ComStock Measure Documentation:

Heat Pump Rooftop Units With Higher Compressor Lockout Temperature for Heating

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Acknowledgments

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List of Acronyms

CBECS	Commercial Buildings Energy Consumption Survey
COP	coefficient of performance
DX	direct expansion
EIR	energy input ratio
EUI	energy use intensity
HP-RTU	heat pump rooftop unit
HVAC	heating, ventilating, and air conditioning
kW	kilowatt
LRMER High RE	long-run marginal emissions rate high renewable energy
MMT	million metric tons
NREL	National Renewable Energy Laboratory
PSZ-AC	packaged single-zone air conditioner
RTU	rooftop unit
TBtu	trillion British thermal units
URDB	Utility Rate Database

Executive Summary

Building on a 3-year effort to calibrate and validate the U.S. Department of Energy's ResStock™ and ComStock™ models, this work produces national datasets that empower analysts working for federal, state, utility, city, and manufacturer stakeholders to answer a broad range of questions regarding their commercial building stock.

ComStock is a highly granular, bottom-up model that uses multiple data sources, statistical sampling methods, and advanced building energy simulations to estimate the annual energy consumption (at subhourly resolution) 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 and results of the baseline model are discussed in the final technical report of the End-Use Load Profiles project.

The goal of this work is to develop energy efficiency and demand flexibility end-use load shapes that cover high-impact, market-ready (or nearly market-ready) measures. "Measures" refers to various "what-if" scenarios that can be applied to buildings.

An *end-use savings shape* is the difference in energy consumption between a baseline building (or collection of buildings) and a building with an energy efficiency or demand flexibility measure applied. It results in a time-series profile broken down by end use and fuel (electricity or on-site gas, propane, or fuel oil use) at each time step, as well as annual aggregations.

This report describes the modeling methodology for a single end-use savings shape measure—heat pump rooftop units (HP-RTUs) with higher compressor lockout temperature for heating—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 case (e.g., filter to a specific county).

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

Table ES-1. Key Modeling Specifications

Technology Description	• This study investigates replacing existing gas or electric resistance RTUs with standard efficiency heat pump RTUs, but with higher compressor lockout temperature of 32°F for heating (compared to 0°F used in the other ComStock HP RTU studies). • Our previous work ("Heat Pump Rooftop Units With Standard Performance," released in November 2024) analyzing HP-RTUs with standard performance used the setting of 0°F compressor lockout temperature and followed common specifications (e.g., two stage cooling, single stage heating, electric resistance supplemental heating) of HP-RTUs in the market. • There are two common methods used to lock out compressor operation. In most cases, the controller has a low-pressure cutoff switch for the suction pressure to maintain compressor reliability. Additionally, many but not all units also have a switch that shuts off the compressor based on a certain outdoor air temperature (i.e., lockout temperature). In this case, the product offers a range of temperatures so that the unit's lockout temperature can be set during the commissioning stage. • Understanding the stock-level impact of HP-RTU with 0°F compressor lockout temperature (i.e., HP-RTUs with 0°F lockout temperature applied to 34% of the total stock floor area) may be more ideal than how we expect installers to commission equipment in reality. It is also unclear if there is a reasonable lockout temperature we can apply to heat pumps modeled in our numerous models across different sizes of buildings and under different climates because the lockout setting in the field is based on heating, ventilating, and air conditioning (HVAC) sizing, local commissioning practices, and local control setup in addition to real or perceived limitations of heat pumps. • Because we already published a dataset with 0°F lockout temperature, the data released in this analysis will be a comparable dataset to the previous dataset.
Performance Assumptions	• This report is part of a series and will primarily discuss the additional changes of lockout temperature of the standard efficiency HP-RTUs, whereas a comprehensive overview of the performance assumptions can be found in the original documentation ("Heat Pump Rooftop Units With Standard Performance," released in November 2024).
Applicability	• The HP-RTU measure is applicable to ComStock models with either gas furnace RTUs ("PSZ-AC with gas coil") or electric resistance RTUs ("PSZ-AC with electric coil"). • Buildings that do not have RTUs are not applicable, nor are kitchen spaces. • This accounts for about 34% of the ComStock floor area.
Release	2024 Release 2: 2024/comstock_amy2018_release_2/

National annual results for site energy, greenhouse gas emissions, and energy bills are summarized in Table ES-2 to Table ES-4. Savings shown in these tables are comparisons between the baseline (0°F lockout temperature) and 32°F lockout temperature scenario. Note: The impact on electricity usage when replacing applicable HVAC systems with standard-performance HP-RTUs depends on several factors: improved cooling efficiency with HP-RTUs, improved fan efficiency with HP-RTUs, improved heating efficiency with HP-RTUs when switching from electric resistance heating to heat pump heating, and additional electricity usage when replacing gas heating with HP-RTUs. Additionally, buildings in hotter climates with electric resistance heating will see annual electricity usage savings from HP-RTU upgrades, while buildings in colder climates with gas heating will experience higher electricity usage as heating demand is now met by electricity through heat pump heating.

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

Fuel Type	Absolute Savings (TBtu)	Baseline Total (All Buildings, TBtu)	Percent Savings (All Buildings)	Baseline Total (Applicable Buildings Only, TBtu)	Percent Savings (Applicable Buildings Only)
Natural Gas	277.6	1467.5	18.9	543.4	51.1
Electricity	-93.5	3052.0	-3.1	1085.1	-8.6

Table ES-3. Key Results for Annual Greenhouse Gas Emissions Savings

Fuel Type	Absolute Savings (MMT CO_2e)	Baseline Total (All Buildings, MMT CO_2e)	Percent Savings (All Buildings)	Baseline Total (Applicable Buildings Only, MMT CO_2e)	Percent Savings (Applicable Buildings Only)
Natural Gas	18.5	98.0	18.9	36.3	51.1
Electricity	-10.7	231.4	-4.6	81.0	-13.2
Fuel Oil	0.6	5.5	11.3	0.7	86.1
Propane	1.2	2.7	43.5	1.6	71.5
Total	9.7	337.7	2.9	119.7	8.1

Electricity emissions avoided in this table are calculated using Cambium Long-Run Marginal Emissions Rate (LRMER) High Renewable Energy (RE) Cost 15-Year grid scenario. Other grid scenarios are presented in this report and in the public dataset.

