ComStock Measure Scenario Documentation: Thermostat Setbacks During Unoccupied Periods

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Acknowledgments

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List of Acronyms

ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BMS	building management system
BPR	base-to-peak ratio
CBECS	Commercial Buildings Energy Consumption Survey
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
HVAC	heating, ventilating, and air conditioning
IECC	International Energy Conservation Code
IES	Illuminating Engineering Society
kBtu	thousand British thermal units
RTU	rooftop unit
TBtu	trillion British thermal units
URDB	Utility Rate Database
VAV	variable air volume

Executive Summary

Building on the 3-year End-Use Load Profiles project to calibrate and validate the U.S. Department of Energy's ResStock™ and ComStock™ models, this work produces national datasets that enable cities, states, utilities, and other stakeholders to answer a broad range of questions regarding their commercial building stock.

ComStock is a highly granular, bottom-up model that uses various data sources, statistical sampling methods, and advanced building energy simulations to estimate the annual sub-hourly energy consumption of the commercial building stock across the United States. The "baseline" model intends to represent the U.S. commercial building stock as it existed in 2018. The methodology of the baseline model is discussed in the ComStock Reference Documentation.

The goal of this work is to develop energy efficiency and demand flexibility measures that cover market-ready technologies and study their mass-adoption impact on the baseline building stock. "Measures" refers to various "what-if" scenarios that can be applied to buildings. The results for the baseline and measure scenario simulations are published in public datasets that provide insights into building stock characteristics, operational behaviors, utility bill impacts, and annual and sub-hourly energy usage by fuel type and end use.

This report describes the modeling methodology for a single ComStock measure scenario—Thermostat Setbacks During Unoccupied Periods—and briefly introduces key results. The full public dataset can be accessed on the ComStock data lake or via the Data Viewer at comstock.nrel.gov. The public dataset enables users to create custom aggregations of results for their use cases (e.g., filter to a specific county or building type).

Key modeling assumptions and technology details are summarized in Table ES-1.

Table ES-1. Summary of Key Modeling Specifications

Technology Description	• This measure implements thermostat setbacks during unoccupied periods in zones where they are not already present. Thermostat setbacks save heating and cooling energy (and in some cases fan energy) by reducing thermal loads during unoccupied periods.
Performance Assumptions	• This measure implements thermostat setbacks of 10°F in heating and 5°F in cooling during unoccupied periods and an optimum start over a 3-hour period before occupancy. Minimum (55°F) and maximum (82°F) values on unoccupied heating and cooling setpoints are also imposed. • An optimum start gradually ramps setpoints from their unoccupied to occupied values for greater thermal comfort once occupancy begins. • The setback ranges, minimum and maximum setpoint values, and optimum start duration are based on a literature review.
Applicability	• The measure is applicable to spaces that do not currently have thermostat setbacks or an operational requirement for continuous space conditioning at fixed setpoints (such as data centers, laboratory spaces, and patient-serving areas for medical care). Hotel guest rooms are also exempted from this measure because of the method by which their occupancy is modeled in ComStock. • **41% stock floor area applicable**
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National annual results for site energy and energy bills are summarized in Table ES-2 and Table ES-3

Table ES-2. Summary of Key Results for Annual Site Energy Savings

"Applicable" buildings are those that receive the upgrade based on criteria defined for this study.

End Use/Fuel Type	Percent Site Energy Savings (All Buildings)	Percent Site Energy Savings (Applicable Buildings Only)	Absolute Site Energy Savings (trillion British thermal units [TBtu])
Natural gas	4.8%	12%	68.6
Electricity	1.2%	2.7%	39.4
Fuel oil	3.9%	11%	2.04
Propane	6.6%	11%	2.81
Total	**2.3%**	**5.6%**	**116**

Table ES-3. Summary of Key Results for Annual Utility Bill Savings

Electricity bill savings in this table are calculated using the mean available electricity rate available for each building. Other electricity rate structures are available in this report and in the public dataset. "Applicable" buildings are those that receive the upgrade based on criteria defined for this study.

End Use/Fuel Type	Percent Savings (All Buildings)	Percent Savings (Applicable Buildings Only)	Absolute Savings (million USD, 2022)
Electricity	0.9%	1.9%	$957
Natural gas	5.6%	14%	$911
Fuel oil	3.9%	12%	$69
Propane	6.9%	12%	$85
Total	1.6%	3.4%	$2,022

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1 Introduction

Thermostat "setbacks" refer to scheduled adjustments of heating and cooling setpoints during periods when the building is generally unoccupied to reduce heating and cooling needs. Heating setpoints are decreased and cooling setpoints are increased. If applied in heating and cooling modes, setbacks typically save heating, cooling, and fan energy (by reducing fan operating hours). The implementation mechanism for thermostat setbacks depends on the building's control system. In buildings with centralized building management systems (BMS), setbacks are implemented through the BMS. In commercial buildings without a centralized BMS, heating, ventilating, and air conditioning (HVAC) are typically controlled through zone-level thermostats, which may be programmable or (less often) non-programmable [1]. Thermostat setbacks can be implemented through a programmable thermostat or by manually adjusting the setpoint in the case of a non-programmable thermostat.

A variety of factors influence the potential energy savings from setbacks, including climate, the building's operating schedule, and the magnitude of the setbacks. In the absence of other variables, buildings with longer unoccupied periods will have greater opportunity for energy savings from setbacks. The distribution of unoccupied periods by time of day and year influences the opportunity for heating and cooling energy savings. For example, unoccupied periods overnight, when outdoor air temperatures are generally cooler, create more opportunity for heating energy savings through setbacks. Unoccupied periods during the day, or for full days over the summer, create more opportunity for cooling energy savings through setbacks. Khalilnejad et al. [2] evaluated the effects of cooling setbacks on commercial buildings through data-driven models. They used a random forest approach to rank the importance of various parameters in predicting energy savings from cooling setbacks and found that cooling degree days and the building's electrical base-to-peak ratio (BPR) were the most influential factors [2]. They also found that buildings with lower BPRs had higher potential savings from cooling setbacks, which the authors said reflected the presence of unoccupied periods with steeper load reductions [2]. It is unclear how exactly Khalilnejad et al. defined the BPR. While a BPR close to 1 likely reflects continuous operations and little opportunity for setbacks, the variation between 0 and 1 in a ratio of minimum to maximum loads (or values at some threshold in a load distribution) does not necessarily reflect the amount of time during which setbacks could be applied.

Khalilnejad et al. [2] analyzed impacts of cooling setbacks on a sample of 432 real commercial buildings (including offices, grocery stores, industrial facilities, educational buildings, and retail stores) in the northeastern and western United States with a data-driven modeling approach. The sample used by Khalilnejad et al. had statistically significant subsets in four climate zones. They found a median of 1.1% electricity savings across the sample from a 1°C setback during unoccupied hours. After a certain threshold, they found diminishing returns with increasing cooling setbacks. They found that across the sample, an 8°C setback resulted in 8.5% electricity savings, whereas increasing the setback to an unrealistically high 22°C resulted in only an additional 1% electricity savings [2]. These diminishing returns are expected since at very high cooling setpoints relative to the location's typical summer temperatures, space cooling is no longer required during unoccupied periods, or it is required for only a small number of hours.

Szydlowski et al. [3] carried out a field study of heating setbacks in six wood-frame office buildings in various conditions at a military base (Fort Devens) in northcentral Massachusetts. The buildings were all built around 1941; two were uninsulated and were deemed to be the least energy efficient. Two others had been renovated 10 or more years prior to the writing of this report and were deemed moderately energy efficient, and two had been renovated more recently and were deemed the most energy efficient in the sample. Buildings with poor envelopes are expected to have higher energy savings with the implementation of heating setbacks. Because of thermostat limitations in most of the buildings, setbacks were implemented only during nighttime hours (14 hours a day) every day, though the buildings were also unoccupied during weekend daytimes. Szydlowski et al. [3] found heating season natural gas use savings of between 14% and 25% through the implementation of setbacks, with a mean savings of 19.2%, relative to constant setpoints in heating. (Note that this does not represent annual natural gas energy savings. The authors defined the heating season as November through March for this location.) Based on results from the one building in which a fully programmable thermostat (enabling weekend setbacks) was present, Szydlowski et al. [3] suggest that 7% additional heating season natural gas savings could have been achieved by adding weekend setbacks in buildings with only nighttime setbacks. In most of the buildings in their sample, setbacks were implemented manually by building occupants, who were advised to use 68°F for occupied conditions and 50°F for unoccupied conditions. Differences in available thermostat features among the buildings made it difficult to extract trends based on building vintage.

The baseline heating setpoint appears to have been 73°F in the study by Szydlowski et al. [3] The study monitored indoor air temperature during the baseline and test periods. The authors reported mean indoor air temperatures of 71°F in the daytime and 64°F at night during the study. The authors say that the slightly lower temperatures during the daytime do not reflect a different heating setpoint but rather highlight the inability of the buildings' furnaces to recover to the occupied setpoint after a nighttime setback. In buildings with a BMS, this problem can be addressed through an "optimum start," which automatically and gradually ramps up (in heating) or down (in cooling) setpoints before the occupied period begins.

Fernandez et al. [4] analyzed the effects of various energy efficiency and demand response measures related to controls on the U.S. commercial building stock. They simulated the measures in nine U.S. Department of Energy (DOE) prototype buildings and applied the savings estimates to five additional prototypes that were like the original nine in locations across all U.S. climate zones. Fernandez et al. then scaled the results to the building stock level for the considered building types. The building types considered represent 51% of commercial building floor area, and 57% of commercial building energy use, in the United States [4]. Fernandez et al. [4] found 7.5% site energy savings from implementing wider thermostat deadbands and nighttime setbacks across their subset of the commercial building stock. They did not disaggregate the energy savings associated with the setbacks and deadbands components of the measure. (The authors also did not specifically note if setbacks were also implemented during unoccupied periods on weekends.) In the baseline used by Fernandez et al. [4] all buildings had heating setpoints of 71°F and cooling setpoints of 73°F during daytime periods, which were modified to 69°F in heating and 75°F in cooling through the measure. The nighttime heating setpoint was reduced from 65°F to 60°F. It appears that Fernandez et al. [4] used a cooling setback temperature of 80°F.

Talami et al. [5] modeled the effects of optimal heating and cooling setpoints on energy consumption in office buildings across a range of climate zones and occupancy rates and patterns. They determined daily optimal heating and cooling setpoints and setbacks for minimizing HVAC energy consumption, subject to thermal comfort constraints. Talami et al. [5] considered occupied setpoints within a range of roughly 67°F to 78°F, with unoccupied heating setpoints in the range of 63°F to 66°F and unoccupied cooling setpoints in the range of 79°F to 82°F. They considered weekdays only in their analysis. Talami et al. [5] found that optimal cooling setpoints were higher during conditions with higher outdoor air temperatures. They also found that lower occupancy rates and longer unoccupied periods throughout the day resulted in more extreme (higher in cooling and lower in heating) optimal setpoints for both occupied and unoccupied periods. Talami et al. [5] carried out their analysis relative to a baseline building with full occupancy throughout the day and with a constant heating and cooling setpoint of 72.5°F. Relative to this baseline (and removing energy savings associated with lower occupancy rates), they found that optimally determined occupied and unoccupied setpoints reduced HVAC energy use by 38.1% [5]. Relative to the same baseline, a conventional strategy of fixed occupied setpoints and setbacks during unoccupied periods reduced HVAC energy use by 11.8% [5].

Thermostat setbacks can be readily implemented, generally at a low cost, through either a BMS or programmable thermostats. ANSI/ASHRAE/IES[1] Standard 90.1-2022 requires that HVAC systems in new buildings be equipped with controls configured for setbacks of at least 10°F in heating and at least 5°F in cooling, if feasible while maintaining humidity control (with an exception for radiant cooling systems) [6]. The low barriers to implementation of thermostat setbacks can also limit the measure's persistence. Setbacks can often be removed or overridden as easily as they can be implemented resulting from occupant dissatisfaction or other reasons [1] [3]. Additionally, Malinick et al. [1] reported that in an evaluation of small businesses who participated in a utility's programmable thermostat installation program, around two-thirds of respondents had been performing manual thermostat setbacks prior to receiving a programmable model.

