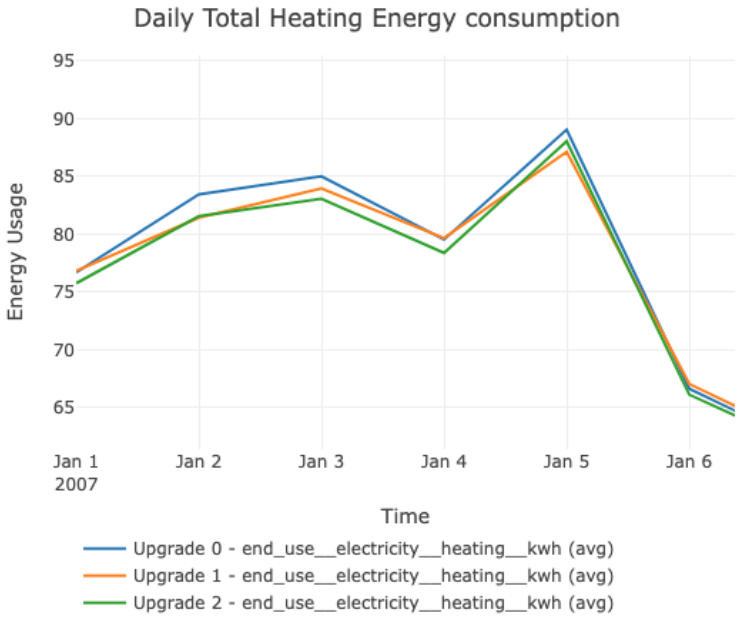

Figure 6. Validation of daily energy consumption in one building

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Figure 7 shows a more consistent pattern of which upgrade uses the most energy when we consider more buildings. The results show that upgrade 1 consumes more energy on average than the baseline, and upgrade 2 consumes less energy than the baseline; however, the single-building example shows that there are exceptions, from both day-to-day and building-to-building perspectives.

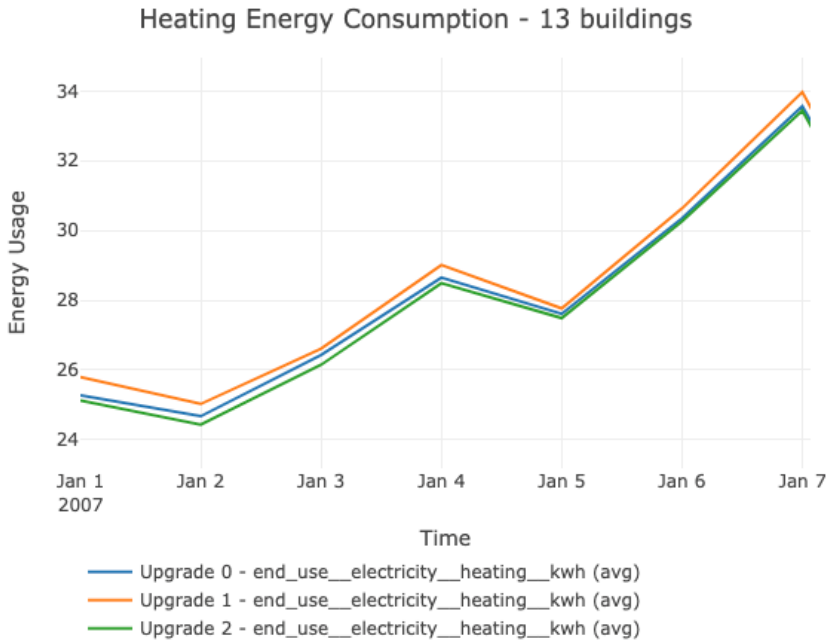

Figure 7. Validation of daily energy consumption in 13 buildings

4.2 Initial Sensitivity Analysis

To determine how the performance of load flexibility varies across the range of event durations and set point magnitudes in real-world smart demand response thermostat programs, we performed an initial sensitivity analysis using a small test run of 1,000 buildings across the United States. The range of inputs was parametrized across a set of 17 different upgrades, as shown in Table 6.

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Table 6. Test Run Specification for Initial Sensitivity Analysis

	Pre-Peak		On-Peak	
Upgrade	Duration	Offset (°F)	Duration	Offset (°F)
1	No pre-peak	N/A	4 hours	2
2	15 minutes	2	4 hours	2
3	30 minutes	2	4 hours	2
4	1 hour	2	4 hours	2
5	2 hours	2	4 hours	2
6	4 hours	2	4 hours	2
7	No pre-peak	N/A	4 hours	4
8	15 minutes	4	4 hours	4
9	30 minutes	4	4 hours	4
10	1 hour	4	4 hours	4
11	2 hours	4	4 hours	4
12	4 hours	4	4 hours	4
13	15 minutes	6	4 hours	4
14	30 minutes	6	4 hours	4
15	1 hour	6	4 hours	4
16	2 hours	6	4 hours	4
17	4 hours	6	4 hours	4

4.2.1 Quantifying Demand Flexibility Impacts

Traditional energy efficiency measures are often evaluated based on how much energy or utility bills they save on an annual basis. Because the goal of demand flexibility is to modify the load profile for a small number of days per year, metrics that evaluate the ability to modify the load are more useful than annualized energy consumption impacts.

There are many ways that the peak load impact of demand flexibility can be quantified. For this analysis, we adopted the demand decrease percentage (D3) metric, as defined by (Jingjing Liu, 2022). This metric is defined as:

$$D3\text{: } Demand\ decrease\ percentage\ (\%) = \frac{Average\ demand\ decrease\ during\ a\ single\ \text{“}shed\text{”}\ period\ (kW)}{Baseline\ average\ demand\ during\ \text{“}shed\text{”}\ period\ (kW)}$$

The D3 metric can be computed for a single building or a group of buildings in aggregate. It can also be computed for the whole building load or for individual end uses.

This metric was adopted because it quantifies the impact for a single demand response event (in our case, each day where demand response is dispatched), but it can easily and meaningfully be

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summarized over multiple events. For example, the mean or quartile values can be used to describe how the impact changes during a year, a season, or a month. This is particularly useful when the demand flexibility impacts are later used as the input to other models seeking to represent demand flexibility but that do not endogenously represent building physics. Examples of such models include Lawrence Berkeley National Laboratory's DR-Path (Brian Gerke, 2019) and the Brattle Group's LoadFlex model (Ryan Hledik A. F., 2019).

Because the goal of this analysis is to feed results into downstream modeling efforts, we calculated the D3 metric for the aggregate load of groups of buildings of a common type located in a common geography.

Figure 8 shows how the D3 metric varies with different pre-peak durations for cooling load flexibility on the hottest day of the year for each state. We used an approximate 20% reduction for the 2°F offset and an approximate 40% reduction for the 4°F offset. Although only the peak offset without any precooling can provide a significant percentage reduction, pairing that with precooling can push the reduction even further—more so in some states than others. Also, the longer the duration of precooling, the higher the percentage reduction, with the highest reduction coming from 4-hour precooling.

Figure 9 shows the same metrics calculated year-round. That is, we calculated the average cooling energy consumption during the peak period for the whole year for both the baseline and the upgrade, and we calculated the difference as a percentage reduction. Some states have more percentage savings year-round than their hottest day, whereas others have less. Regardless, most show a positive correlation with the duration of the pre-peak period (at all offset levels) except for a handful of states that show a surprising negative correlation. We examined the results with the largest negative correlation—an identification with a 6°F pre-peak offset to investigate how a larger precooling duration (or having precooling at all) could result in a *higher* load during the peak.