Table ES-4. Key Results for Annual Utility Bill Savings

Fuel Type	Absolute Savings (Billion USD, 2022)	Baseline Total (All Buildings, Billion USD, 2022)	Percent Savings (All Buildings)	Baseline Total (Applicable Buildings Only, Billion USD, 2022)	Percent Savings (Applicable Buildings Only)
Natural Gas	3.0	16.7	18.0	6.2	48.6
Electricity	-2.8	103.8	-2.7	38.0	-7.5
Fuel Oil	0.2	2.1	11.4	0.3	86.1
Propane	0.4	1.0	44.1	0.6	71.2
Total	0.8	123.6	0.7	45.1	1.8

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.

Compared to the baseline scenario, HP-RTUs with a 32°F lockout temperature show higher site energy usage compared to HP-RTUs with a 0°F lockout temperature. The difference between the two lockout temperature scenarios mostly comes from the heating choice between heat pump heating and supplemental electric resistance heating depending on the lockout temperature as depicted in Figure 4. The results shown in this study only reflect standard performance HP-RTUs, as opposed to advanced performance units. This was intentionally designed to evaluate the implications of higher lockout temperature on the low end of the HP-RTU performance spectrum. In order to assess the impact of this upgrade more comprehensively, other factors such as life cycle cost analysis of the HP-RTU system should also be considered.

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1 Technology Summary

Many technologies are used to generate the heat provided by commercial building heating, ventilating, and air conditioning (HVAC) systems. Packaged rooftop units (RTUs) are currently used to heat 37% of commercial buildings in the United States (representing 50% of the total commercial floor space) [1]. Heat pumps currently provide space heating for only approximately 11% of commercial buildings (representing 15% of the total floor area) [1].

Heat pumps offer an energy-efficient electric option for commercial building space heating. Based on 2018 Commercial Buildings Energy Consumption Survey (CBECS) data estimates, fewer than 15% of commercial buildings utilize heat pumps for space heating equipment, and when they are in use, they are more commonly found in the warmer southern region of the United States [1].

Heat pump technologies are available on the market today to replace existing gas-fired or electric resistance RTU systems. Most manufacturers offer heat pump rooftop units (HP-RTUs) with compressors capable of providing up to 105 kW (30 tons) of cooling capacity. There is a remarkable opportunity for the growth and widespread adoption of this technology, and expansion of the field could have an extensive impact on building fuel switching efforts.

In some climates, HP-RTUs require the use of supplemental (or backup or auxiliary) heating systems, as a heat pump's heating capacity (using the compressor) generally reduces with lower outdoor temperature, and current practice often sizes the refrigeration system to cooling, not heating. Additionally, below a certain threshold, compressor-based heat pump heating is not available and supplemental heating (typically with electric resistance heating) should be used. Supplemental heating types vary, but electric resistance is a common choice for many applications. The heating operation of an all-electric HP-RTU can be categorized into three scenarios: (1) heating demand is present and the compressor-based heat pump meets all demand without using supplemental heating, (2) heating demand is present but compressor-based heat pump heating cannot meet all the demand, so both the heat pump and supplemental heating operate together to meet the demand, and (3) the compressor is locked out due to unfavorable operating conditions and the supplemental heating meets all the demand.

For the third operating scenario above, there are two possible scenarios where the compressor gets locked out. The first is when the product offers a range of temperatures (with default setting) so that the actual product's "lockout temperature" can be set during commissioning. This means if the outdoor air temperature falls below the compressor lockout temperature, the heat pump is disabled and supplemental heating is exclusively used to address the entire heating load. The second scenario is when there is no setting for the lockout temperature but the controller shuts off the compressor based on the suction pressure level. This lockout occurs on low pressure, and its purpose is to maintain compressor reliability. The correlation between a certain outdoor air temperature versus the suction pressure shut-off was hard to find from the manufacturer spec sheets.

Our previous work ("Heat Pump Rooftop Units With Standard Performance," released in November 2024) analyzing HP-RTUs with standard performance used the setting of 0°F compressor lockout temperature and followed the common specifications of prevalent products in the current market. Because there is uncertainty in the lockout temperature values that will be selected in the field during equipment commissioning, we want to understand the implications of this setting on the building stock. However, it is also unclear if there is a reasonable lockout temperature we can apply to heat pumps modeled in our numerous models across different sizes of buildings and under different climates. Thus, this analysis includes a sensitivity analysis to show the impact of different lockout temperatures (i.e., 0°F, 5°F, 10°F, 17°F, and 32°F) using a reduced set of stock models. It also provides the full stock modeling results (via data release) for one of the temperatures (32°F). Because we already published a dataset with 0°F lockout temperature, the data released in this analysis will be a comparable dataset to the previous dataset.

This document primarily discusses changes to the compressor lockout temperature, whereas a comprehensive overview of the fundamental modeling methodology and background, including applicability, sizing scheme, and other key assumptions, can be found in the original documentation, "Heat Pump Rooftop Units With Standard Performance."

2 ComStock Baseline Approach

The characteristics of existing RTUs in ComStock, the U.S. Department of Energy's commercial building stock model, are based on a combination of when the buildings were built and how the HVAC equipment has been assumed to have been updated over time. This is described in detail in the ComStock Documentation report [2]. HVAC equipment performance is assumed to meet the energy code requirements in force at the time and place of installation. For this reason, most existing RTUs are modeled as constant air volume with single-speed compressors and either gas or electric resistance supplemental heating.