A potential downside of thermostat setbacks is that if the setpoint is only "set up" once the space is scheduled to become occupied, the space could be uncomfortable while the HVAC system brings the building to the occupied setpoint, and the sudden change in setpoint could lead to high electrical demand, especially if electric resistance is used as a primary or supplemental heat source [7]. A reduction in heating setbacks for air-source heat pumps to mitigate demand charges is explored in the Reduced Thermostat Setbacks for Heat Pumps measure [7]. Additionally, frequent switching between occupied and unoccupied setpoints can cause repeated on/off cycling of HVAC equipment, which has an energy penalty and which causes wear and tear on the equipment [5]. "Optimum start" controls sequences seek to mitigate both effects by more gradually ramping up (or down) thermostat setpoints with the goal of meeting occupied setpoints in the space by the time occupancy starts. ANSI/ASHRAE/IES Standard 90.1-2022 requires optimum start controls in "individual heating and cooling systems" with direct digital controls and setback controls (with an exception for systems serving residential spaces) [6]. In the

[1] ANSI = American National Standards Institute; ASHRAE = American Society of Heating, Refrigerating and Air-Conditioning Engineers; IES = Illuminating Engineering Society

International Energy Conservation Code (IECC), this requirement is applicable to systems delivering a design supply air capacity of at least 10,000 cfm [8].

Cheng et al. [9] evaluated the performance of an optimum start sequence along with a fixed setpoint strategy and a setback with a compressed optimum start over a several-day period in a community college building in Northern California. The optimum start sequence gradually ramped zone setpoints from the 60°F setback value to the 70°F occupied setpoint over a 3-hour period. The compressed optimum start sequence ramped the setpoint up over only 1.5 hours. The compressed optimum start sequence reflected the sequence configured by default in the BMS at the site, which had not been properly tuned [9]. Optimum start sequences often leverage learning algorithms to calculate how quickly a zone or the building changes temperature when the HVAC equipment is operating [9] [10]. Throughout the nights during the test period, the average hourly outdoor air temperatures ranged from 40°F to 60°F. The 3-hour optimum start sequence reduced the peak heating hot water load by 22% to 40% relative to the setback with a compressed optimum start. Heating energy consumption under the two scenarios with setbacks (the optimum start and compressed optimum start) was very similar. The optimum start sequence reduced peak fan power draw by 22% to 41%, and fan energy use by about 10%, relative to the compressed optimum start. Though the study by Cheng et al. [9] reflects a very short time, their results are promising for the potential of appropriately configured optimum start sequences to reduce power demand without a notable penalty on energy consumption.

This measure implements heating and cooling setbacks in buildings that currently have constant setpoints, and among those buildings, it implements a deterministic optimum start sequence in air systems with a design flow greater than 10,000 cfm to align with ANSI/ASHRAE/IES Standard 90.1-2022. A deterministic sequence is selected for tractability of modeling. Deterministic approaches also have the advantage of being more robust and reliable in implementation. Such a deterministic sequence could be implemented through a BMS or through a programmable thermostat, which are either present or could be readily implemented in most buildings. Note that in applications with electric heating, thermostat setbacks can result in electric demand spikes that are undesirable. This phenomenon is explored in another report focused on reducing heating setbacks for air-source heat pumps [7].

2 ComStock Baseline Approach

In the ComStock™ baseline, thermostat setpoints are characterized with square-wave schedules, with one setpoint during occupied periods and potentially a different setpoint during unoccupied periods, representing a thermostat setup/setback. Where setbacks are present, the occupied and unoccupied periods align with the building occupancy schedules. As a starting point, building occupancy schedules in states other than California align with occupancy schedules in the DOE prototype buildings. Schedules from the Database of Energy Efficiency Resources (DEER) prototype models are used for buildings in California [11]. These schedules are then modified in ComStock based on the building's hours of operation.

In the baseline, thermostat setpoint schedules (including occupied and unoccupied setpoints, where applicable) for all building types except hospitals, outpatient healthcare facilities, storage areas in warehouses, and hotels are characterized based on a distribution obtained from data from real building automation systems. The master building automation system dataset includes time-series heating and cooling setpoints. Where sufficient samples are available, distributions are created by building type. For building types with fewer than 25 samples, the entire dataset is used to generate the distribution. The prevalence of thermostat setbacks in each building type is based on data from the 2012 Commercial Buildings Energy Consumption Survey (CBECS), which reports automated and manual setbacks, with an adjustment to account for the expected lack of persistence of manual thermostat setbacks. The proportion of buildings in the baseline having a thermostat setback varies by building type, ranging from 46% for quick-service restaurants to 95% for secondary schools. For buildings represented in the building automation system dataset and having thermostat setbacks, thermostat setback temperatures are populated from distributions in a similar manner to the occupied temperature setpoints [12] [13].

For the storage areas of warehouse buildings, heating setpoints are adjusted from the DOE/DEER prototype building models to better calibrate warehouse energy consumption to data from CBECS 2018, and to engineering judgement [11]. Setpoints from OpenStudio® standards, scaled to individual building hours of operation, are used for hospitals, outpatient healthcare facilities, and hotels.

Some air handling units in the ComStock baseline with airflow over 10,000 cfm have an optimum start control sequence enabled. The optimum start sequence seeks to adjust setpoints over a several-hour period before the building is occupied to ensure comfortable conditions once the building opens.

ComStock equipment sizing in general accounts for design day conditions, not setbacks, so implementation of this measure is not expected to directly affect equipment sizing.

3 Modeling Approach

3.1 Applicability

This measure is generally applicable to all baseline system types. The measure is applied to any zone that currently lacks a setback in a given space conditioning mode (heating or cooling) but has an occupancy schedule (to infer a thermostat schedule) and is not otherwise excluded due to a need for continuous operation at fixed conditions.

This measure will not be applied to spaces with 24/7 operation because of the nature of the building or space, such as data centers and spaces in hospitals requiring constant operation. This measure will also not be applied to hotel guest rooms. ComStock randomly assigns occupants to rooms to achieve a 65% occupancy rate across the building, in line with industry averages [11].

Figure 1 illustrates the applicability of the Thermostat Setbacks measure by building type.

This measure is applicable to 41% of the ComStock floor area, or about 26 billion square feet in weighted floor area.

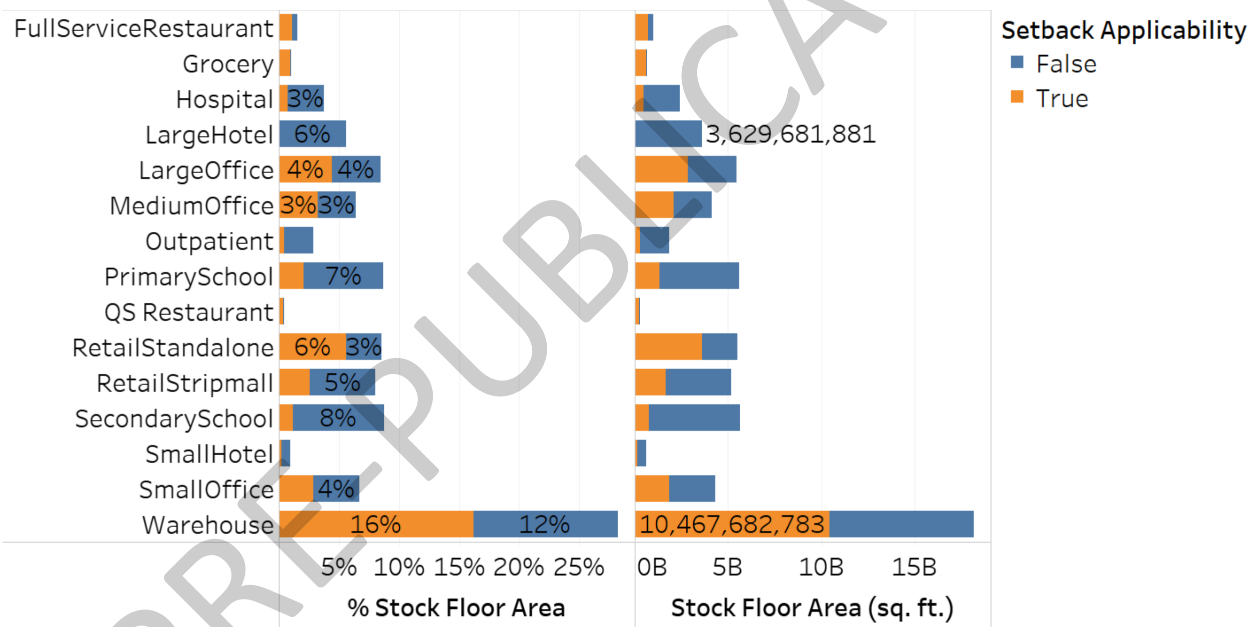

Figure 1. Applicability of Thermostat Setbacks measure by building type.

QS = quick service

3.2 Measure Scenario Modeling Methodology

This measure implements setbacks in both heating and cooling mode in zones within a building that do not currently have setbacks. In zones in which setbacks are being implemented, the measure also implements an optimum start sequence if the air loop serving the zone is subject to requirements for optimum start under the IECC [8]. If a given zone in a building already has a thermostat setback in a given mode (heating or cooling), regardless of the magnitude, the setback will not be adjusted by this measure.

As part of the analysis, we applied setbacks of 10°F in heating, and 5°F in cooling. We also evaluated heating setbacks of 5°F and selected 10°F because it provided greater energy savings while not compromising thermal comfort during occupied periods. Thus, only the run with a 10°F setback in heating and 5°F setback in cooling is included in the dataset.

As part of the setback logic, we imposed a constraint to cap the unoccupied cooling setpoint at 82°F, and we imposed a minimum on the unoccupied heating setpoint of 55°F. The upper limit in cooling corresponds to the upper range of values considered in past studies, and the lower limit in heating is a frequently recommended conservative lower limit to avoid the risk of freezing pipes. The cooling setback magnitude corresponds to the minimum threshold recommended by ANSI/ASHRAE/IES Standard 90.1-2022 and is also sufficient, with an occupied cooling setpoint of 76°F, to approach the upper limit on the unoccupied setpoint. A heating setback of a greater magnitude, such as 15°F, would be capped by the lower limit of 60°F and thus was not considered. **Error! Reference source not found.** summarizes heating and cooling setback magnitudes and unoccupied setpoints reported in the literature and discussed in the Introduction along with the values selected in this study.

Table 1. Setback Magnitudes and Unoccupied Setpoints Reported in the Literature

Source	Range of Heating Setbacks	Range of Cooling Setbacks	Range of Heating Unoccupied Setpoints	Range of Cooling Unoccupied Setpoints	Setback Magnitude Findings
ASHRAE 90.1	At least 10°F in heating	At least 5°F in cooling	N/A	N/A	N/A
Fernandez et al. [4]	9°F	5°F	60°F	80°F	N/A
Khalilnejad et al. [2]	N/A	1.8°F–39°F	N/A	N/A	Diminishing returns in cooling after 14.4°F
Szydlowski et al. [3]	18°F	N/A	50°F	N/A	N/A
Talami et al. [5]	1°F–4°F	1°F–4°F	63°F–66°F	79°F–82°F	Higher optimal cooling setpoints with higher outdoor air temperature; lower occupancy corresponded to more extreme optimal setpoints
ComStock EUSS (this study)	**10°F**	**5°F**	**≥55°F**	**≤82°F**	

In buildings currently lacking setbacks, an optimum start will be implemented in air systems with design flows greater than 10,000 cfm, aligning with the threshold for an optimum start requirement under the IECC [8]. An optimum start will not be implemented in dedicated outdoor air systems. The optimum start will ramp setpoints to occupied values over a 3-hour period, with setpoints increasing by an equal increment each hour. This is based on the approach taken by Cheng et al. [9].

3.3 Utility Bills

ComStock provides utility bill estimates for several fuel types in buildings: electricity, natural gas, propane, and fuel oil. The current implementation represents utility bills circa 2022, which is the most current year of utility data available from the U.S. Energy Information Administration (EIA). This section provides a high-level overview of the methodology behind utility bills in ComStock, but more detailed information is available in the ComStock Reference Documentation [12]. Summary statistics from this implementation are shown in Table 2. Note that ComStock does not currently estimate utility bills for district heating and cooling.