The answer is in how the precooling and preheating was initially implemented. In the sensitivity analysis, we always chose to either precool or preheat, depending on the daily average temperature. If the daily average temperature was less than 66°F, we classified that as a heating day, otherwise we classified the day as a cooling day; however, this might not always work neatly. For some days in shoulder season with mostly low temperatures during the morning but a hot afternoon, we classified the day as a heating day even though the building needed more cooling than heating; therefore, we mistakenly preheated a building that needed precooling (or at least not preheating).

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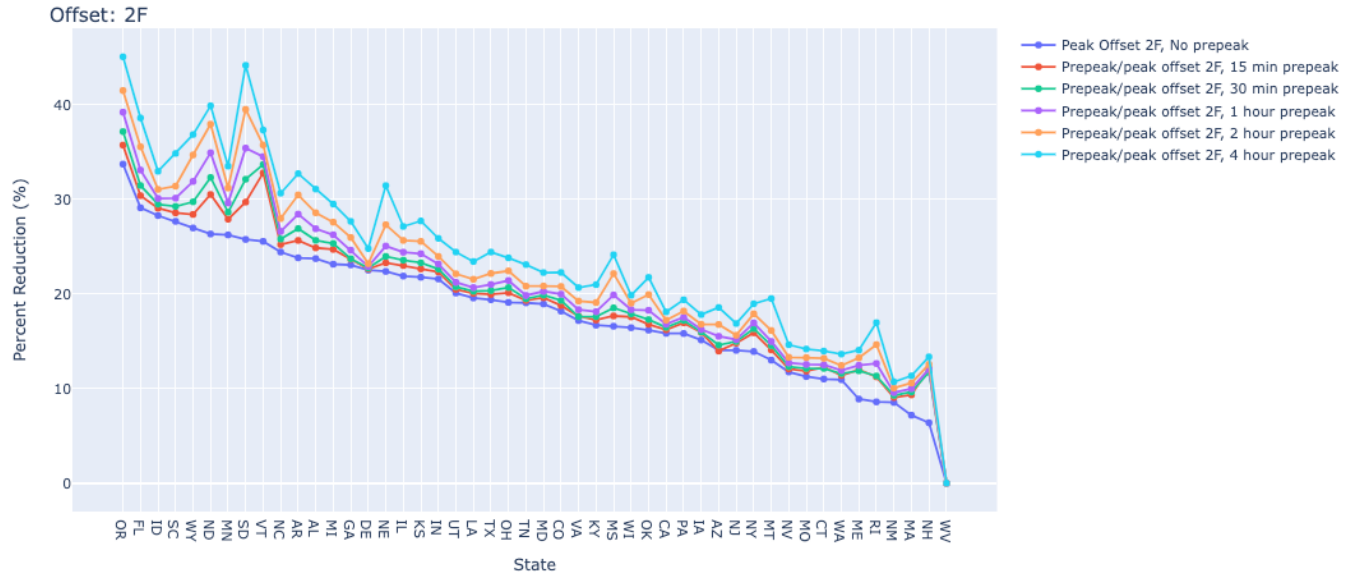

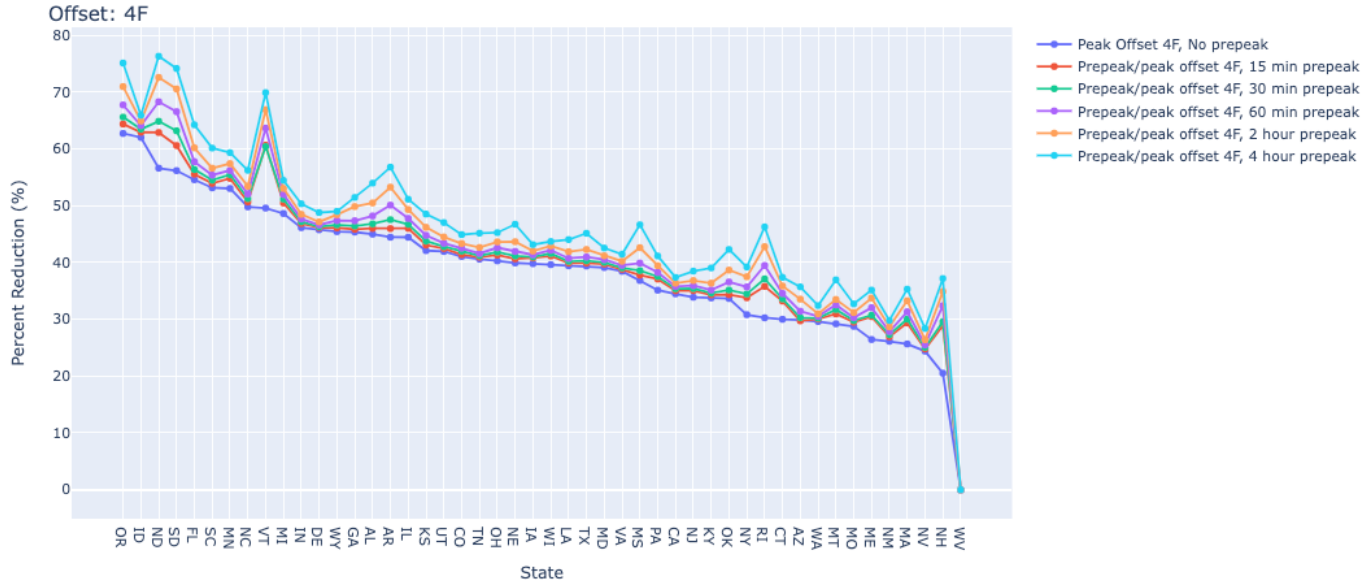

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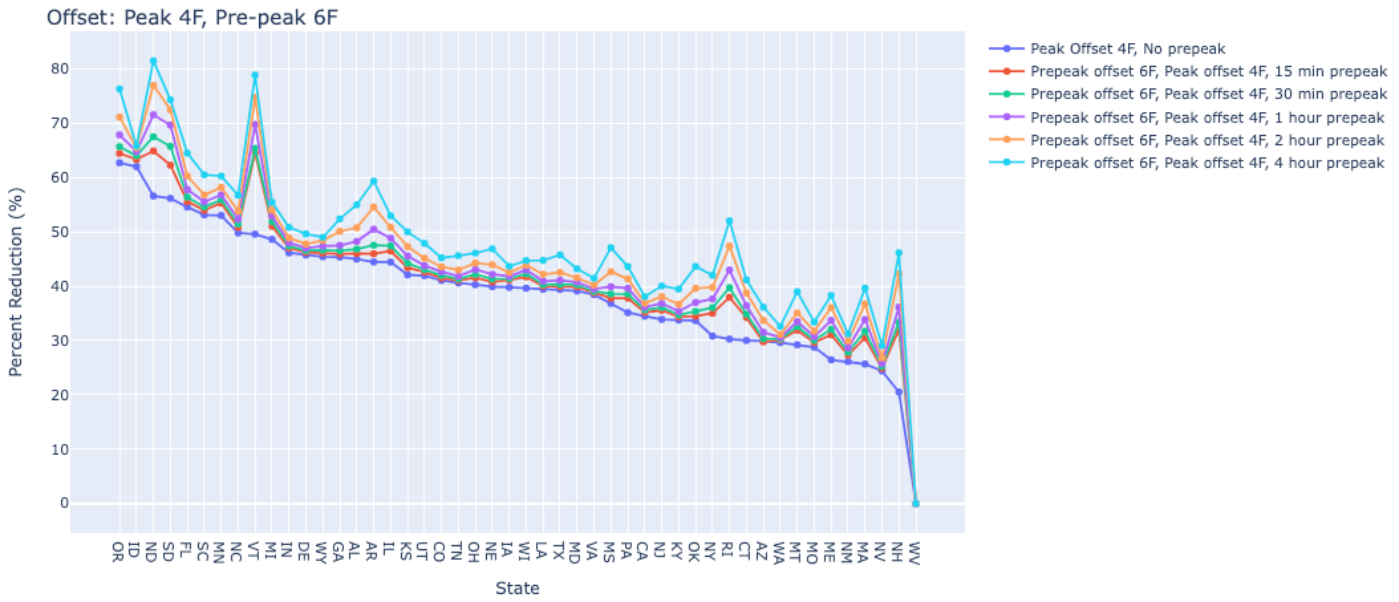