The in-force energy code for the ComStock baseline is shown as a percentage of applicable floor area in Figure 1. Applicable floor area for this analysis includes ComStock buildings with "PSZ-AC with gas coil" and "PSZ-AC with electric coil" HVAC system types (where PSZ-AC stands for packaged single-zone air conditioner). Most ComStock baseline RTUs follow energy code requirements from the early 2000s. Other energy efficiency features, such as demand control ventilation, energy recovery, and economizer control, are only applied to baseline ComStock RTUs if required by the in-force energy code. The ComStock workflow checks the necessary characteristics of each RTU to determine whether the feature is required. Similarly, heating, cooling, and fan efficiencies are set based on the in-force code year. For models with the "PSZ-AC with electric coil" HVAC system type, the ComStock baseline uses electric resistance coils that have an efficiency of 100%. For models with the "PSZ-AC with gas coil" HVAC system type, the ComStock baseline generally uses a gas furnace efficiency of around 80%.

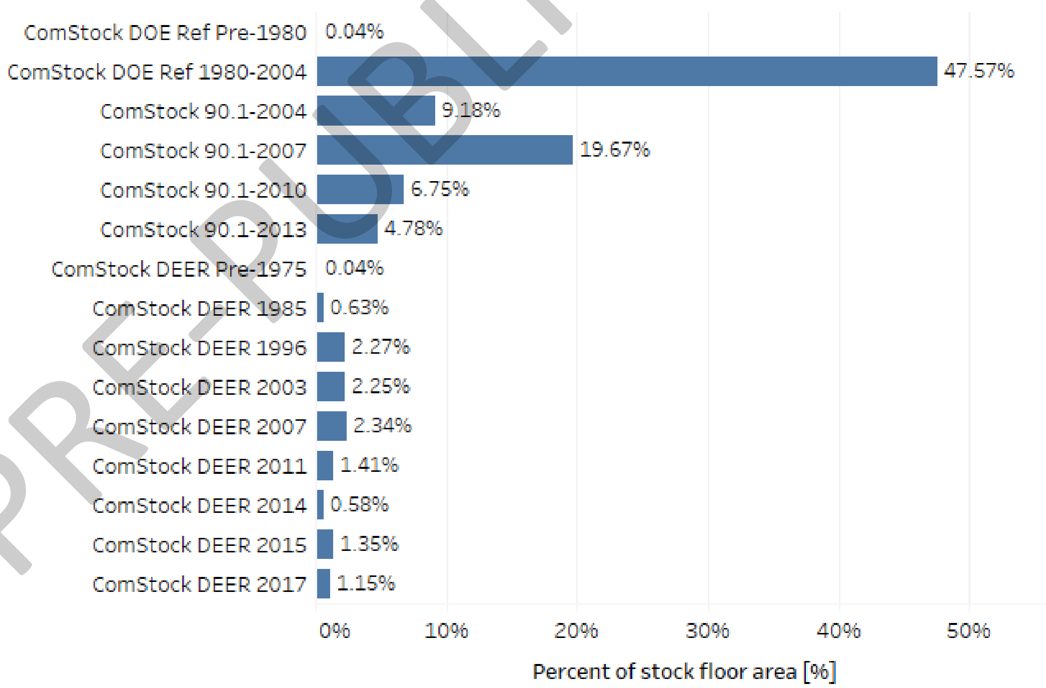


Figure 1. ComStock baseline in-force energy code followed as a percentage of applicable floor area.

Applicable floor area includes ComStock buildings with "PSZ-AC with gas coil" and "PSZ-AC with electric coil" HVAC system types. DEER stands for Database for Energy Efficiency Resources, which represents building characteristics for California models following Title 24.

3 Modeling Approach

3.1 Applicability

The HP-RTU measure is applicable to ComStock models with either gas furnace RTUs ("PSZ-AC with gas coil") or electric resistance RTUs ("PSZ-AC with electric coil"). This accounts for about 34% of the ComStock floor area (Figure 2). ComStock HVAC distributions are informed by the 2012 CBECS. The methodology for interpreting CBECS data to create HVAC probability distributions for ComStock is discussed in the ComStock Documentation report [2]. The measure is not applicable to space types that directly serve kitchens, spaces that are unconditioned, or RTUs with outdoor air ratios above 65% (due to an EnergyPlus® bug with cycling operation).