Table 2. Summary Statistics of Utility Bill Implementation in ComStock by Fuel Type

Fuel Type	Minimum Price ($)	Average Price ($)	Maximum Price ($)
Natural gas	$0.007/kBtu ($0.70/therm)[a]	$0.012/kBtu ($1.20/therm)	$0.048/kBtu ($4.80/therm)
Propane	$0.022/kBtu ($2.20/therm)	$0.032/kBtu ($3.20/therm)	$0.052/kBtu ($5.20/therm)
Fuel oil	$0.027/kBtu ($2.70/therm)	$0.033/kBtu ($3.30/therm)	$0.036/kBtu ($3.60/therm)
Electricity	$0.003/kBtu ($0.01/kWh)	$0.035/kBtu ($0.12/kWh)	$3.530/kBtu ($12.04/kWh)

[a] kBtu = thousand British thermal units

Natural gas bills are estimated using 2022 EIA averages by state. 2022 U.S. EIA Natural Gas Prices – Commercial Price and EIA Heat Content of Natural Gas Delivered to Consumers are used to create an energy price in dollars per thousand British thermal units ($/kBtu) [14].

Propane and fuel oil bills are estimated using 2022 EIA averages by state. Residential No. 2 Distillate Prices by Sales Type and EIA residential Weekly Heating Oil and Propane Prices (October–March) and EIA-assumed heat content for these fuels are used to create an energy price in units of $/kBtu [15]. Click or tap here to enter text. Residential prices are used because commercial prices are only available at the national resolution. Additionally, most commercial buildings using these fuels are assumed to be smaller buildings where a residential rate is likely realistic. For states where state-level pricing was available, these prices are used directly. For other states, Petroleum Administration for Defense District (PADD)-average pricing is used. For states where PADD-level pricing is not available, national average pricing is used.

The primary resource for ComStock electric utility rates is the Utility Rate Database (URDB), which includes rate structures for about 85% of the buildings and 85% of the floor area in ComStock [16] . The URDB rates include detailed cost features such as time-of-use pricing, demand charges, ratchets, etc. ComStock only uses URDB rates that were entered starting in 2013, and a cost adjustment factor is applied such that the rates reflect 2022 U.S. dollars.

URDB rates are assigned to ComStock models at the census tract level. The URDB can include several rate structures for a census tract. Instead of attempting to presume any single rate, multiple rates from the model's census tract are simulated; the ComStock dataset includes the minimum, median, mean, and maximum simulated rates for each model.

Many precautions are implemented to prevent less reasonable rates from being applied. This includes removing non-commercial rates, rates with non-building-load keywords (e.g. Security Light, Irrigation, Snow, Cotton Gin), rates where the load profile does not follow any potential min/max demand or energy consumption qualifiers, and rates that cause unrealistically low (<$0.01/kWh) or high (>$0.45/kWh) blended averages. Additionally, any bill that is lower than 25% of the median or higher than 200% of the median is eliminated to avoid extreme bills.

For buildings with no URDB electric utility assigned, or for buildings where none of the stored rates are applicable, the annual bill is estimated using the 2022 EIA Form-861 average prices based on the state each model is located in [17]. While this method does not reflect the detailed rate structures and demand charges, it is a fallback for the 15% of buildings in ComStock with no utility assigned.

3.4 Limitations and Concerns

As discussed previously, thermostat setbacks can lead to spikes in electrical demand, especially for electric heating equipment [7]. This measure seeks to explore the effects of thermostat setbacks across all HVAC equipment types. A separate measure investigates the effects of reduced heating setbacks for heat pumps [7].

The applicability, and thus energy savings, associated with thermostat setbacks in this measure is based on ComStock's understanding and assumptions of thermostat setpoints and setbacks in the existing building stock. Due to the heterogeneity of the building stock, this understanding is imperfect, which will affect the calculated energy savings.

Also as discussed previously, in real buildings, thermostat schedules may not persist due to changes in BMS programming intended to accommodate temporary shifts, or temporary changes to programmable thermostats that are never adjusted back [1]. This measure seeks to quantify the effects of thermostat setbacks if implemented perfectly.

4 Output Variables

Table 3 includes a list of output variables that are calculated in ComStock. These variables are important for understanding the differences between buildings with and without the Thermostat Setbacks During Unoccupied Periods measure applied. These output variables can also be used for understanding the economics of the upgrade (e.g., return on investment) if cost information is available (i.e., material, labor, and maintenance costs for technology implementation).

Table 3. Output Variables Calculated From the Measure Application

Variable Name	Description
com_stock_sensitivity_reports.com_report_has_at_least_one_htg_setback	At least one zone in the baseline building has a heating setback
com_stock_sensitivity_reports.com_report_has_at_least_one_htg_setback	At least one zone in the baseline building has a cooling setback
com_stock_sensitivity_reports.com_report_average_cooling_setpoint_max_c	Maximum of zone average cooling setpoints
com_stock_sensitivity_reports.com_report_average_cooling_setpoint_min_c	Minimum of zone average cooling setpoints
com_stock_sensitivity_reports.com_report_average_heating_setpoint_max_c	Maximum of zone average heating setpoints
com_stock_sensitivity_reports.com_report_average_heating_setpoint_min_c	Minimum of zone average heating setpoints

5 Results

In this section, results are presented both at the stock level and for individual buildings through savings distributions. Stock-level results include the combined impact of all the analyzed buildings in ComStock, including buildings that are not applicable to this measure. Therefore, they do not necessarily represent the energy savings of a particular or average building. Stock-level results should not be interpreted as the savings that a building might realize by implementing the measure.

Total site energy savings are also presented in this section. Total site energy savings can be a useful metric, especially for quality assurance/quality control, but this metric on its own can have limitations for drawing conclusions. Further context should be considered, as site energy savings alone do not necessarily translate proportionally to savings for a particular fuel type (e.g., gas or electricity), source energy savings, or cost savings. This is especially important when a measure impacts multiple fuel types or causes decreased consumption of one fuel type and increased consumption of another. Many factors should be considered when analyzing the impact of an energy efficiency or electrification strategy, depending on the use case.

5.1 Single-Building Measure Tests

In this section, we describe the operation of a large office building in Lawrence, Massachusetts, climate zone 5A, to demonstrate the measure scenario application on a single building. The baseline model uses packaged rooftop units (RTUs) with direct expansion cooling, hot water primary heating coils (supplied by an oil-fired boiler), and electric resistance supplemental heating coils. Outdoor ventilation air is provided directly through the RTUs.

In the baseline, the building has fixed setpoint schedules. Two measure scenarios are considered: one with a 5°F heating setback and one with a 10°F heating setback. In both cases, a 5°F setback is applied in cooling, and an optimum start is implemented over a 3-hour period before morning occupancy, gradually ramping the setpoint up or down to the occupied values. Note that in this case, for purposes of demonstrating the optimum start feature, the 10,000-cfm threshold that is generally used in the measure for implementation of an optimum start, consistent with 2022 ASHRAE 90.1, was not considered.

Figure 2 shows the modified zone-level heating setpoint schedules when applying the measure for a 5°F setback with the building occupancy schedule for a week starting on Monday, January 2. The measure treated the space as occupied if it had an occupancy fraction greater than 0.05. The measure successfully implements the setback during unoccupied hours and an optimum start, during which the temperature gradually ramps to the occupied value during a 3-hour period before occupancy. Figure 3 shows the same plots for a 1-day period to highlight the implementation of the optimum start. Based on the assumed threshold for occupancy, the building is occupied from 10:45 a.m. to 11:30 p.m. on weekdays. (Note that in ComStock, a building's hours of operation are assigned via distributions based on the building type [12].)

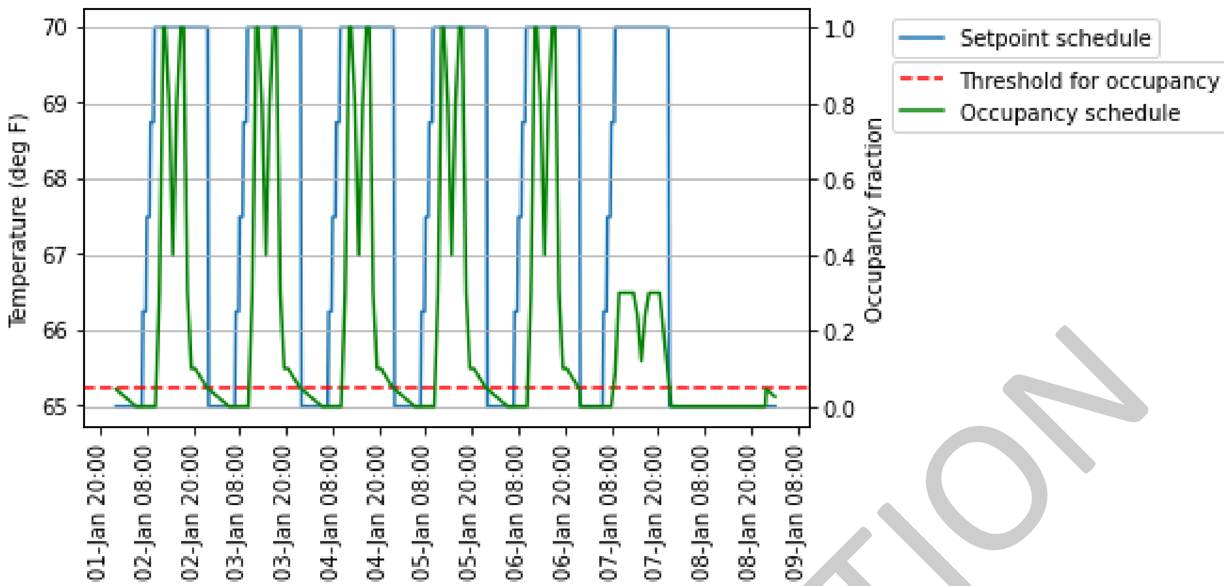

Figure 2. Thermostat heating setpoint schedule with setbacks and building occupancy schedule for the first week of January, 5°F setback

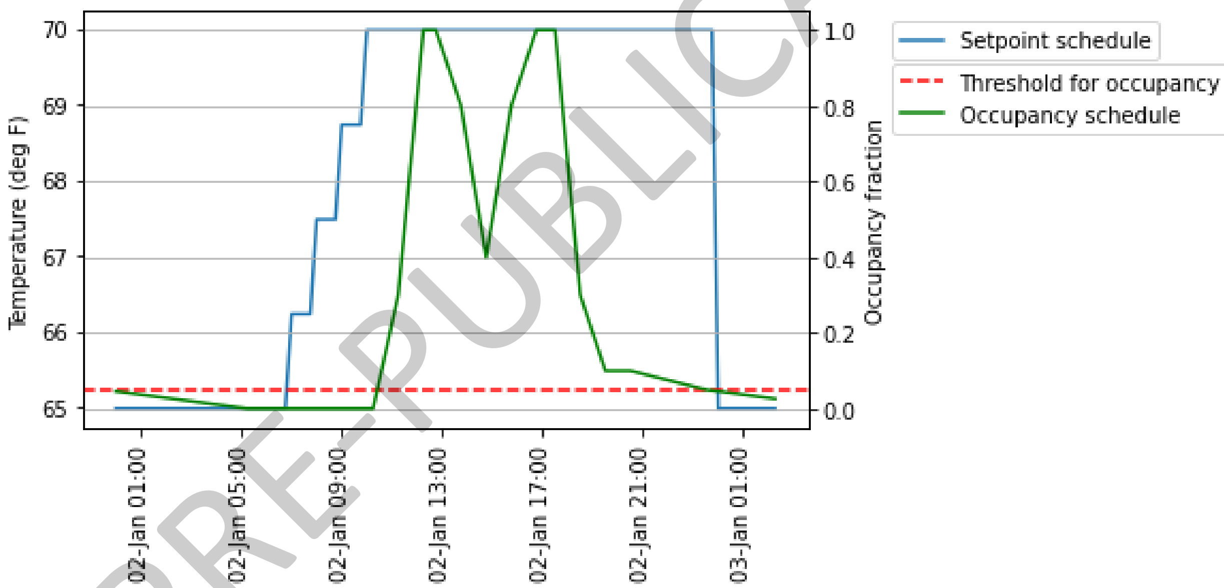

Figure 3. Thermostat heating setpoint schedule with setbacks and building occupancy schedule for one day in January, 5°F setback

Figure 4 shows a comparison of the setpoint schedules under the baseline and measure-modified conditions. Figure 5 shows the same comparison for the cooling setpoint schedules for a week in June. The measure successfully modifies the thermostat schedule and implements an optimum start in cooling mode as well as heating mode. Figure 6 demonstrates the successful implementation of the 10°F heating setback.