Figure 8. D3 percentage reduction of cooling energy consumption during the peak period on an extreme day and at various pre-peak durations (including no pre-peak). The top figure shows a 2°F offset for both the pre-peak and peak periods, the middle shows a 4°F offset for both, and the bottom shows a 6°F offset for the pre-peak period and a 4°F offset for the peak period. Note that the ordering of states varies.

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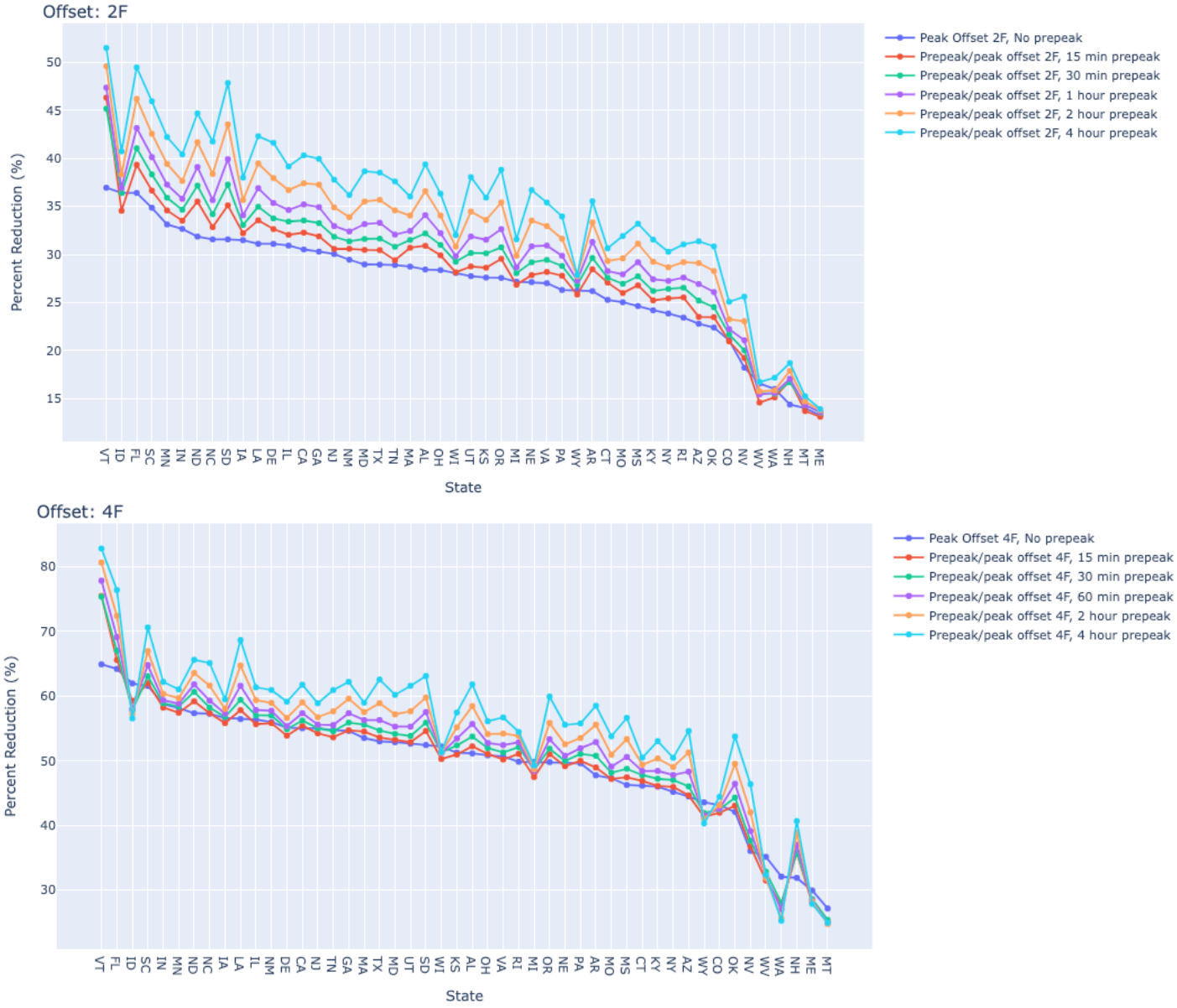

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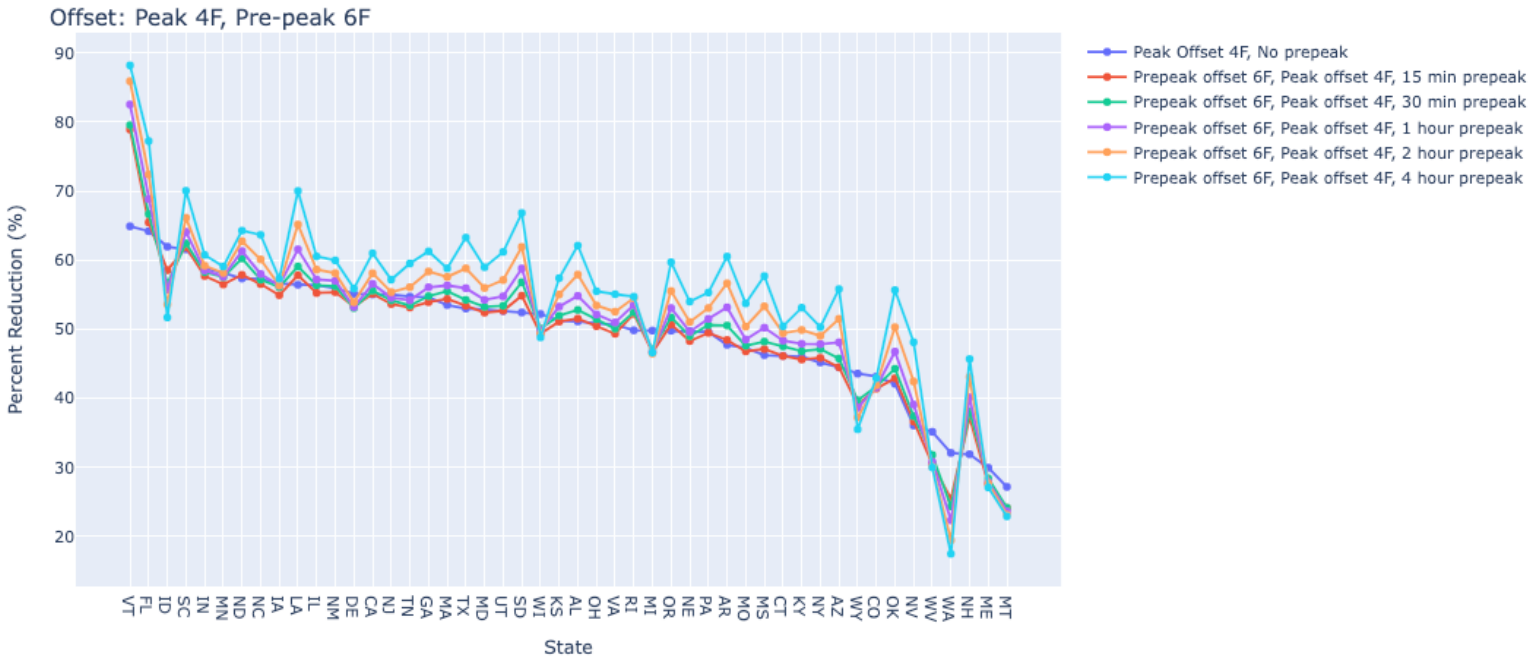