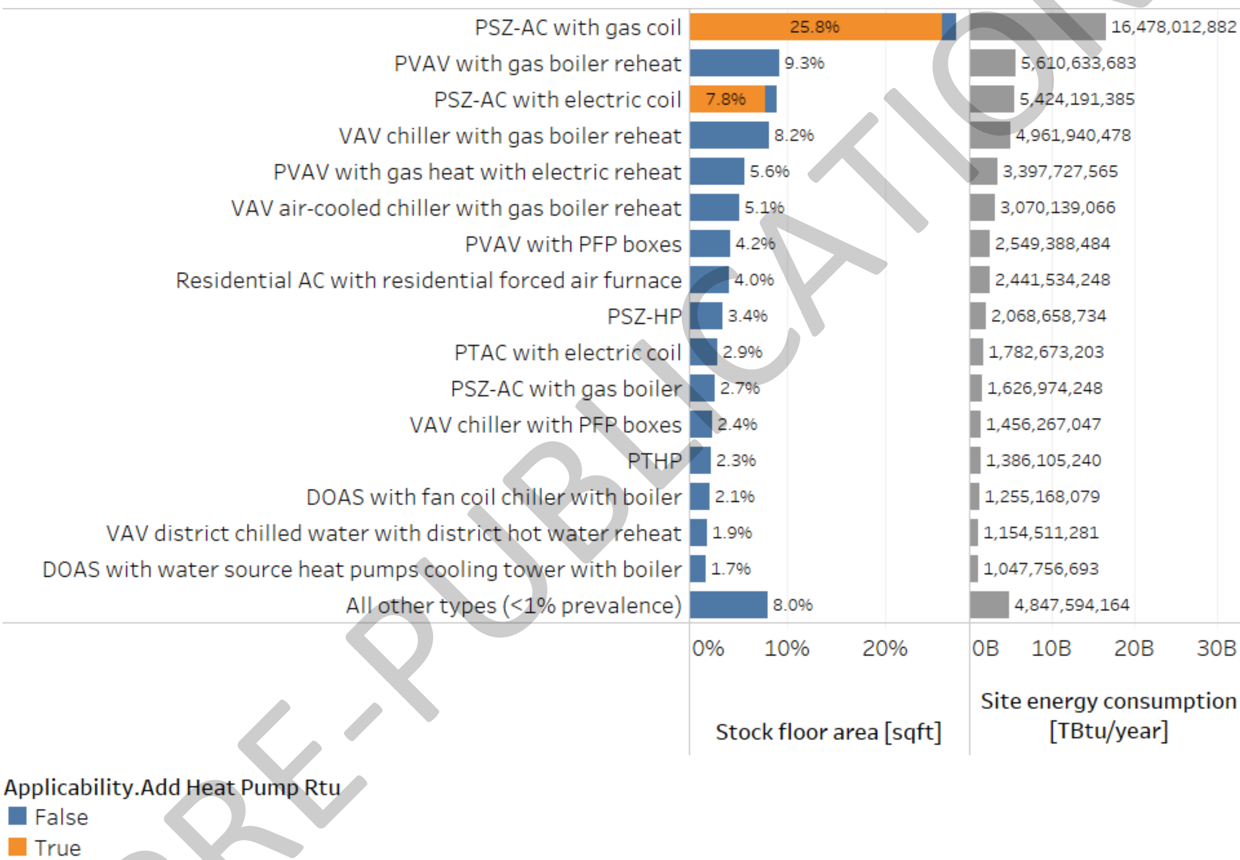


Figure 2. ComStock HVAC system type prevalence by stock floor area.

PTHP stands for packaged terminal heat pump, PTAC stands for packaged terminal air conditioner, PVAV stands for packaged variable air volume, DOAS stands for dedicated outdoor air system, and PFP stands for parallel fan-power.

3.2 Technology Specifics

This report is an iteration of the previous Heat Pump RTU measure (please refer to the documentation of "Heat Pump Rooftop Units With Standard Performance"). The only difference is the configuration of the heat pump (e.g., minimum operating temperature). The original measure uses 0°F as the compressor lockout temperature for the heat pump heating operation, but this study explores the impact if that compressor lockout temperature changes to 32°F. This document will only minimally discuss core modeling assumptions and details. For a more comprehensive overview of the HP-RTU modeling, such as performance maps, data sources, controls, etc., please refer to the documentation of the previous study.

3.2.1 Reasoning for Selecting 32°F Compressor Lockout Temperature

Our previous work analyzing the HP-RTU with standard performance used the setting of 0°F compressor lockout temperature following the common specifications of prevalent products in the current market. This means if the outdoor air temperature falls below the compressor lockout temperature, the heat pump is disabled and supplemental heating is exclusively used to address the entire heating load. However, based on our review of product documentation and informal discussion with manufacturer representatives, there are two scenarios that can happen. The first is when the product offers a range of temperature (with default setting) so that the actual product's lockout temperature can be set during the commissioning stage. Table 1 shows some of the actual descriptions of lockout temperature from manufacturer documentation [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14]. As shown in Table 1, the available minimum and maximum lockout temperatures vary between products and the default setting also varies between 15°F and 35°F, which is range that can have a large impact on the performance of the heat pump system in some climates. The second scenario is when there is no setting for the lockout temperature, but the controller shuts off the compressor based on the suction pressure level. This lockout occurs on low pressure, and its purpose is to maintain compressor reliability. The specific description of this reliability feature (i.e., low pressure switch) is also available in manufacturer publications [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14]. Note: While most of the manufacturer's documentation clearly indicated whether the specific lockout temperature was intended for locking the mechanical heating (and using a temperature delta to set the cooling lockout), the documentation from Carrier was not clear enough. We made our best judgment to interpret the values in the table as the lockout for the mechanical heating operation.

Table 1. Descriptions of Compressor Lockout Temperature in Manufacturer Manuals [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14]

Brand from data	Model name	Keywords	Lockout description in actual manuals
Carrier	WeatherMaker 50FCQ	EcoBlue	adjustable from –45°F (–43°C) to 80°F (27°C), set at a factory default of **32°F (0°C)**.
	WeatherMaster 50GCQ	EcoBlue	adjustable from –45°F (–43°C) to 80°F (27°C), set at a factory default of **32°F (0°C)**.
	WeatherMaker 50TCQ	Std efficiency	adjustable from –45°F to 80°F (–43°C to 27°C), set at a factory default of **32°F (0°C)**.
	WeatherMaster 50HCQ	High efficiency	adjustable from –45°F (–43°C) to 80°F (27°C), set at a factory default of **32°F (0°C)**.
Lennox	Enlight	High efficiency	min = -50F, default = **-15F**, max = 0F. This parameter controls when heat pump operation will be locked-out. If mechanical heating is already active and OAT drops to or below this setpoint, mechanical heating will be stopped.
	Xion	Std efficiency	N/A
Trane	Impack	2-5 tons	N/A
	Precedent	3-25 tons	The factory default setpoint is **0°F**, but is user adjustable between -18 and 45°F.
Rheem	Resolute line classic	Std efficiency	Compressor lockout sensor on the unit controller is factory set at **35°F** and is adjustable from 30°F (-1°C) to 50°F (10°C) and resets the cooling lockout at 5°F (+2.7°C) above the set point.
	Renaissance line classic	High efficiency	N/A
	Endeavor line classic	2-5 tons	N/A
	Commercial classic	-	Compressor lockout sensor on the unit controller is factory set at **35°F** and is adjustable from 30°F (-1°C) to 50°F (10°C) and resets the cooling lockout at 5°F (+2.7°C) above the set point.
Daikin	Rebel	High efficiency	Default **0°F** and range -20°F–50°F. 45°F if 100% OA unit w/o ER and range 45°F–50°F.
	Maverick	Std efficiency	
YORK	Sun Core	3-10 tons	N/A based on compressor suction pressure
	Sun Pro	6.5-12.5 tons	N/A
	Sunline	15-20 tons	N/A