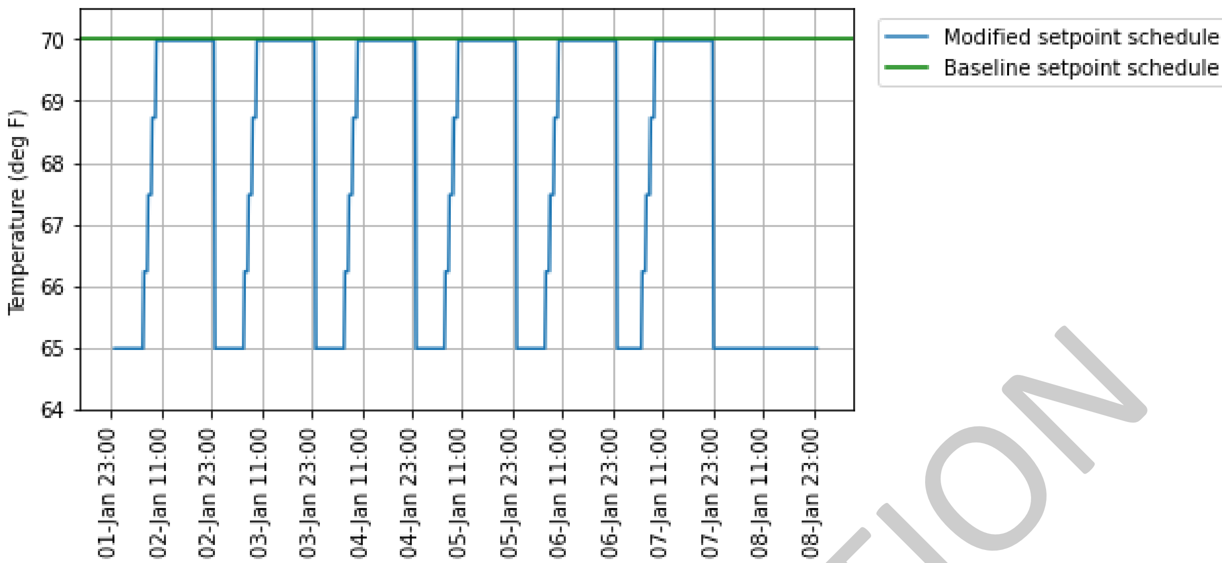

Figure 4. Baseline and modified heating thermostat setpoint schedules for one week in January, 5°F setback case

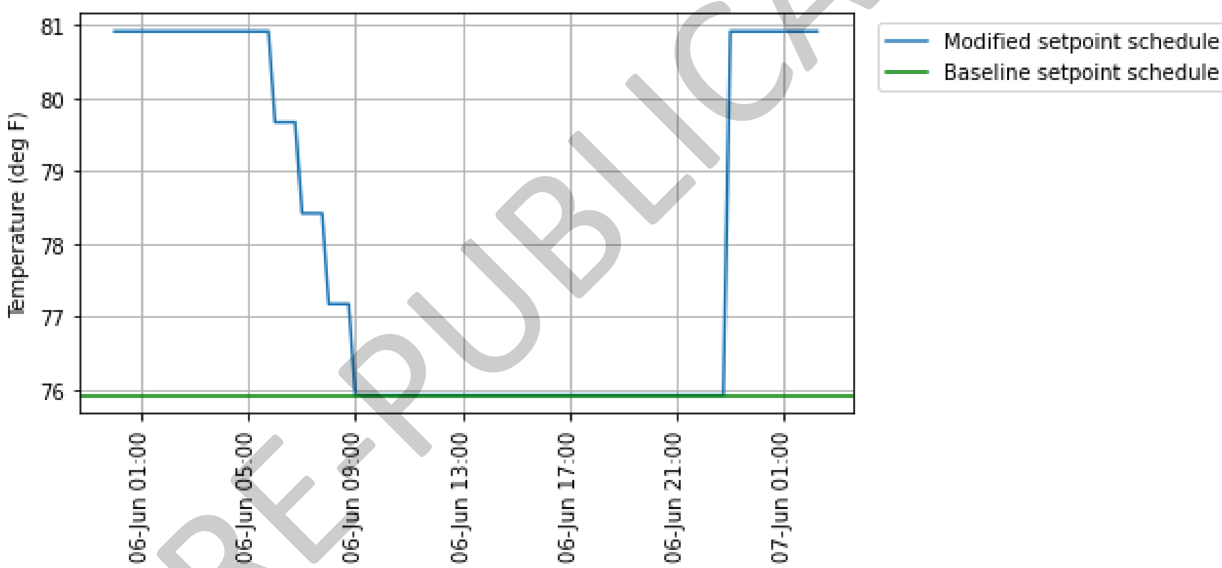

Figure 5. Baseline and modified cooling thermostat setpoint schedules for one week in June

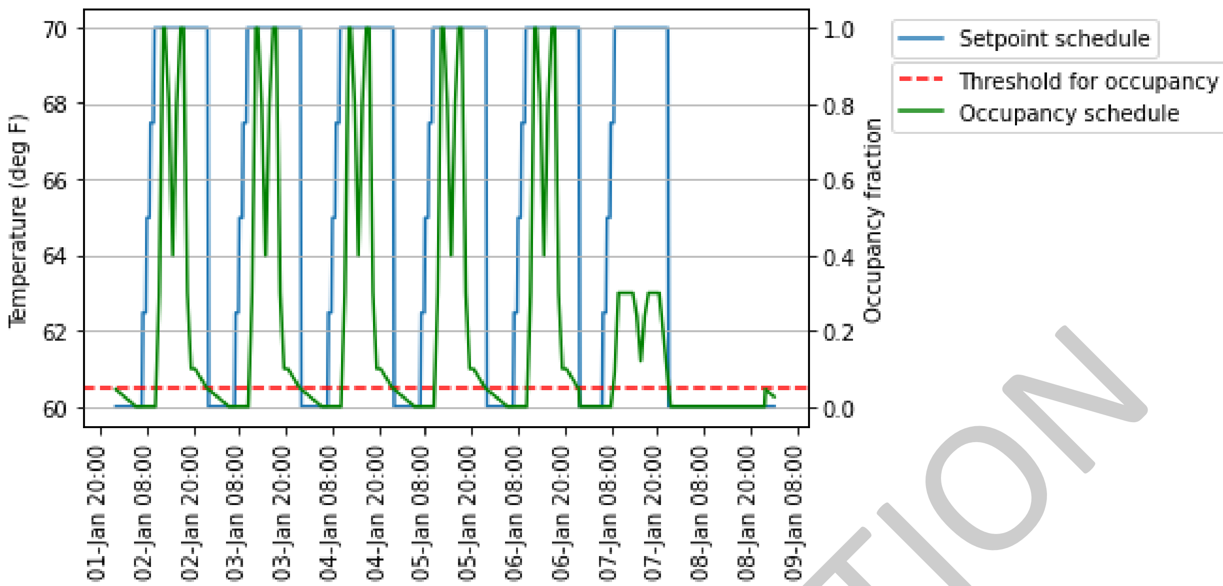

Figure 6. Thermostat heating setpoint schedule with setbacks and building occupancy schedule for one week in January, 10°F setback case

Table 4 shows site energy savings by applicable end use for the two scenarios (5°F and 10°F heating setbacks) of the measure applied to the office building in Massachusetts, relative to the baseline. To reiterate, both scenarios had a 5°F cooling setback and optimum start. This measure results in cooling energy savings of around 9% and fuel oil heating energy savings of 17% to 25%, with greater savings resulting from the higher setback. In this building, the HVAC system fans run throughout the day and night to provide ventilation, whether the heating and cooling setpoints are met. As a result, there are no fan energy savings when applying the measure for this building. In general, fan energy savings from this measure are expected in buildings in which fans cycle on and off during unoccupied periods to meet thermostat setpoints as well as in variable air volume (VAV) systems (due to modulating airflow) and systems with decoupled ventilation and space conditioning. (In the latter case, energy savings would be expected from fans supplying air for space conditioning.) There is a small amount of electric supplemental heating energy use in the baseline, which is virtually eliminated through this measure. Note that in this case, there are no annual peak demand impacts when applying this measure since the peak is set by cooling energy use on a summer afternoon.

Table 4. Summary of Site Energy Savings From Single Building Run of Thermostat Setbacks Measure

End Use/Fuel Type	Baseline	Measure Applied 5°F Heating Setback	Percent Savings 5°F Setback	Measure Applied 10°F Heating Setback	Percent Savings 10°F Setback
Electric cooling (kWh)	153,333	140,278	8.5%	140,000	8.8%
Fuel oil heating (therms)	18,264	15,175	16.9%	13,639	25.3%
Electric heating (kWh)	28	0.0	100%	0.0	100%
Electric fans (kWh)	453,334	453,334	0%	453,334	0%
Annual peak demand (kW)	409	409	0%	409	0%

5.2 Stock Energy Impacts

The Thermostat Setbacks measure demonstrates 2.3% total site energy savings (116 TBtu) for the U.S. commercial building stock modeled in ComStock (Figure 7Figure). The savings contributions by end use and fuel type are summarized in Table 5 and are illustrated in Figure 7. The primary driver of this savings is heating energy, reflecting the larger magnitude of heating setbacks and the fact that heating loads tend to be more prevalent than cooling loads during nighttime unoccupied periods (due to both lower internal loads and lower outdoor temperatures). Many buildings represented in ComStock have a combination of gas and electric heating systems (for example, electric preheat coils before natural-gas-fired primary heating coils). Thus, the combination of heating energy savings from electricity, natural gas, and other heating fuels is more informative than the effects on an individual heating fuel. The overall heating energy use savings among applicable buildings (18%) is like the heating season natural gas energy savings (19%) reported by Szydlowski et al. [3] for a study focusing on buildings with natural gas heating. The authors of that study did not document savings for the rest of the year. Szydlowski et al. [3] considered an unoccupied heating setpoint of 50°F, lower than the unoccupied heating setpoint that resulted in most ComStock buildings after the setback (generally at least 58°F). However, for a given building, diminishing returns are expected from further setpoint reductions after a certain point.