Figure 9. D3 percentage reduction of cooling energy consumption during the peak period for the whole year and at various pre-peak durations (including no pre-peak). The top figure shows a 2°F offset for both the pre-peak and peak periods, the middle shows a 4°F offset for both, and the bottom shows a 4°F offset for the peak period and a 6°F offset for the pre-peak period. Note that the ordering of the states varies.

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Figure 10 shows an example of a heating day misclassified as a cooling day for a single model. The day was misclassified as a heating day, and preheating was performed from 14:00 to 18:00, resulting in a large reduction in cooling load later in the day because the preheating increased both the heating and the cooling set points[2]; however, once the peak period begins at 18:00, the increased cooling set point is reset to normal, resulting in increased cooling energy consumption. Essentially, we tried to preheat when precooling would have been appropriate, resulting in increased load during the peak. The solution was to avoid preheating or precooling when the average daily outdoor temperature is near the threshold (66°F) because it is hard to predict whether precooling or preheating would be the more appropriate action. In the final run, we implemented this correction.

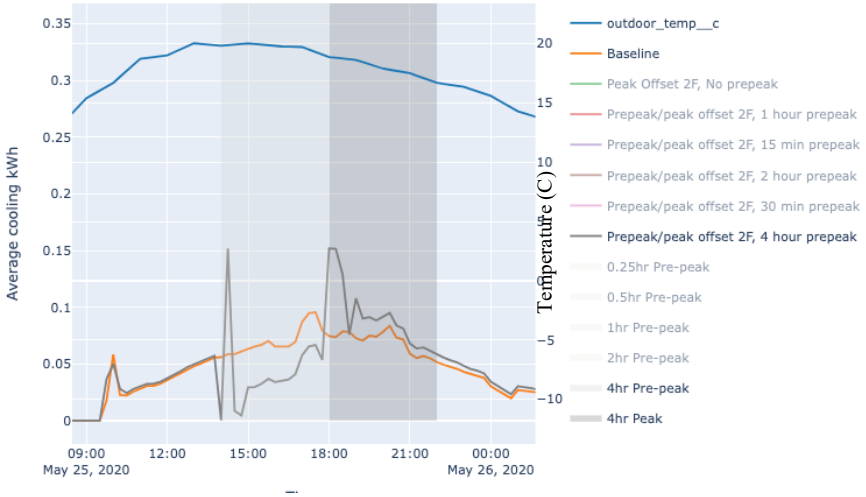

Figure 10. Anomalous demand response in a shoulder season day in Idaho

To help decide the appropriate switchover temperatures, we looked at the distribution of the average heating and cooling loads during the peak period across various daily average temperatures, as shown in Figure 11 and Figure 12.

[2] Preheating does not require raising the cooling set point by default—it only requires raising the heating set point; however, to prevent an inverted set point (where the cooling set point is lower than the heating set point), the algorithm raises the cooling set point as well when the heating set point exceeds the cooling set point.

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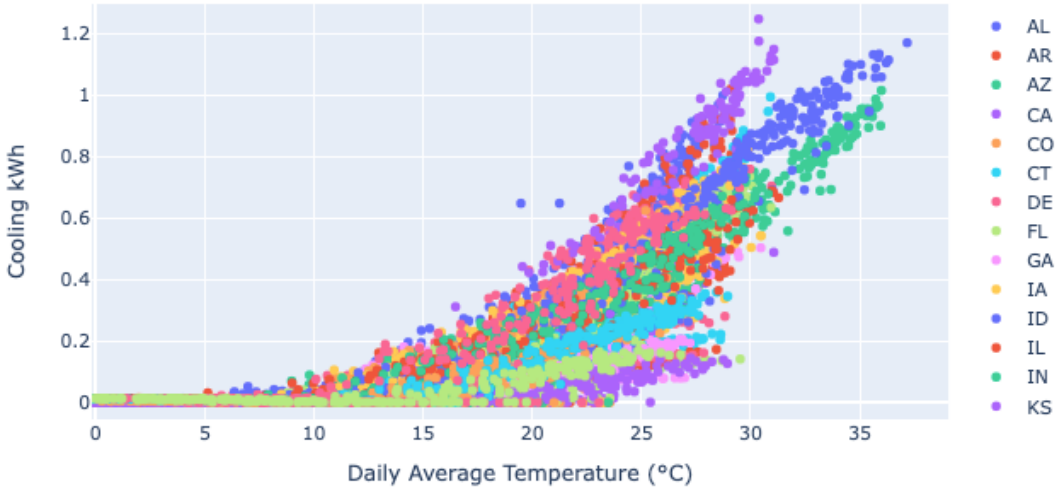