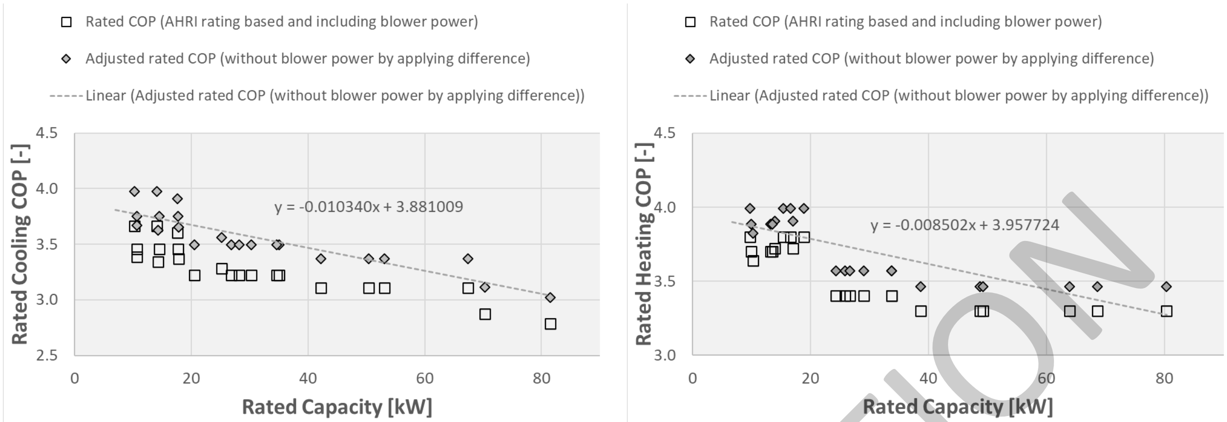
Additionally, based on the feedback from the NREL reviewers of this report, the stock-level impact of HP-RTUs with a 0°F compressor lockout temperature (i.e., HP-RTUs with 0°F lockout temperature applied to 34% of the total stock floor area) may be too ideal because the minimum lockout temperature in the field may be higher, forcing heat pumps to switch to supplemental heating at higher outdoor air temperatures. Because there is uncertainty in how the lockout temperature will be set during equipment commissioning, we want to understand the implications of modification on the building stock. However, it is also unclear if there is a reasonable lockout temperature we can apply to heat pumps modeled across different sizes of buildings and under different climates. Thus, this analysis includes the impact of different lockout temperatures (i.e., 0°F, 5°F, 10°F, 17°F, and 32°F) on reduced stock models to provide a context around sensitivity and also provides the full stock modeling results (via data release) by selecting one of the temperatures (i.e., 32°F). Because we already published a dataset with 0°F lockout temperature, the data released in this analysis will be a comparable dataset to the previous dataset.

3.2.2 Other Key Considerations Compared to Previous Work

Aside from the changes to the compressor lockout temperature applied in this study, most of the other modeling assumptions are the same as in the "Heat Pump Rooftop Units With Standard Performance" study. Key assumptions include:

- Two stages of cooling.
- Single-stage heat pump heating (i.e., all compressors running at the same time).
- Supplemental electric resistance heating.
- Supplemental heating runs at the same time as heat pump heating, if above the lockout temperature.
- For units with capacity of 5 tons and below, seasonal energy efficiency ratio of 14 (seasonal energy efficiency ratio2 of 13.3) and heating seasonal performance factor of 8 (heating seasonal performance factor2 of 6.7). Unit conversion referenced from [15].
- For units with capacity of 6 tons and above, integrated energy efficiency ratio between 10.8 and 14.1 and coefficient of performance (COP) at 47°F (8.3°C) between 3.2 and 3.5.
- This measure replaces AC-RTUs with either gas-fired or electric resistance heating with HP-RTUs.
- All energy efficiency features in the existing RTUs (energy recovery, demand control ventilation, etc.) as well as operating schedule are transferred to the new HP-RTU system for consistency.
- The heat pump system is sized to the design cooling load, with supplemental heating (i.e., electric resistance heating) used to address any heating loads not met by the heat pump.
- Heating capacity retention around 40% (of the rated capacity) and COP retention around 38% (of the rated COP) when the outdoor air temperature is 0°F (-17.8°C) and when the indoor air temperature is 70°F.