Table 5. Summary of Site Energy Savings From Upgrade Measure Application vs. the ComStock Baseline

End Use/Fuel Type	Percent Site Energy Savings (All Buildings)	Percent Site Energy Savings (Applicable Buildings Only)	Absolute Site Energy Savings (TBtu)
Total natural gas	4.8%	12%	68.6
Total electricity	1.2%	2.7%	39.4
Total heating	7.0%	18%	91.4
Gas heating	7.2%	19%	68.6
Electric heating	7.3%	18%	17.9
Electric fans	1.0%	1.8%	5.8
Electric cooling	2.0%	4.8%	14.8

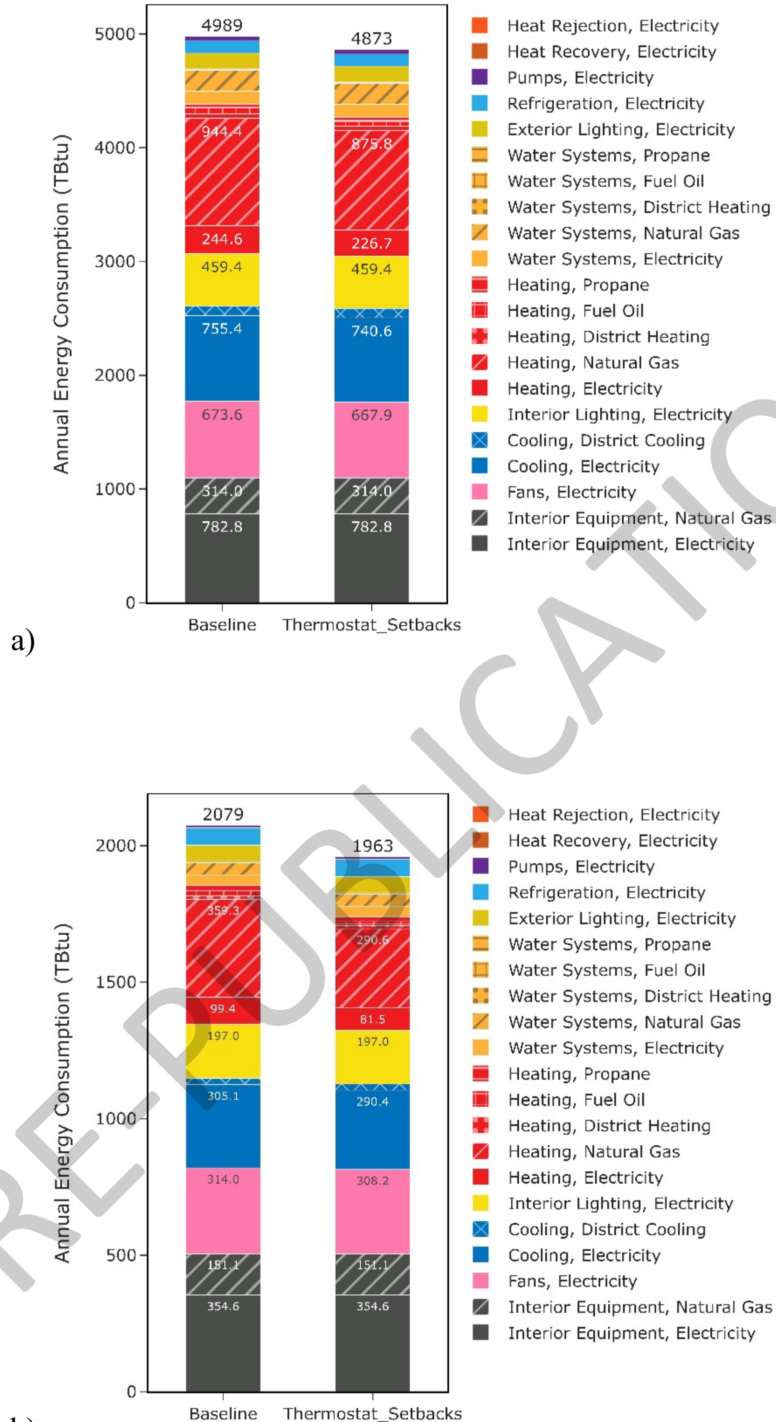

Figure 7. Comparison of annual site energy consumption between the ComStock baseline and the Thermostat Setbacks measure scenario.

Energy consumption is categorized by fuel type and end use. (a) The entire building stock modeled in ComStock; (b) only models applicable to the Thermostat Setbacks measure.

Khalilnejad et al. [2] reported electricity savings from 1.1% to 8.5% for cooling setbacks of about 2°F to 15°F. The rate of electricity savings observed in this study for applicable buildings (2.7%) falls close to the lower end of that range. Note that this analysis accounts for setbacks implemented in both heating and cooling, resulting in both heating and cooling electricity savings, while Khalilnejad et al. [2] addressed cooling setbacks only. The fraction of overall building electricity attributable to heating or cooling is highly variable and depends on climate and magnitude of non-heating and cooling electrical loads. Fernandez et al. [4] reported 7.7% site energy savings for thermostat setbacks and expanded deadbands across a sample intended to represent the commercial building stock (accounting for the effects of setbacks already present). Fernandez et al. [4] did not disaggregate the energy savings by expanded deadband vs. setback. It is expected that this value would be higher than the site energy savings identified for setbacks in ComStock (2.3% across the overall sample, including non-applicable buildings), due to the inclusion of the widened deadbands. Additionally, Fernandez et al. [4] assumed fixed thermostat setpoints across the building stock in both the baseline and "setback" cases, whereas ComStock populates the baseline setpoints in a probabilistic way, which is also reflected in this measure case (since the setback applied was fixed with maximum and minimum temperatures).

The relatively low magnitude of fan energy savings (1.8% among applicable buildings) reflects the fact that in many buildings to which this measure was applicable, the baseline fan schedule was configured for 24/7 operation for ventilation [2], which was not altered by the heating setback. This reduces the availability of fan energy savings in such models and therefore reduces the aggregate stock fan energy savings potential. This is investigated in more detail in Section 5.6.

5.3 Thermal Comfort Impacts

To ensure that the measure resulted in operation within the intended temperature bounds, distributions of hours in which cooling and/or heating setpoints are unmet in the underlying building energy models were examined. In general, temperature setbacks can potentially create problems with a system's ability to "recover" to the occupied setpoint at the desired time. The optimum start sequence implemented is intended to help mitigate that. Results for "unmet hours" are shown in Figure 8. In heating, the median number of unmet hours increases from around 1 hour in the baseline to 8 hours in the measure case. The values also increase at the 75th percentile but are not extreme. In both heating and cooling, the median values in the baseline are not visible because they are very close to 0, the 25th percentile value. The results in cooling are similar. This confirms that the setback strategy implemented does not compromise thermal comfort by notably increasing unmet hours.

[2] For most building types in ComStock, operation of air handling units during unoccupied periods is based on distributions reflecting an industry-provided building automation system (BAS) data set.

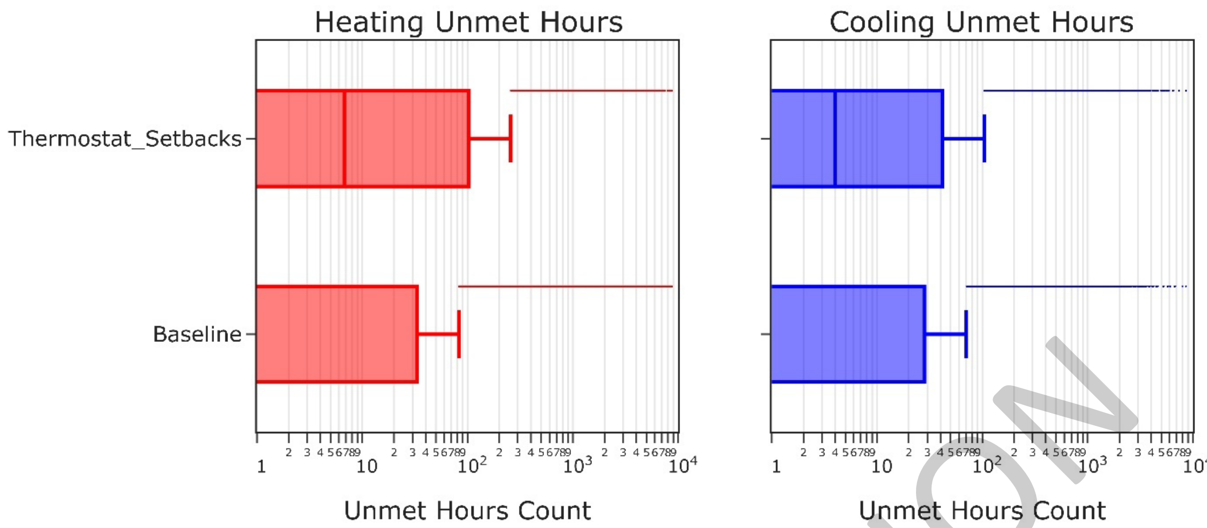

Figure 8. Distributions of time (in hours) with heating or cooling setpoints unmet for the baseline and Thermostat Setbacks scenarios shown on a boxplot. Note that that the horizontal axis is a logarithmic scale.

5.4 Stock Utility Bill Impacts

The stock-level impacts of the Thermostat Setbacks measure on utility bills are summarized in Table 6 and Figure 9. Note that ComStock considers all potential electricity rates for a given location, and thus the results are presented based on maximum, mean, and minimum electricity rates. The Thermostat Setbacks measure results in utility bill savings of 1% to 2% across the three cases, which corresponds to about $2 billion in all cases. The end-use utility bill savings for electricity and natural gas generally track the energy savings of those commodities for both applicable buildings and the full sample. Note that many utility rate tariffs for electricity in commercial buildings incorporate demand and time-of-use charges, and electricity savings from this measure would typically occur at off-peak times.

Table 6. Summary of Key Results for Annual Utility Bill Savings

Electricity bill savings in this table are calculated using the mean available electricity rate available for each building. Other electricity rate structures are available in this report and in the public data set. “Applicable” buildings are those that receive the upgrade based on criteria defined for this study.

End Use/Fuel Type	Percent Savings (All Buildings)	Percent Savings (Applicable Buildings Only)	Absolute Savings (million USD, 2022)
Electricity	0.9%	1.9%	$957
Natural gas	5.6%	14%	$911
Fuel oil	3.9%	12%	$69
Propane	6.9%	12%	$85
Total	**1.6%**	**3.4%**	**$2,022**

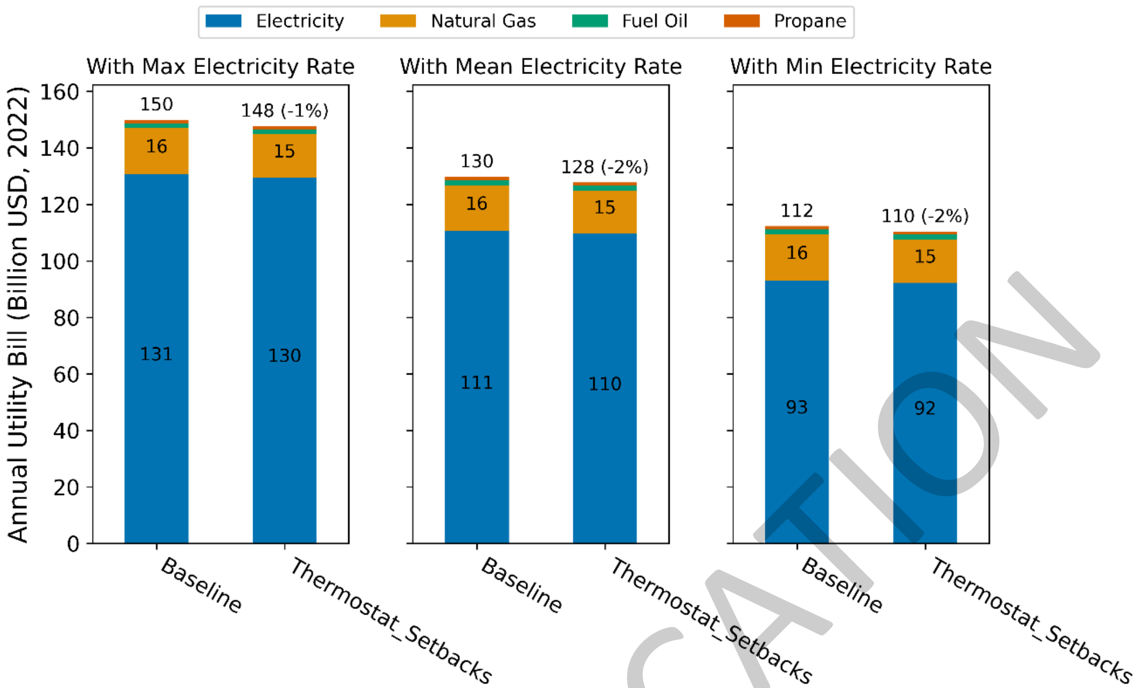

Figure 9. Annual utility bill impacts using the max, mean, and minimum bills across available rate structures for buildings for the baseline and Thermostat Setbacks scenarios.

Includes buildings not applicable to the Thermostat Setbacks scenario.