Figure 11. State average hourly cooling load per building during the peak period

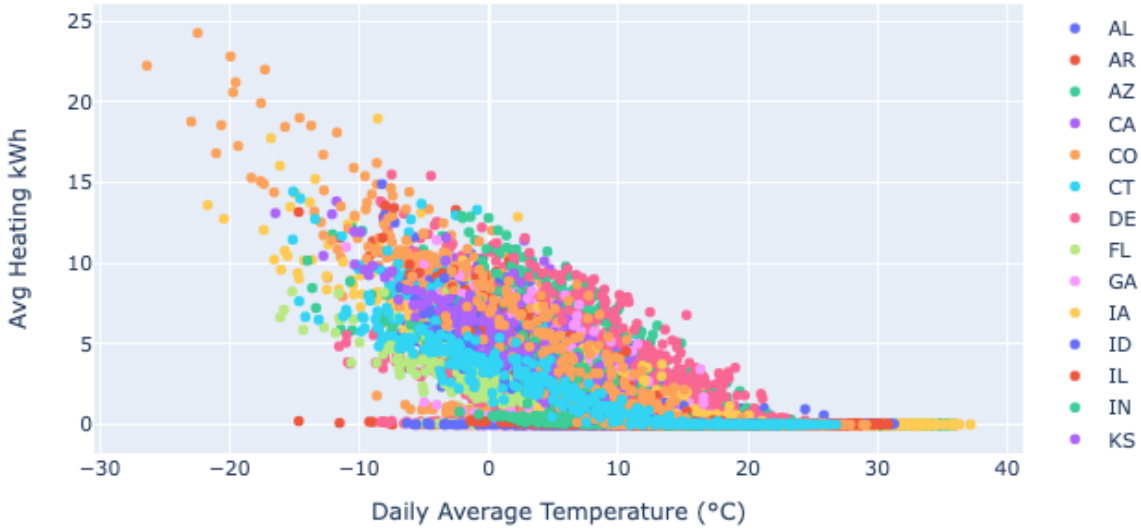

Figure 12. State average hourly heating load per building during the peak period

The average load at a given average daily temperature for a given state varies among different days (different dots in the figure), depending on the specific temperature profile for the day and the internal heat generated in the building via various occupancy-driven end uses. Figure 11 shows minimal cooling below an average daily temperature of 10°C (50°F), and Figure 12 shows minimal heating above an average daily temperature of 25°C (68°F). Based on these results, in the final implementation, we precooled only if the daily average temperature is above 68°F, and we preheated only if the daily average temperature is below 50°F. We did not need to follow these thresholds for load shedding—decreasing the heating set point and increasing the cooling set point during the peak period will reduce the demand regardless of the building having a cooling or a heating load.

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4.3 Final Sensitivity Analysis

After further reviewing the real-world demand response programs and reviewing the initial sensitivity analysis results, we narrowed the analysis space. First, we narrowed the offset to only 2–4°F, and then we limited the precooling windows to 1 hour and 4 hours. More details can be seen in Table 7.

In this round, we also introduced a random shift. This was used to reduce the "snapback," or rebound, seen after the peak period when all thermostats reset to the normal set point at the same time. A maximum random shift of ± 30 minutes will make some buildings start their peak period up to 30 minutes early or up to 30 minutes late (i.e., the shift can be anything ranging from +30 minutes, to +15 minutes, to 0 minutes, to -15 minutes, to -30 minutes). This random shifting was assigned on a building-by-building basis, not on a per-event basis. In a real deployment, this staggering of individual homes could be accomplished through a combination of intentional control, inherent time delays, and equipment states found across the portfolio at any point in time.

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Table 7. Test Run Specification for Final Sensitivity Analysis

	Pre-Peak		On-Peak	
Upgrade	**Duration**	**Offset (°F)**	**Duration**	**Offset (°F)**
1 (peak only)	No pre-peak	N/A	4 hours	2
2 (pre-peak only)	4 hours	2	No on-peak	N/A
3 (both)	4 hours	2	4 hours	2
4 (peak only)	No pre-peak	N/A	4 hours	4
5 (pre-peak only)	4 hours	4	No on-peak	N/A
6 (both)	4 hours	4	4 hours	4
7 (peak only)	No pre-peak	N/A	4 hours	2
8 (pre-peak only)	1 hour	2	No on-peak	N/A
9 (both)	1 hour	2	4 hours	2
10 (peak only)	No pre-peak	N/A	4 hours	4
11 (pre-peak only)	1 hour	4	No on-peak	N/A
12 (both)	1 hour	4	4 hours	4

First, as shown in Figure 13, the impacts of precooling only are the lowest, followed by on-peak reduction, followed by the largest impacts when both precooling and the on-peak set point changes were applied on the same day. The anomalous behavior in West Virginia and South Dakota was not investigated for this test run, but it is believed to be a product of the small number of samples and the characteristics of the dwelling units in the test run. Figure 14 shows the same pattern but for heating. The anomalous behavior in California was not investigated for this test run, but it is believed to be a product of the relatively mild weather and the associated low absolute heating demands for most dwellings in the state.

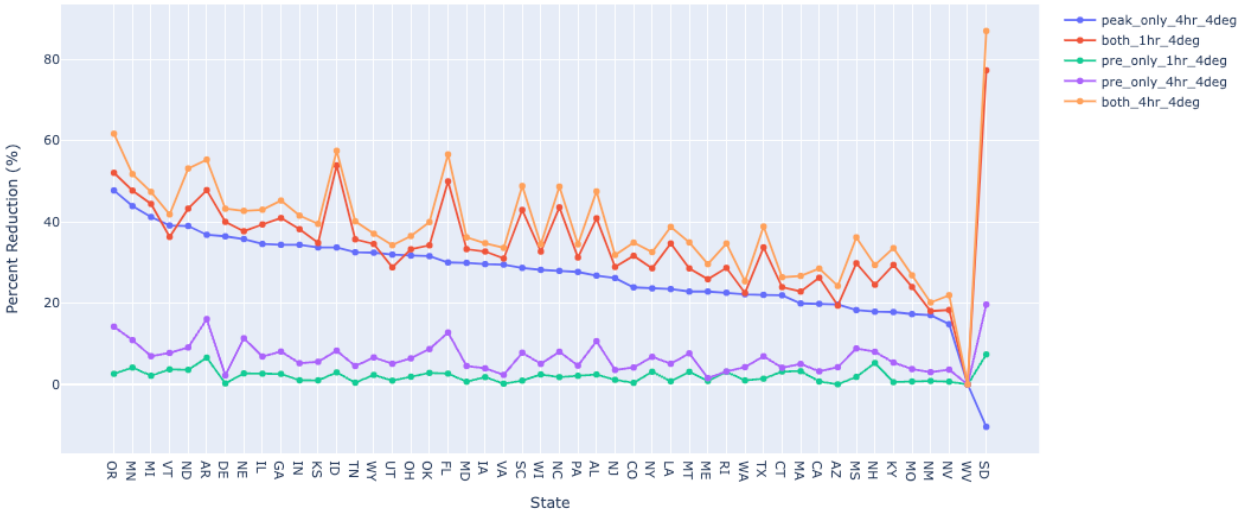

Figure 13. D3 percentage reduction of the cooling energy consumption during the peak on the day of the year with the highest daily average temperature

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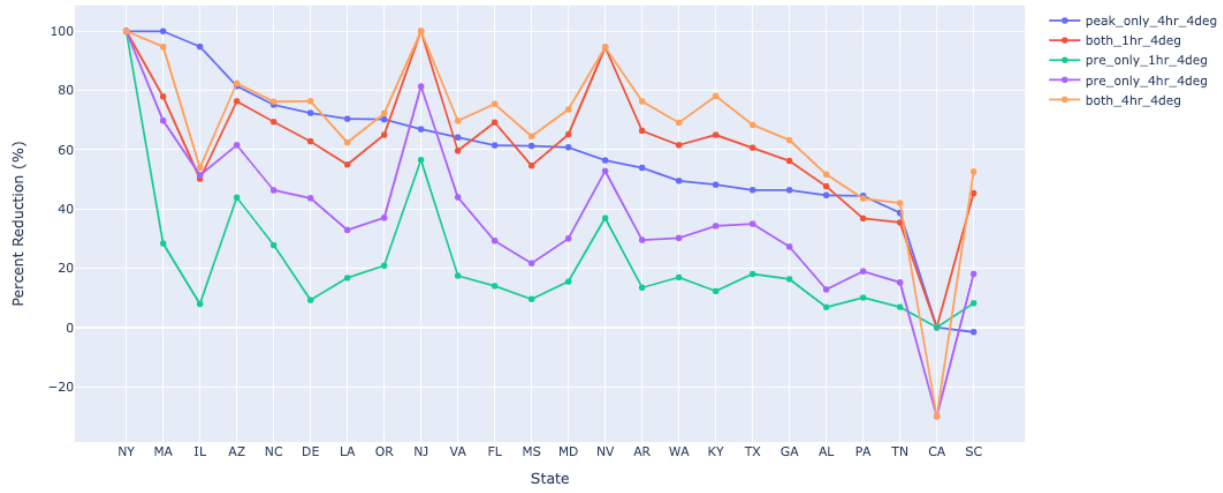

Figure 14. D3 percentage reduction of the heating energy consumption during the peak on the day of the year with the lowest daily average temperature

Another notable result, though not shown in the figures, was a minimal difference between a pre-peak offset of 2°F and 4°F for pre-peak durations of 1 hour. This makes sense because the rate of the temperature increase possible in a home within 1 hour is limited by physical characteristics, such as the thermal mass of the dwelling and the capacity of the heating equipment.