The gross rated COPs (for both heating and cooling) shown in this study and used in EnergyPlus do not include indoor fan power or heat. Air-Conditioning, Heating, and Refrigeration Institute (AHRI) ratings are net ratings and include indoor fan power and heat. Thus, the gross rated COPs reported in this study are different from the AHRI rated COPs. In order to properly translate "what is more commonly used (i.e., AHRI rated COP)" to "what is applied in EnergyPlus (i.e., gross rated COP) and also to reflect equipment efficiency varying by equipment size, 1) we collected AHRI ratings from public specification data, 2) converted AHRI ratings to EnergyPlus-compatible gross rated COPs, and 3) created regression equations to approximate a linear trend. For the conversion, we made an engineering judgement to apply 8.5% and 5% increases for cooling and heating, respectively, from AHRI rated COPs to EnergyPlus-compatible gross rated COPs (without fan power). Figure 3 is shows the results of two regression equations for heating and cooling. To provide more context, the two values were derived by reverse calculating the EnergyPlus-compatible rated COP from the AHRI rated COP using the blower fan performance data that were included in spec sheets of eight Lennox products. This is also an update for the previous work ("Heat Pump RTU" measure, 2023 release 1), and data released from this point will reflect this rated COP change depending on the size of the units. The COP values for both heating and cooling are capped based on minimum and maximum COP values (corresponding to minimum and maximum rated capacity values from all data points) shown by the linear regression curve when applied to the model. For example, if a unit is sized to 90 kW, then the rated COP for cooling is not extrapolated for 90 kW from the linear curve shown in Figure 3 (a). Instead, the rated COP that corresponds to the data point with the largest capacity (i.e., slightly higher than 80 kW) is applied. This is to prevent extrapolation that can lead to unrealistic COP values.



(a) for cooling (b) for heating

Figure 3. Rated COP calculations for different size units

3.3 Greenhouse Gas Emissions

Three electricity grid scenarios are presented to compare the emissions of the ComStock baseline and the HP-RTU standard performance scenario. More are available in the full public dataset. The choice of grid scenario will impact the grid emissions factors used in the simulation, which determines the corresponding emissions produced per kilowatt-hour. Two scenarios—Long-Run Marginal Emissions Rate (LRMER) High Renewable Energy (RE) Cost 15-Year and LRMER Low RE Cost 15-Year—use the Cambium dataset, and the last uses the eGrid dataset [16], [17]. All three scenarios vary the emissions factors geospatially to reflect the variation in grid resources used to produce electricity across the United States. The Cambium datasets also vary emissions factors seasonally and by time of day. This study does not imply a preference for any particular grid emissions scenario, but other analysis suggests that the choice of grid emissions scenario can impact results [18]. Emissions due to on-site combustion of fossil fuels use the emissions factors shown in Table 2, which are from Table 7.1.2(1) of draft American National Standards Institute/Residential Energy Services Network/International Code Council 301 [19]. To compare total emissions due to both on-site fossil fuel consumption and grid electricity generation, the emissions from a single electricity grid scenario should be combined with all three on-site fossil fuel emissions factors.

Table 2. On-Site Fossil Fuel Emissions Factors

Natural gas	147.3 lb/MMBtu (228.0 kg/MWh)[a]
Propane	177.8 lb/MMBtu (182.3 kg/MWh)
Fuel oil	195.9 lb/MMBtu (303.2 kg/MWh)

[a] lb = pound; MMBtu = million British thermal units; kg = kilogram; MWh = megawatt-hour

3.4 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 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 [20]. Summary statistics from this implementation are shown in Table 3. Note that ComStock does not currently estimate utility bills for district heating and cooling.

Table 3. Summary Statistics of Utility Bill Implementation in ComStock by Fuel Type

Fuel Type	Minimum Price ($)	Average Price ($)	Maximum Price ($)
Natural gas	$0.070/kBtu	$0.012/KBtu	$0.048/kBtu
Propane	$0.022/kBtu	$0.032/kBtu	$0.052/kBtu
Fuel oil	$0.027/kBtu	$0.033/kBtu	$0.036/kBtu
Electricity	$0.003/kBtu	$0.035/kBtu	$3.530/kBtu

Natural gas bills are estimated using 2022 EIA averages by state. 2022 U.S. EIA Natural Gas Prices (Commercial Price) and U.S. EIA Heat Content of Natural Gas Delivered to Consumers are used to create an energy price in dollars per kBtu [21]. Propane and fuel oil bills are estimated using 2022 EIA averages by state. Residential No. 2 Distillate Prices by Sales Type and U.S. 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 dollars per kBtu [22]. 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 [23]. 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 suspiciously 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 [24]. 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. To note, the utility bill implementation described in this section does not include possible future rate changes specifically those designed for electric heating.

3.5 Limitations and Concerns

Comprehensive heat pump performance maps, which are required for detailed energy modeling, are not publicly available. Consequently, understanding of heat pump performance and operation in this area is also limited. Heat pump modeling is sensitive to performance assumptions given the strong dependency of both efficiency and capacity on outdoor air temperature (both dry-bulb [capacity] and wet-bulb [defrost needs]). This impacts both annual energy consumption and peak demand. The work presented here attempts to use the most informative data available and makes documented assumptions about heat pump operation and performance. These will notably impact results. Please consider these assumptions.

- Stock savings are sensitive to ComStock baseline assumptions.
- In order to place a safety measure whenever heat pump heating either (1) cannot meet the full heating load or (2) cannot operate because the outdoor air temperature is extremely cold, supplemental heating is implemented in HP-RTU models. While the simple concept is to operate supplemental heating during those two conditions mentioned above, there can be different control logics in reality. One example based on an informal conversation we had with one of the manufacturer representatives was that the compressor operating stage can be reduced (for multi-speed systems) when the supplemental electric resistance heating coil gets energized. This is mostly to stay within the safe amperage in a given electric panel size by avoiding concurrent operations of all compressors (or full stages) and the supplemental electric resistance coil. While this specific control logic has an implication of reducing the positive impact of HP-RTU implementation because the ratio of supplemental heating over heat pump heating increases, our modeling in this analysis does not capture this specific control logic. The HP-RTU measure's supplemental heating operates concurrently with all available heat pump heating stages in our model. However, we will explore the implementation of this control logic in future analyses.
- Due to the calculation routine in EnergyPlus, which calculates both defrost and heating operation for each applicable time step, supplemental heat is not forced on when heating is needed during defrost cycles. Supplemental heat is only used if the heat pump cannot meet load but operates with the defrost, which cannot occur in reality. This is less of an issue when the heat pump cannot meet the entire heating load and load that is not met by the heat pump is covered by supplemental heating. However, at mild temperatures when the heat pump is defrosting and cycling in the time step in the simulation, EnergyPlus will not include supplemental heat to temper the air during the defrost cycle. This is also one of the future areas to be improved in EnergyPlus.
- Another thing we noticed is related to how the heat pump system delivers the heating needed by controlling the supply air temperature and the airflow. While this issue only happened during unoccupied hours and when heating was required, there were instances where two different lockout temperature scenarios delivered heating differently for the