Figure 10 shows distributions of utility bill savings by end use using the mean electricity rate for each building. As discussed previously, in buildings with heating from multiple fuel sources (electricity and natural gas, for example), implementation of this measure can shift heating energy use and cost from one source to another. The negative areas of the distributions for natural gas, fuel oil, and propane reflect this trend. The effects of this measure on heating fuel distribution are investigated in Section 5.5. Figure 11 shows distributions of utility bill savings by climate zone. There is not a particular trend in the utility bill savings distribution based on climate zone. About 7.5% of the applicable sample experiences a penalty in utility bills because of this measure. In most of this subset, this penalty is small (73% of this subset has a penalty of less than 2%). This utility bill penalty is generally driven by an increase in electricity demand charges. Thermostat setbacks can result in increases in electric demand during morning warmup, which in some cases can result in a new and higher peak.

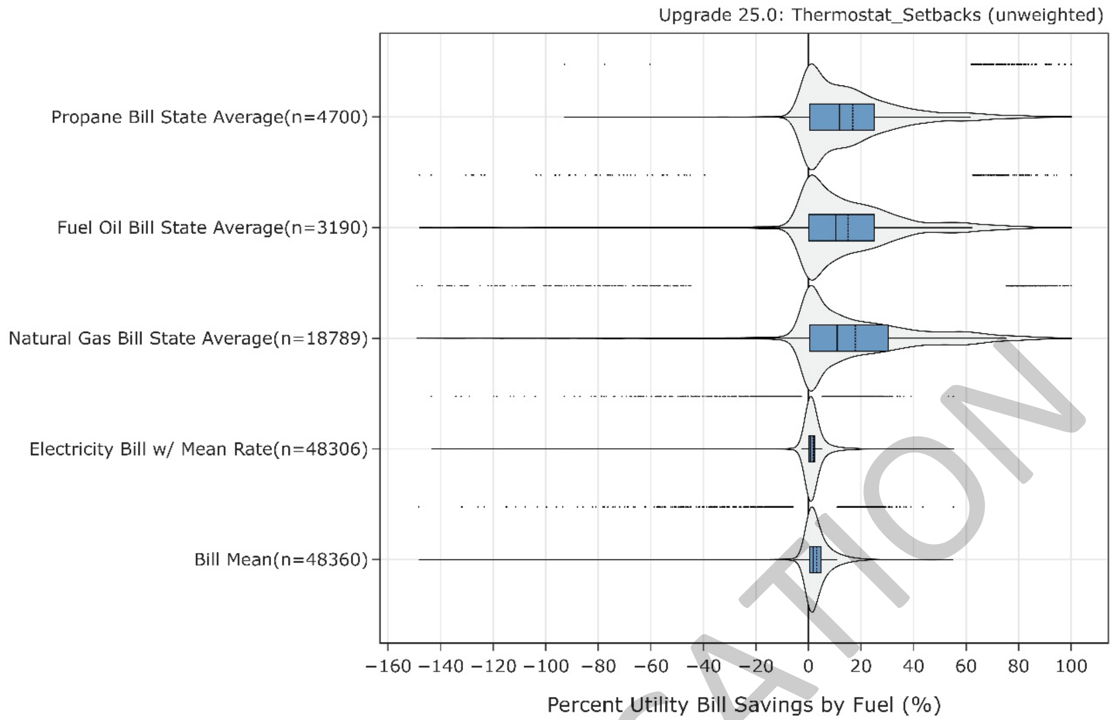

Figure 10. Percentage annual utility bill savings distribution for ComStock models with the Thermostat Setbacks scenario by fuel type.

Results shown in this plot are the savings for the average available utility rate per building. The data points that appear above some of the distributions indicate outliers in the distribution, meaning they fall outside 1.5 times the interquartile range. The value for *n* indicates the number of unweighted ComStock models that were applicable for energy savings for the fuel type category.

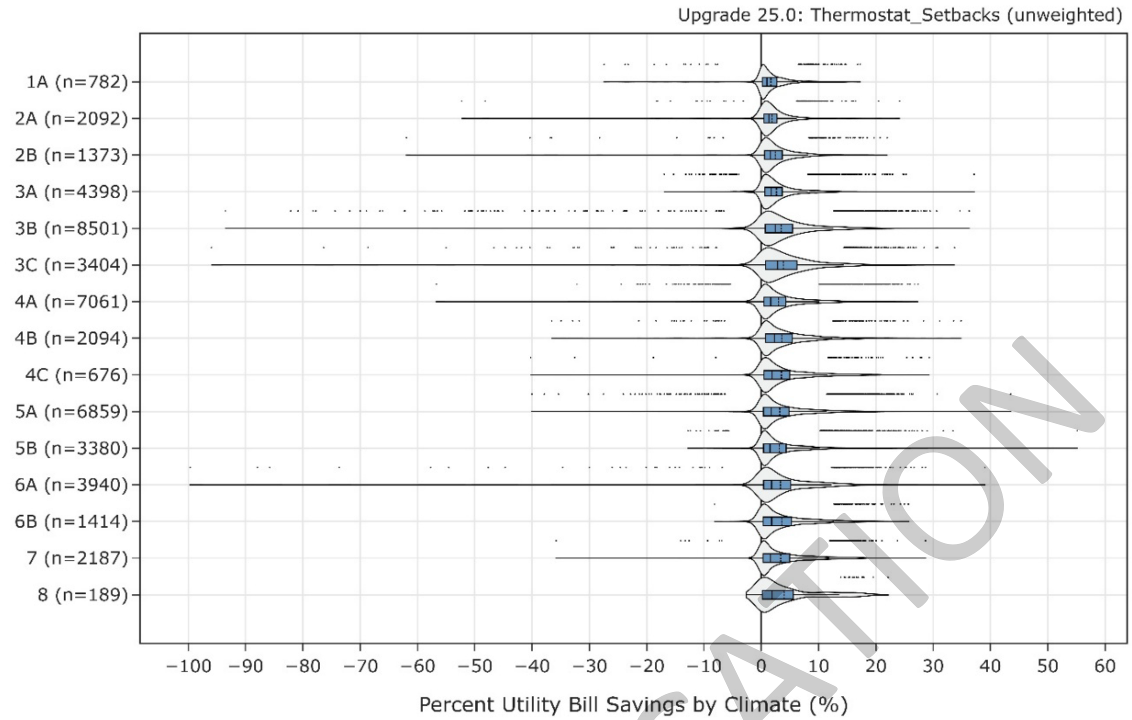

Figure 11. Percentage annual utility bill savings distribution for ComStock models with the Thermostat Setbacks scenario by climate zone.

Results shown in this plot are the savings for the average available utility rate per building. The data points that appear above some of the distributions indicate outliers in the distribution, meaning they fall outside 1.5 times the interquartile range. The value for *n* indicates the number of unweighted ComStock models that were applicable for energy savings for the fuel type category.

5.5 Site Energy Savings Distributions

This section discusses site energy consumption for quality assurance/quality control purposes for the Thermostat Setbacks measure. Note that while site energy savings can be informative for these purposes, it does not always correspond directly to outcomes of greater practical significance, such as source energy savings or reduced energy bills. It is important for a decision maker to consider which metrics best align with their specific goals or context.

Figure 12 shows distributions of the percentage site energy use savings from the Thermostat Setbacks measure by end use. Heating (across various fuel types) and heat recovery (in a smaller subset of buildings) are the end uses with the largest savings rates. Heat recovery energy savings results from reduced heating loads through the thermostat setbacks. The measure also results in cooling and fan energy savings, at lower levels, as shown in the aggregate results. The small changes in refrigeration energy use observed in some buildings result from changes in indoor conditions because of the setback. The small change in interior equipment energy use in some buildings (33) is the result of a known bug in ComStock regarding schedules for elevator operation [18]. This has very minimal impact on the overall energy savings distributions.

As discussed previously, implementation of the thermostat setback can result in changes in distribution of heating energy use by fuel type in buildings with multiple types of heating systems (for example, electricity and natural gas). In Figure 12, all heating fuels have some negative area of savings distribution, but very few buildings in the sample (only 2.2% of applicable buildings) had negative aggregate heating energy savings. Figure 13 shows a distribution of heating energy savings among most of the sample for which this value was non-negative. The largest share of buildings have heating energy savings from this measure of less than 10%. Buildings with proportionately very high (greater than 70%) heating energy savings from this measure tend to be those with low heating energy use in the baseline, which magnifies the effects of small absolute changes. This effect is illustrated in Figure 14, which shows boxplots of absolute heating energy savings for buildings with non-negative savings, those with high savings, and those with negative savings. Those with high proportionate savings have much lower absolute heating energy savings than the full sample, indicating low absolute heating energy use in the baseline. Those with negative savings also have low magnitudes of absolute savings. In some cases, increased operation of heating coils to recover zone temperatures after a large setback can contribute to higher energy use, especially if the coils are now undersized for the "recovery" load. (In ComStock, thermostat setbacks are not considered when sizing heating coils.) This effect was very limited in the sample.

The pump energy end use has a small portion of negative savings distribution. Figure 15 shows boxplots of pump energy savings for buildings with positive and negative pump savings, respectively. As shown in Figure 15, the median value of negative savings is very low, indicating that this effect is primarily due to small fluctuations. Figure 16 shows distribution of site energy savings by fuel type, which generally mirrors the trends shown in Figure 12.

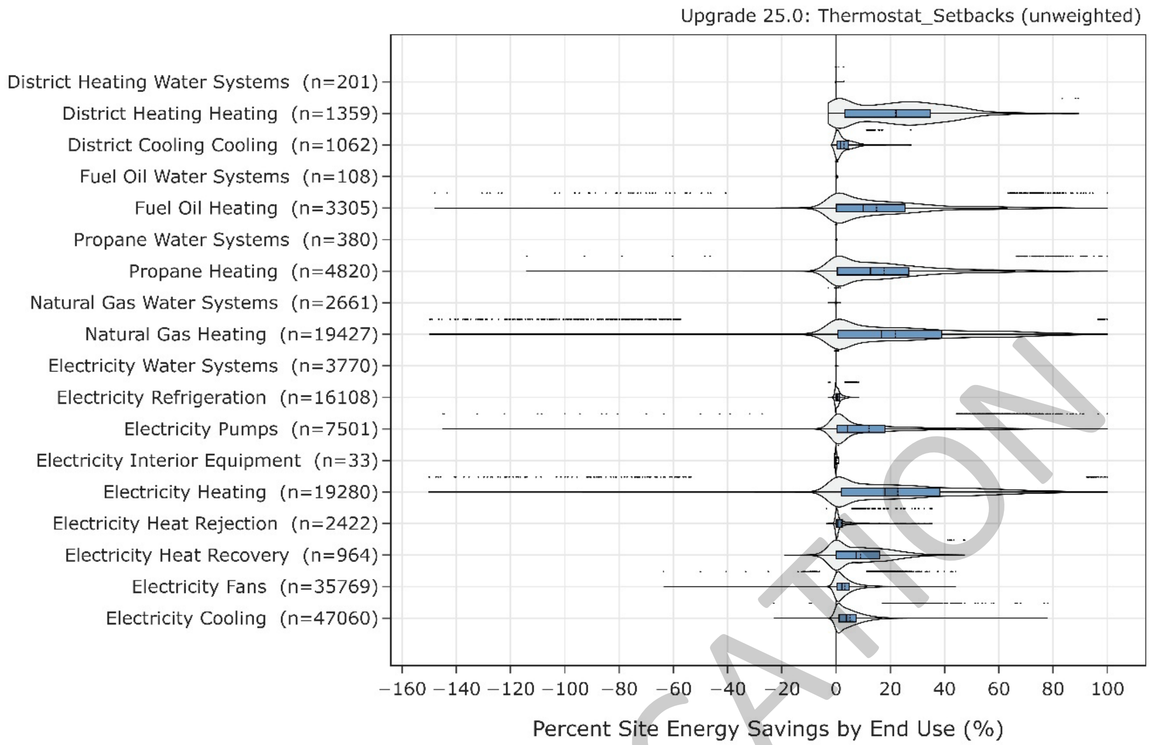

Figure 12. Percentage site energy savings distribution for ComStock models with applied measure scenario by end use and fuel type.

The data points that appear above some of the distributions indicate outliers in the distribution, meaning they fall outside 1.5 times the interquartile range. The value for n indicates the number of ComStock models that were applicable for energy savings for the fuel type category.