4.4 Final Selection of Parameters for HVAC Load Flexibility Measure

After further reviewing the existing demand response programs and considering the limitations of the likely downstream modeling tools, we eliminated scenarios where load shifting and load shedding were applied at the same time. Table 8 shows the final selection of the load flexibility options that we believe cover the likely range of demand flexibility programs.

Table 8. Final Selection of Demand Flexibility Options to Cover the Likely Program Space

	Pre-Peak		On-Peak	
Upgrade	**Duration**	**Offset (°F)**	**Duration**	**Offset (°F)**
1 (on-peak load shedding, 4 hours, 2°F offset)	No pre-peak	N/A	4 hours	2
2 (pre-peak load shifting, 4 hours, 2°F offset)	4 hours	2	No on-peak	N/A
3 (on-peak load shedding, 4 hours, 4°F offset)	No pre-peak	N/A	4 hours	4
4 (pre-peak load shifting, 4 hours, 4°F offset)	4 hours	4	No on-peak	N/A
5 (pre-peak load shifting, 1 hour, 2°F offset)	1 hour	2	No on-peak	N/A

4.5 Stock-Level Results

A test run with 30,000 samples was conducted. The state-level D3 metrics are calculated in the following five steps:

1. Filter out samples that have electric heating and samples that have cooling separately.

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2. Aggregate state-level heating (or cooling) time series for both the baseline and savings from upgrades.
3. Calculate the percentage reduction in heating or cooling during the peak periods for each day.
4. Remove days where heating (or cooling) savings during peak periods are zero, indicating that the thermostat demand flexibility measure is not applicable on those days.
5. Compute the mean, along with the 25th, 50th, and 75th percentiles for the remaining days.

The results for the single-family detached across the five upgrades are shown in Figure 15–Figure 19. States not shown in the figures either lack relevant data due to an insufficient sample size or do not have the specific end use (heating or cooling) savings.

Figure 15 shows an approximate 40% winter and 30% summer reduction in peak load from load shedding for 4 hours with a 2°F offset. As expected, Figure 16 shows an approximate 15% winter and 10% summer reduction from load shifting (preconditioning) for 4 hours with a 2°F offset. This lower reduction relative to Figure 15 is expected because the thermal inertia does not carry through the entire 4-hour peak window. Figure 17 shows an approximate 60% winter and 50% summer reduction in peak load from load shedding for 4 hours with a 4°F offset. This deep reduction is expected because of the significant depth of the set point change. Figure 18 shows an approximate 30% winter and 20% summer reduction from load shifting (preconditioning) for 4 hours with a 4°F offset. As expected, this reduction is larger than the reduction shown from load shifting with a 2°F offset because the deeper set point change for 4 hours allows more charging of the building thermal mass, allowing reduced space conditioning during more of the 4-hour peak window. Last, Figure 19 shows an approximate 10% winter and 5% summer reduction from load shifting (preconditioning) for 1 hour with a 2°F offset. This minimal impact is expected because the short duration of the preconditioning coupled with the small set point offset does not allow much charging of the building thermal mass, leading to a minimal impact during the peak window.

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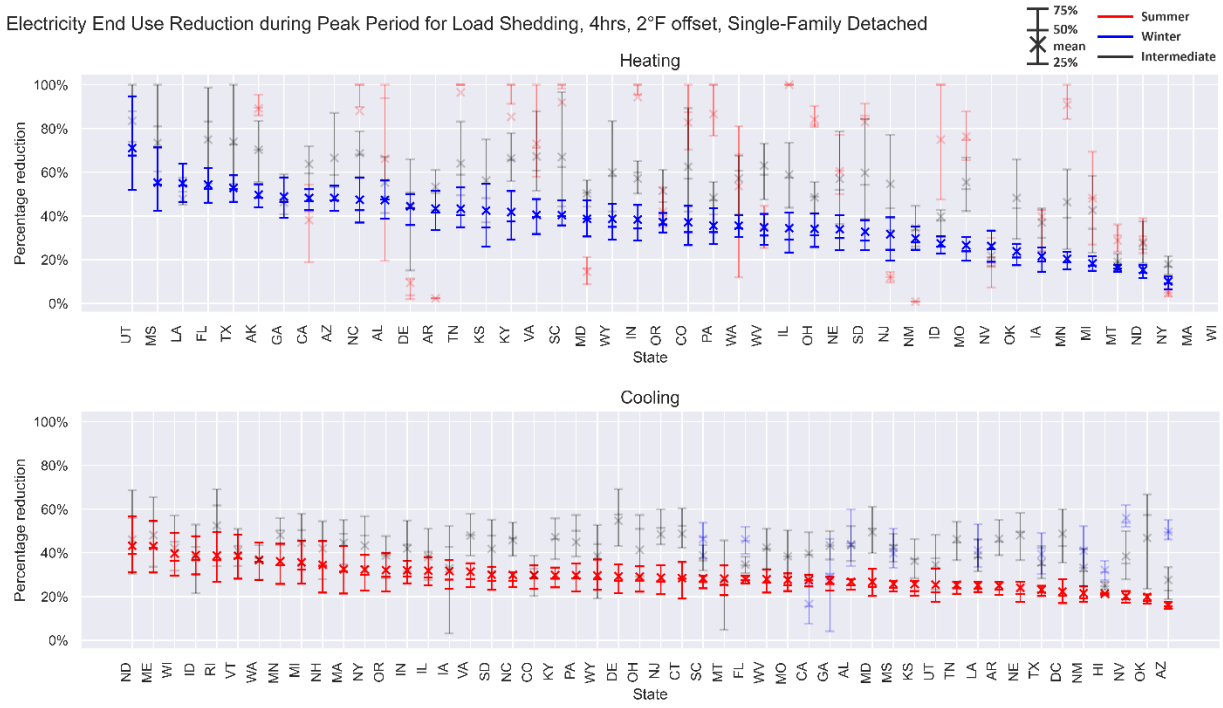