same time period; a simulation with 0°F lockout temperature delivered heating with higher supply air temperature with lower airflow, while another simulation with 32°F delivered the same heating with lower supply air temperature with higher airflow. The heat transfer rates between two scenarios were exactly the same, delivering the same amount of heating. This has an implication of different lockout temperature scenarios resulting in different fan energy usages but heating supply air temperature controlled in a way to compensate for the fan airflow difference. The capacity and electricity consumption (from the compressor and outdoor fan) of the heat pump are also influenced by this variations in operating conditions. However, these variations occurred for only a brief period during the annual simulation, resulting in minimal impact at the stock-level.

- While the power data from Carrier included the exact total consumption of components (i.e., compressor and condenser fan) that is compatible with what EnergyPlus requires, the power data from Lennox only included compressor power. This has an implication of slight underprediction of power, which results in slight overprediction of COP (or underprediction of EIR that EnergyPlus wants) from data points from Lennox. The new EIR curves that include Lennox data, shown in Table 3, are affected by this limitation.
- Any limitations with the original HP RTU measure (Heat Pump RTU measure, 2023 release 1) would transfer to this work.
- In reality, different lockout temperatures would likely be employed across the country, which can impact results, but we are choosing one value.
- We do not have a way to model lockout temperature based on compressor suction pressure, so we are only studying the "minimum lockout temperature" approach in this work.
- This work assumes productive operation of the heat pump down to the specified lockout temperature, but it is unclear if all products can actually operate effectively at these lower temperatures. Field validation will be required to answer this question.

4 Output Variables

Table 4 includes a list of output variables that are calculated in ComStock. These variables are important in terms of understanding the differences between buildings with and without the "HP-RTU with standard performance" measure applied. These output variables can also be used to help understand the economics of the upgrade (e.g., return on investment) if cost information (i.e., material, labor, and maintenance costs for technology implementation) is available.

Table 45. Output Variables Calculated From the Measure Application

Variable Name	Description
out.params.hvac_count_dx_cooling_XX_to_XX_kbtuh	Total number of direct expansion (DX) cooling units within a size bin.
out.params.hvac_count_dx_heating_XX_to_XX_kbtuh	Total number of DX heating units within a size bin.
out.params.hvac_count_heat_pumps_XX_to_XX_kbtuh	Total number of heat pump units within a size bin.
out.params.dx_cooling_average_cop..COP	Average operational COP (compressor only) of DX cooling models during simulation.
out.params.dx_cooling_capacity_tons..tons	Total tons of DX cooling modeled.
out.params.dx_cooling_design_cop..COP	Average rated (compressor only) COP of DX cooling units at rated conditions.
out.params.dx_heating_average_cop..COP	Average operational COP (compressor only) of DX cooling models during simulation.
out.params.dx_heating_average_minimum_operating_temperature..C	Average compressor minimum heating lockout temperature, below which the heat pump heating will be disabled.
out.params.dx_heating_average_total_cop..COP	Average effective COP of DX heating. This includes energy from the defrost cycle and any supplemental heating.
out.params.dx_heating_capacity_at_XXF..kBtu_per_hr	Average available heat pump capacity at a given temperature.
out.params.dx_heating_capacity_at_rated..kBtu_per_hr	Average available heat pump capacity at rated temperature (47°F).
out.params.dx_heating_design_cop..COP	Average design COP of heat pumps.
out.params.dx_heating_design_cop_XXf..COP	Heat pump COP at given temperature, or rated conditions (47°F).
out.params.dx_heating_fraction_electric_defrost	Fraction of heat pump electric defrost energy to DX heating energy.
out.params.dx_heating_fraction_electric_supplemental	Fraction of heat pump electric supplemental heating energy to DX heating energy.
out.params.dx_heating_supplemental_capacity_electric..kBtu_per_hr	Electric coil supplemental heating capacity.

out.params.dx_heating_supplemental_capacity_gas..kBtu_per_hr	Gas coil supplemental heating capacity.
out.params.dx_heating_supplemental_capacity..kBtu_per_hr	Total (gas or electric) supplemental heating capacity.
out.params.dx_heating_fraction_supplemental	Fraction of heat pump heating energy from supplemental heating.
out.params.dx_heating_total_dx_electric..J	Total heat pump heating electric load.
out.params.dx_heating_total_dx_load..J	Total heat pump heating load.
out.params.dx_heating_total_load..J	Total heat pump system heating load.
out.params.dx_heating_total_supplemental_load_gas..J	Total heating output energy from gas supplemental coil.
out.params.dx_heating_total_supplemental_load_electric..J	Total heating output energy from electric supplemental coil.
out.params.dx_heating_defrost_energy..kBtu	Total heat pump electricity energy for defrost.
out.params.dx_heating_ratio_defrost	Ratio of heat pump defrost electricity to heat pump heating energy.
out.params.hours_below_XXF..hr	Number of hours below given outdoor air temperature during simulation.
out.params.unitary_sys_cycling_ratio_cooling	Annual average cycling ratio for cooling operation
out.params.unitary_sys_cycling_ratio_heating	Annual average cycling ratio for heating operation

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, cost savings, or greenhouse gas 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 strategy, depending on the use case.