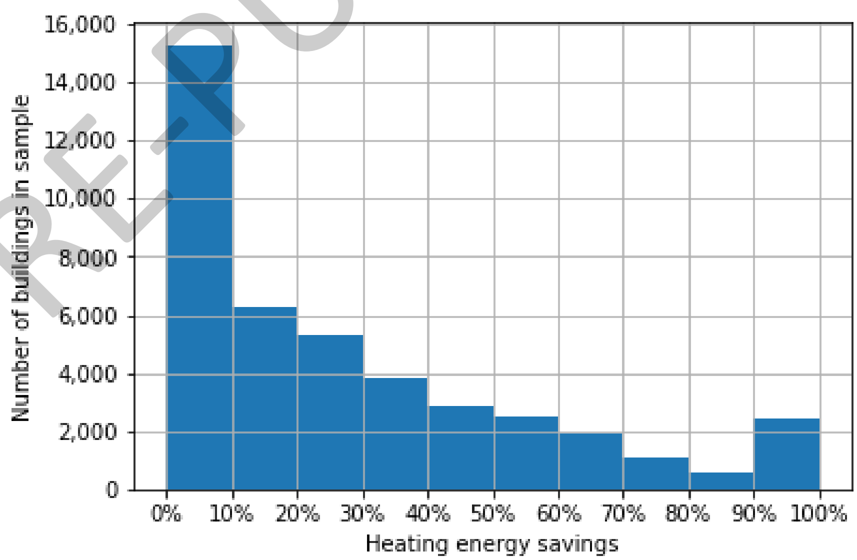

Figure 13. Distribution of heating energy savings among buildings in sample with non-negative energy savings from Thermostat Setbacks measure

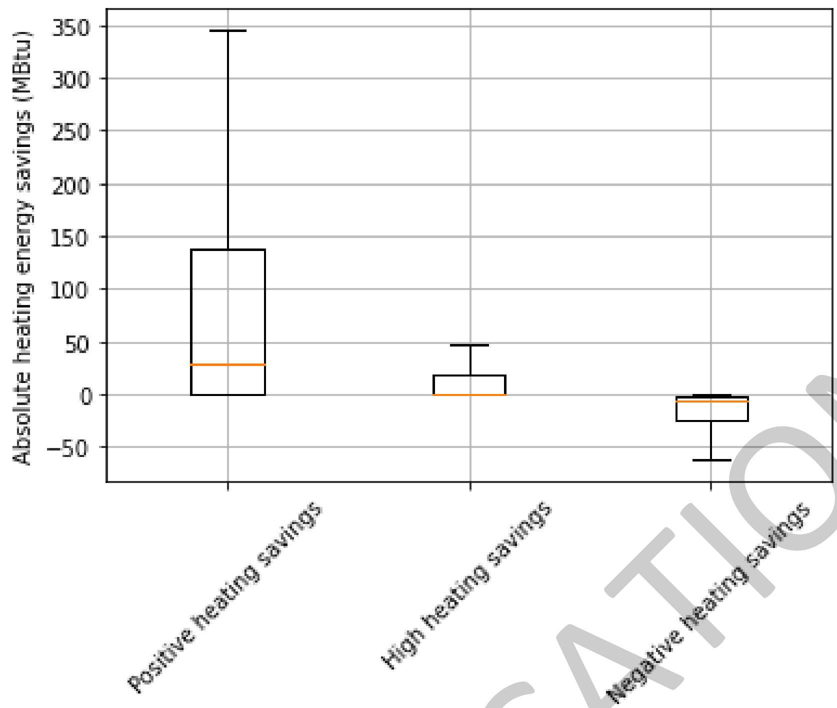

Figure 14. Boxplots of absolute heating energy savings for the full sample with non-negative savings, buildings with high savings (>70%), and buildings with negative savings

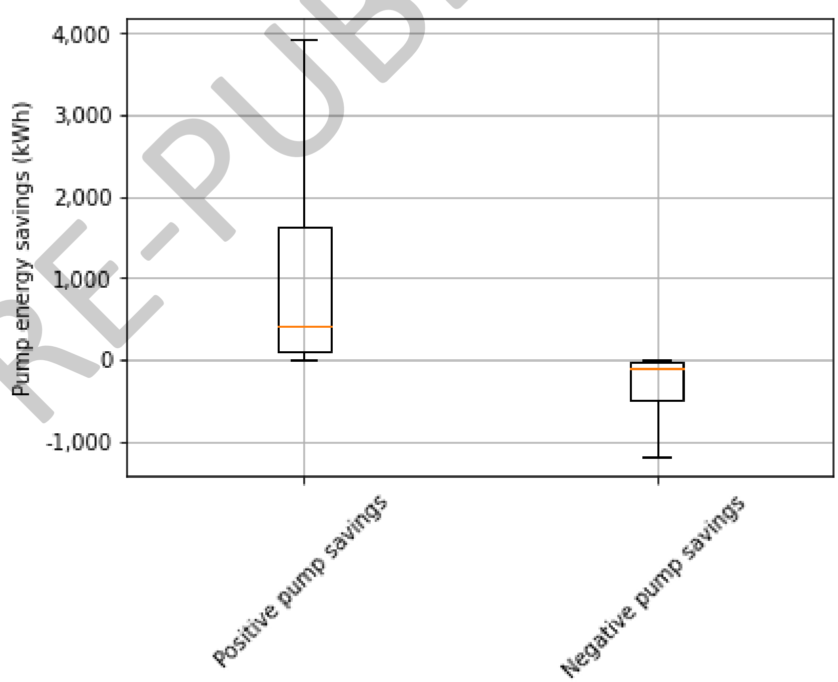

Figure 15. Boxplots of pump energy savings for buildings disaggregated by the nature of the savings

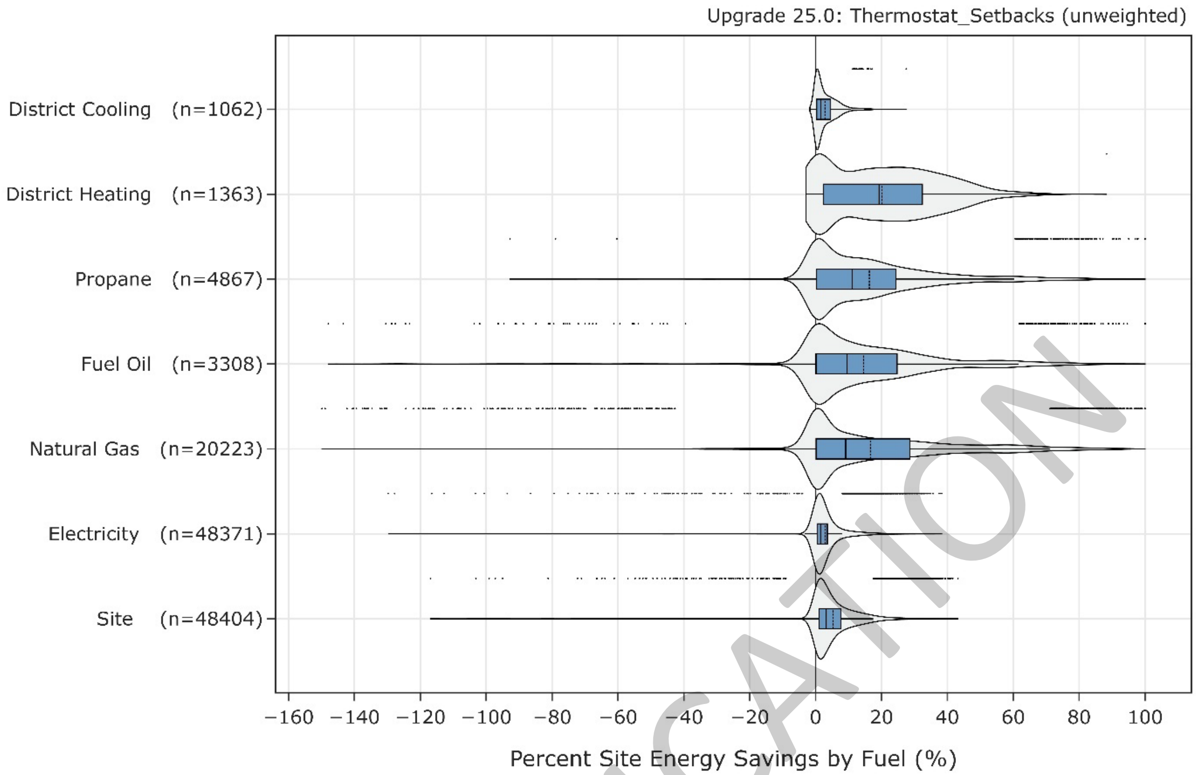

Figure 16. Percentage site energy savings distribution for ComStock models with the applied measure scenario by fuel type.

The data points that appear above some of the distributions indicate outliers in the distribution, meaning they fall outside 1.5 times the interquartile range. The value for n indicates the number of ComStock models that were applicable for energy savings for the fuel type category.

Figure 17 shows distributions of site energy use savings from this measure by building type. Primary and secondary schools have some of the highest savings from this measure, reflecting their relatively high number of unoccupied hours during which the setback can occur. Hospitals and hotels, which have limited space types to which this measure is applicable, have low energy savings. (Guest room spaces in hotels and patient-serving and laboratory areas in hospitals were not eligible for this measure).

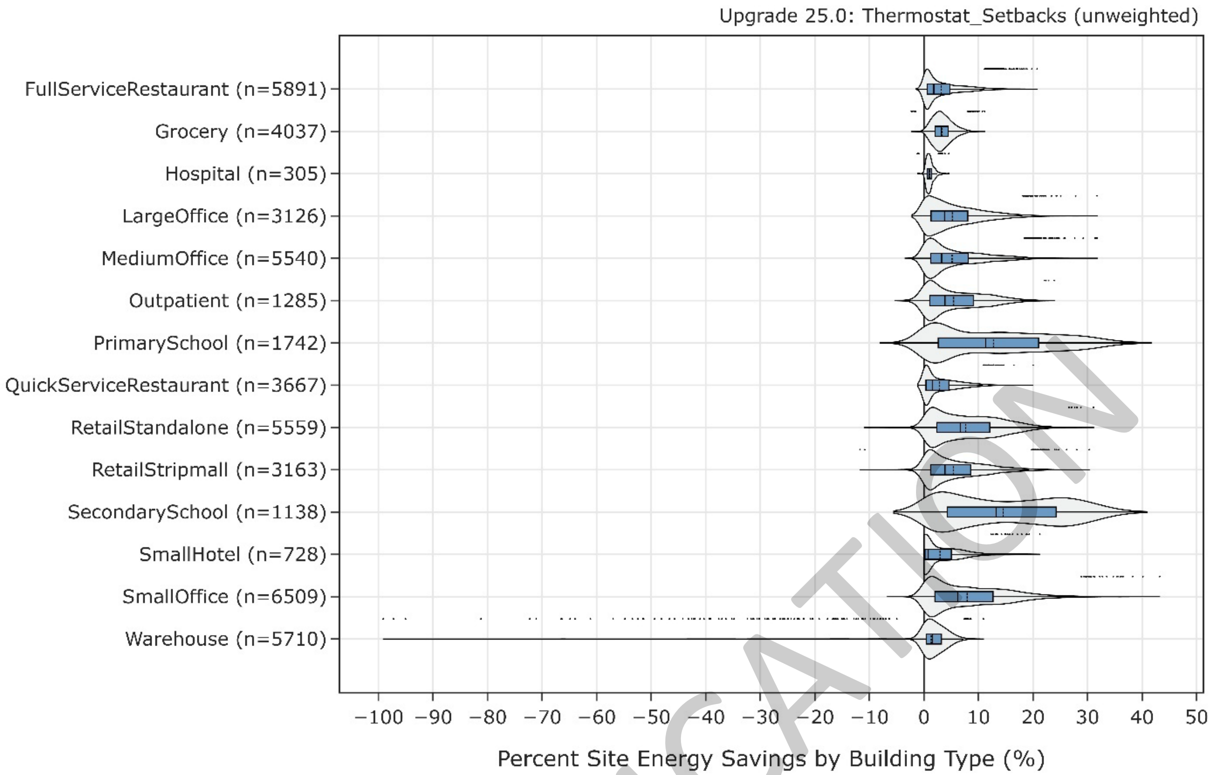

Figure 17. Percentage site energy savings distribution for ComStock models with the applied measure scenario by building type.