Figure 15. State-level D3 metrics for load shedding, 4 hours, 2°F offset

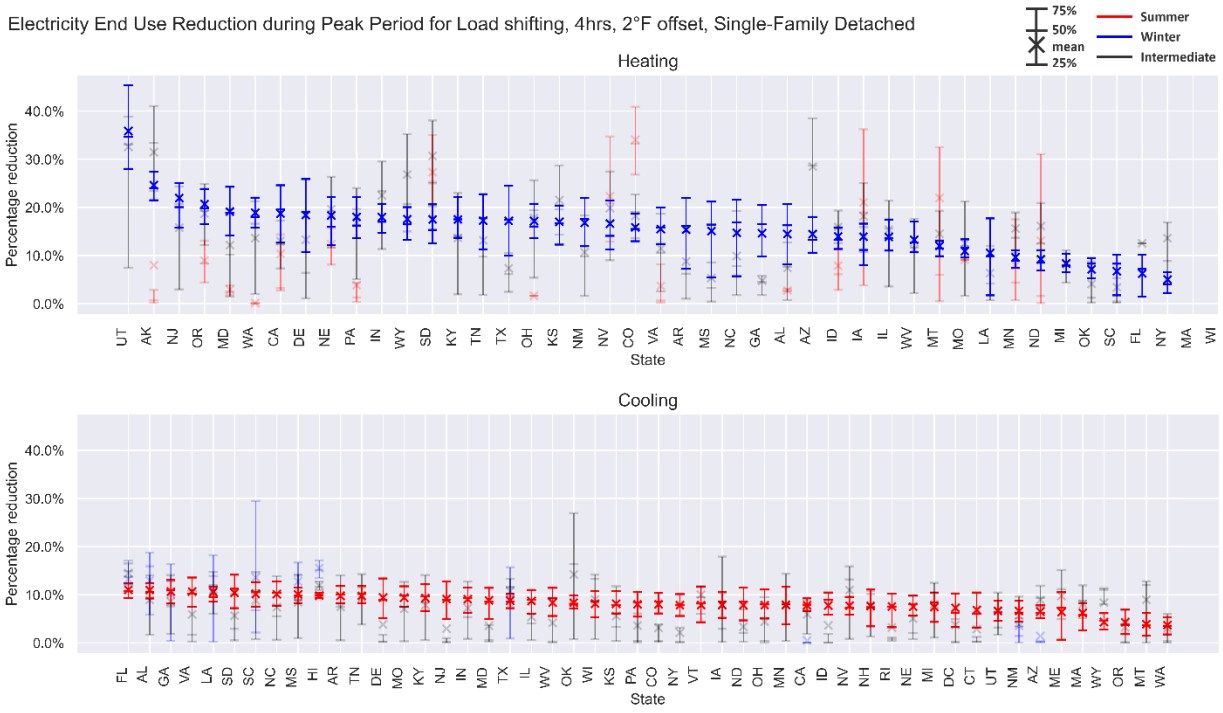

Figure 16. State-level D3 metrics of the single-family detached for load shifting, 4 hours, 2°F offset

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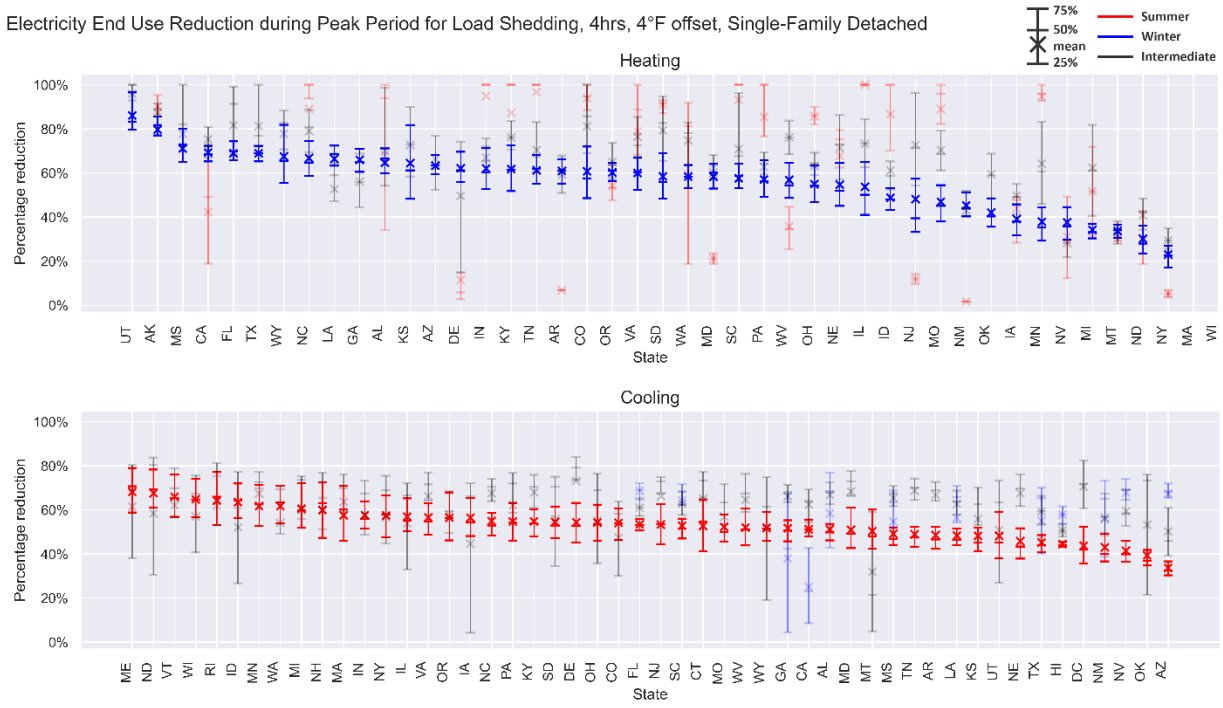

Figure 17. State-level D3 metrics of the single-family detached for load shedding, 4 hours, 4°F offset

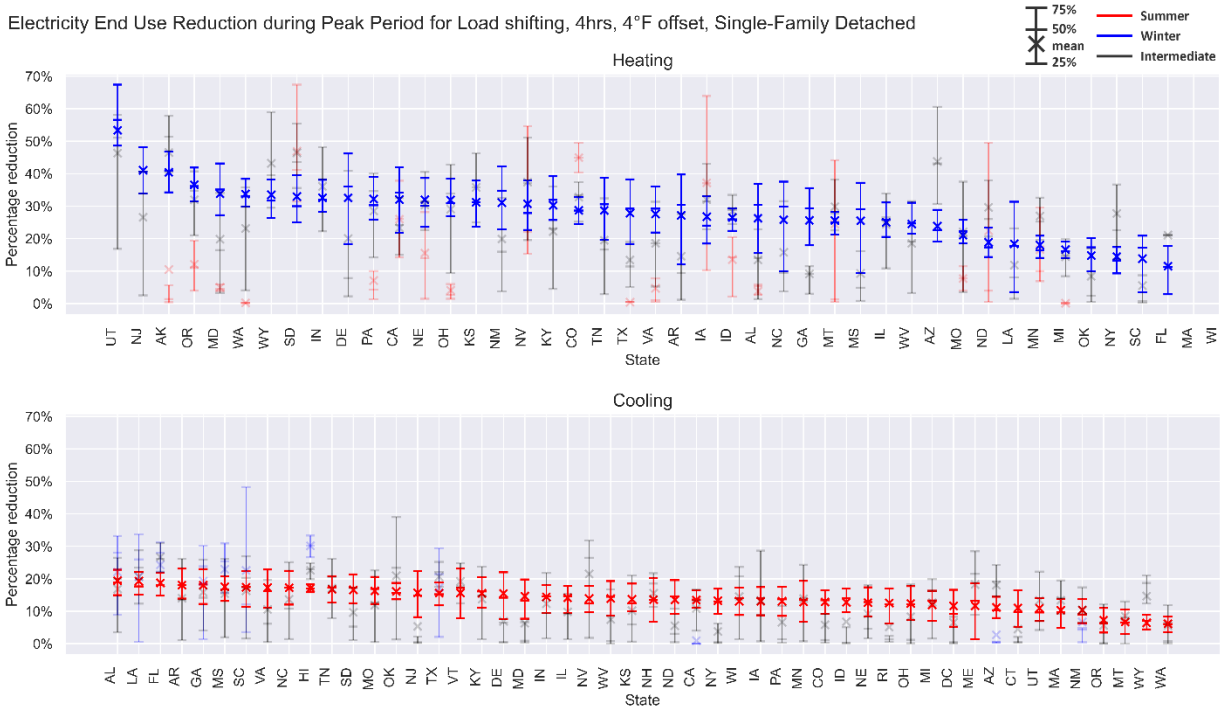

Figure 18. State-level D3 metrics of the single-family detached for load shifting, 4 hours, 4°F offset

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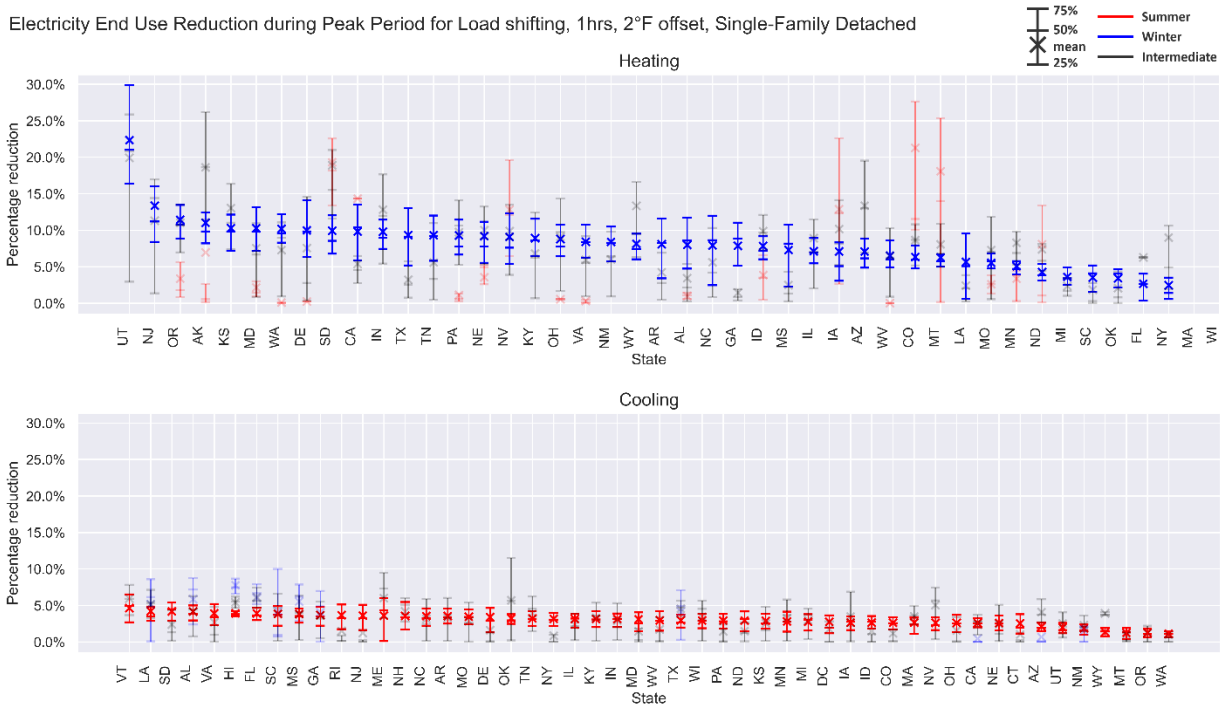

Figure 19. State-level D3 metrics of the single-family detached for load shifting, 1 hour, 2°F offset

4.6 Limitations and Concerns

In this measure, demand response is dispatched every day. This is done to evaluate and estimate the potential impact of demand response over a wide range of day types and weather conditions. For this reason, although the individual day-level results for this measure are realistic, the annual energy consumption savings are not consistent with the current dispatch practices, and **they should not be used directly**. Instead, users interested in estimating annual energy impacts should splice daily time-series results from the baseline model (without demand response) and the time-series results from the upgraded model (with demand response) in the target proportion.

This measure is applied to all dwelling units with electric heating or cooling to investigate load flexibility potential; however, only a subset of these units is ideally suited for this measure. Units already equipped with smart thermostats have a lower barrier to entry into a demand response program. This measure assumes that units without a smart thermostat would be equipped with one as part of the installation process. Alternately, utilities could ask customers to manually adjust thermostats for a small number of events per year, but the participation of such a program would be important to establish. If one wishes to study the impact of the partial penetration of smart thermostats or less than 100% participation in the demand response program, they should take a subset of buildings from the upgrade and take the rest from the baseline.

In previous calibration efforts, the building energy models used in ResStock have shown a temperature decay that is faster than empirical data. To better match the empirical data, ResStock uses an increased thermal capacitance multiplier for the air inside the dwelling units. This could still result in temperature decay profiles that are faster than reality, meaning that this analysis could underestimate the duration of the load reduction before the adjusted thermostat set point is

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reached. If the root cause is an underestimate of the thermal mass, the results could also underestimate the amount of time required to effectively preheat or precool the dwellings.

The models used in ResStock represent the building stock circa 2018 using weather from 2018, but the goal is to estimate the potential of demand flexibility in 2050. Based on the slow speed of retrofits in the building stock and the slow uptake of envelope upgrades, the use of today's building stock is believed to be an acceptable limitation. The impact of not using future weather projections is more difficult to assess. On one hand, average temperatures are not expected to change dramatically by 2050. On the other hand, extreme temperatures, which might or might not be coincident with the peak periods, could change more dramatically.

This measure relies on the inputs for on-peak hours during summer, winter and intermediate seasons. We selected a grid peak load reduction approach for the year 2050 as the target of this study. This could create higher customer costs or grid operation costs, depending on the utility rate design and other factors. The choice of future load scenario in Cambium and the fact that the future load profile does not include wide-scale electrification could also significantly impact the timing of the peak periods. An analysis of these factors would require modeling the future power system, including the dispatch of demand response resources. That modeling is beyond the scope of this analysis.

Finally, the choice of pre-peak and on-peak durations and the set point offset are applied uniformly across the entire building stock; however, optimal settings likely vary, depending on the climate and the building's characteristics. For example, a long pre-peak duration might not be effective for dwellings with poor exterior insulation because they tend to lose heat quickly.

4.7 Future Work

The results provided in this analysis could be expanded in several ways. First, determining the peak period windows for targeting the load reduction could be based on different future load profiles—in particular, load profiles assuming major electrification of vehicles and space heating. If those load profiles significantly shift the timing of the peak load window, performing new analysis might be warranted. If the timing of the windows shifts only minimally, the uncertainty due to other future changes might outweigh the uncertainty in these results. Second, these results could be recreated using a future building stock. In 2050, some dwellings that exist in today's ResStock model will have been demolished, whereas others will have been retrofitted with new equipment, and new dwellings will have been built. All these changes could impact the results. If deep energy efficiency with significant building envelope improvements is widely adopted, the thermal response of the dwellings might change. Last, a further comparison of the thermal decay of the ResStock models to empirical data could be performed. Ideally, this comparison would result in improvements to the ResStock models. How much these changes would affect the presented results is unclear.

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