The data points that appear above some of the distributions indicate outliers in the distribution, meaning they fall outside 1.5 times the interquartile range. The value for n indicates the number of ComStock models that were applicable for energy savings for the fuel type category.

5.6 Fan Energy Savings

As discussed previously, the effect of this measure on fan energy savings is also influenced by the control strategies for AHUs in unoccupied periods present in the underlying models. About 34% of the applicable sample has fan energy savings from this measure of less than 1%. Figure 18 shows a distribution of this portion of the sample by nighttime fan control strategy. Over 60% of this subset of the sample has fans operating continuously at night. In this scenario, the effect of setbacks on fan energy use is expected to be minimal, since fans will continue to operate with or without a cooling or heating load. (In VAV systems with this control strategy, fans may ramp down in the absence of a heating/cooling load.) Additionally, a subset of the buildings grouped in the “default/no change” category also have this control strategy of continuous nighttime fan operation. The data presented reflect the status of a ComStock measure that is used to (in some cases) alter the nighttime fan control strategy. That measure is applied to buildings with AHU-based HVAC systems, and is not applied to building types (hotels, hospitals, outpatient medical facilities, and schools) not represented in an underlying building automation system data set that informs the control strategy application [12].

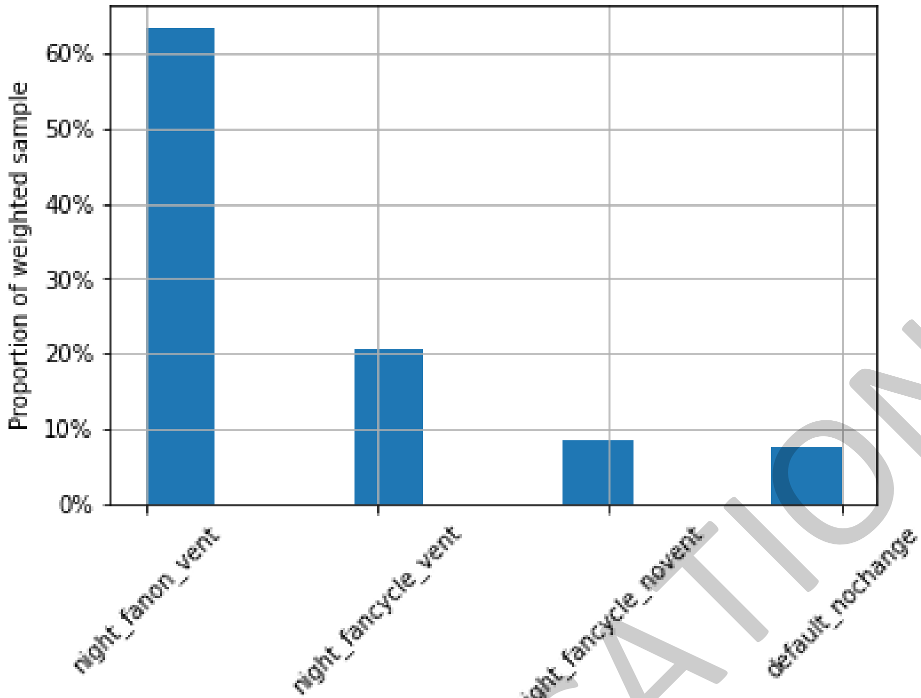

Figure 18. Distribution of buildings with low fan energy savings by nighttime fan control strategy

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Appendix A.

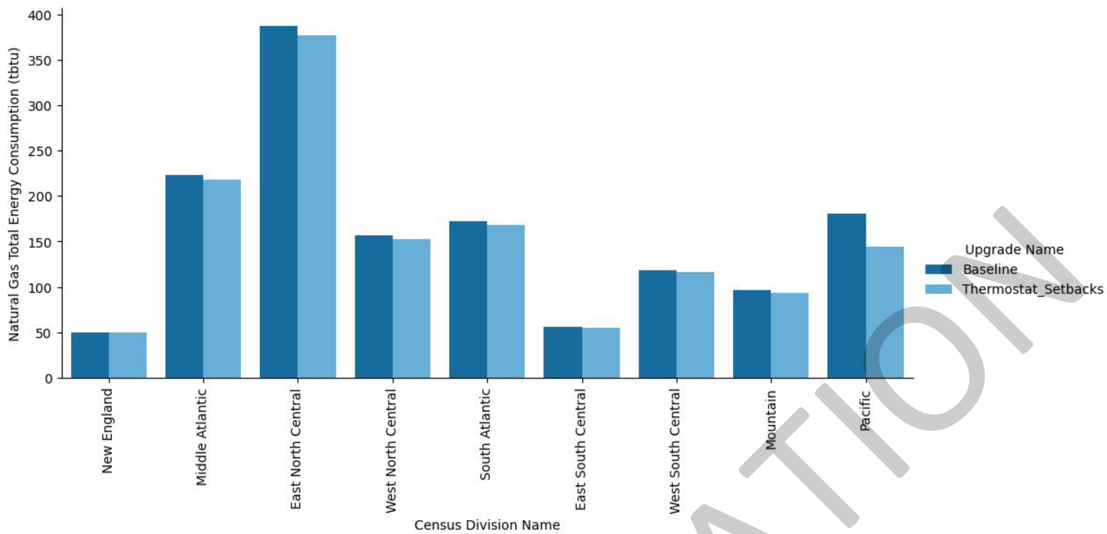

Figure A-1. Site annual natural gas consumption of the ComStock baseline and the measure scenario by census division

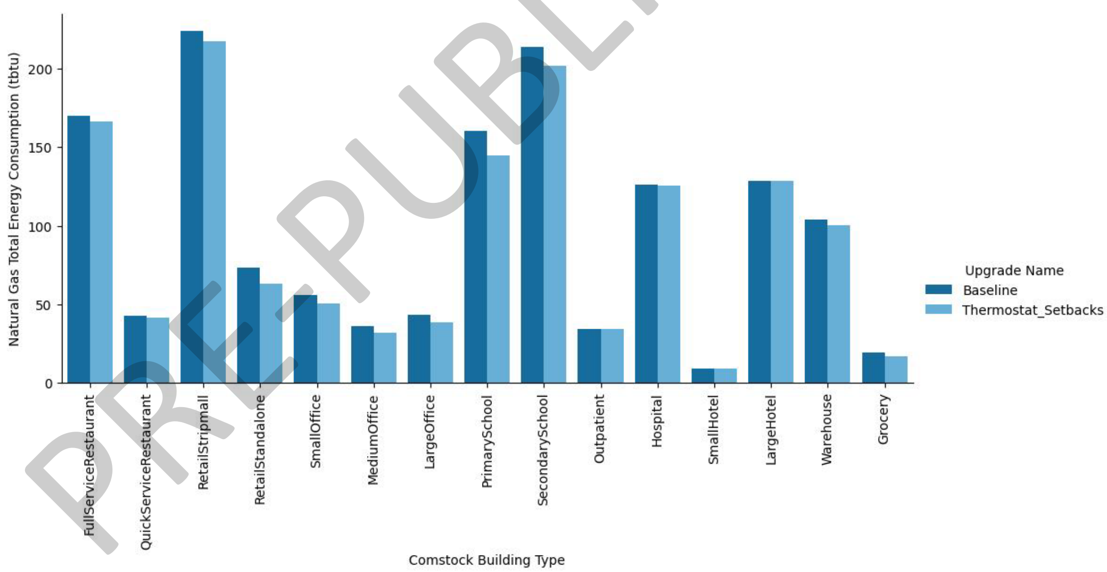

Figure A-2. Site annual natural gas consumption of the ComStock baseline and the measure scenario by building type

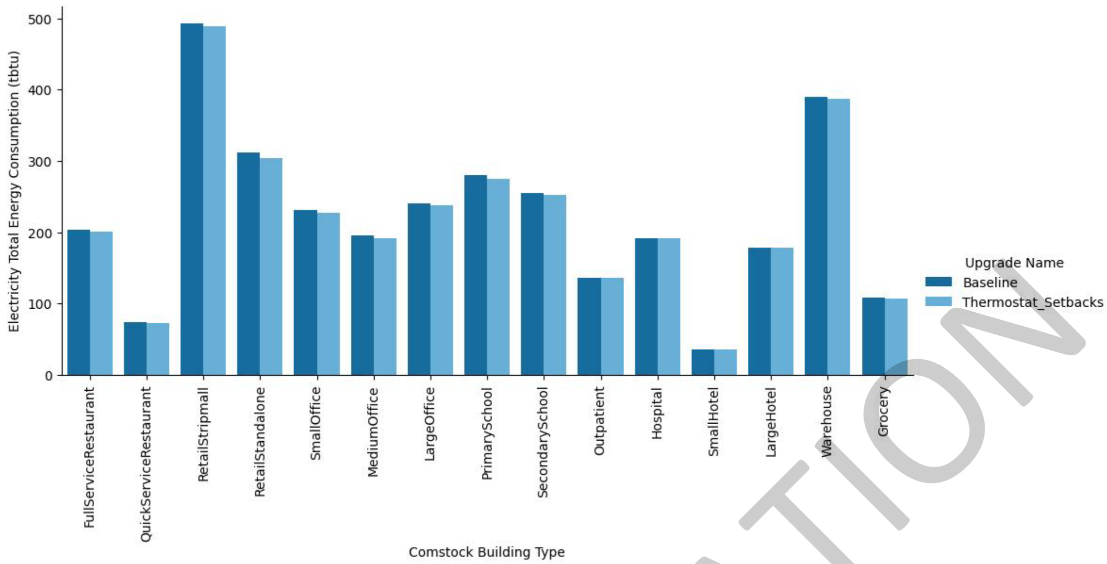

Figure A-3. Site annual electricity consumption of the ComStock baseline and the measure scenario by building type

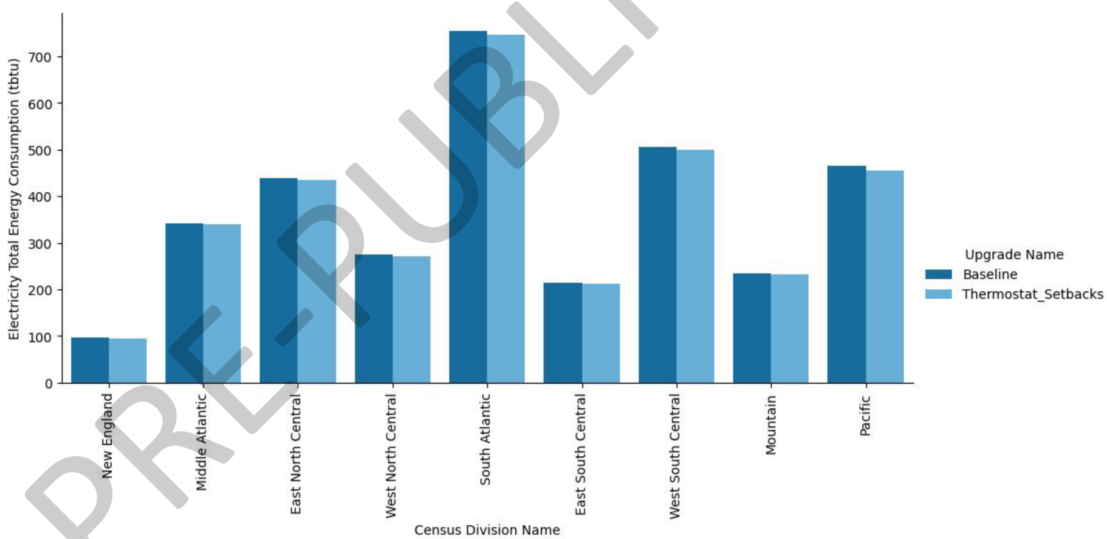

Figure A-4. Site annual electricity consumption of the ComStock baseline and the measure scenario by census division