5.1 Single Building Measure Tests

Five different lockout temperatures (0°F, 5°F, 10°F, 17°F, and 32°F) for the HP-RTU measure are compared using a sample model represented with typical meteorological year 3 weather data for Chicago, Illinois (ASHRAE climate zone 6A). This analysis is meant to illustrate the impact on a single model, as stock-level results are less interpretable for detailed operation comparisons. Again, the original measure (Heat Pump RTU, released in March 2023) represented with the advanced heat pump performance used the lockout temperature of 0°F, and this section discusses the results with higher lockout temperatures with a single example model to understand individual building-level performance variation.

Figure 4 shows time-series heating load data points from an annual simulation, including two different heating mechanisms: heat pump heating and supplemental heating (with electric resistance coil). As shown in Figure 4, heat pump heating operates during a wider temperature range in the 0°F scenario than the 32°F scenario. To meet the heating load, supplemental heating covers more heating load in the 32°F scenario than the 0°F scenario. And as clearly shown in 0°F lockout temperature scenario, the supplemental heating provides some heat when the outdoor temperature is above the lockout temperature (i.e., 0°F–45°F) because the heat pump alone cannot meet the space heating load. This also happens in the other lockout temperature scenarios. Also, as expected, a heat pump's maximum heating rate decreases with lower temperatures because the capacity derates with lower temperatures.

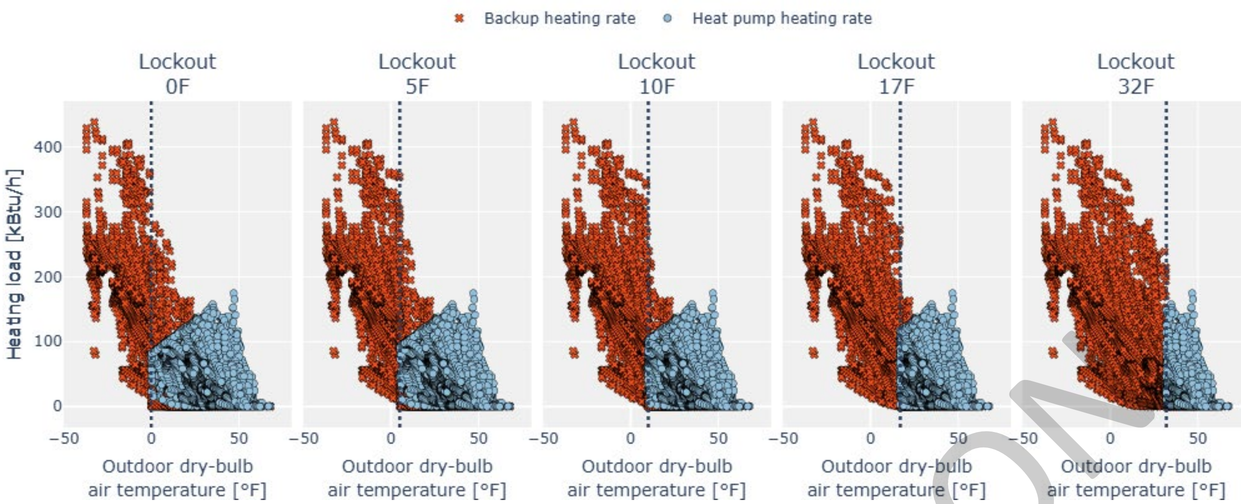


Figure 4. Single building model results: heating load with respect to outdoor air temperature

While Figure 4 shows the heating load met by two different mechanisms, the whole-system heating efficiency differences of each scenario are not reflected in the figure. However, the overall efficiency of the HP-RTU becomes better 1) if the heat pump can cover more heating load than the supplemental heating (i.e., 0°F lockout scenario rather than 32°F lockout scenario) and 2) the heat pump COP can maintain the COP higher than 1 (which means better than the electric resistance coil). Although there have been improvements[1] in heat pump heating performance under colder temperatures in the last decade (i.e., cold-climate heat pumps), heat pump heating capacity under colder climates can still degradewith lower temperature, as shown in Figure 4 (e.g., heat pump heating data points within 0°F–20°F in the 0°F lockout scenario). Thus, this analysis has captured the impact of the higher lockout temperature, as well as the degradation of heating capacity and COP under colder temperatures based on the advanced heat pump performance in the current market. More extensive results are included in the following sections.

5.2 Sensitivity Results With Reduced Stock Models

Before deciding on a single compressor lockout temperature for the final data release, we conducted a sensitivity analysis by (1) varying the lockout temperature among 0°F, 5°F, 10°F, 17°F, and 32°F and (2) applying these different lockout temperatures to ComStock with reduced stock models (i.e., 10,000 instead of ~150,000 models that are reasonably representing variations of the commercial building stock). This section includes the results of this sensitivity analysis to provide partial snapshots of how these different lockout temperatures propagate to the stock of building models. Note that because the sensitivity analysis in this section uses far fewer models to represent the building stock than a full ComStock run, results should be used for understanding generalized and conceptual trends only. And results with the full ComStock run shown in section 5.3 and after might show slightly different trends because of including the

[1] The performance applied to the advanced HP-RTU models can be found in our previous analysis "Heat Pump RTUs," released in March 2023.

remaining ~140,000 models. More detailed analyses should always utilize the available scenarios in the full published ComStock datasets.

Figure 5 shows distributions of COPs related to heating from 10,000 ComStock models: rated heating COP (without indoor blower power), annual average operating heating COP (without supplemental heating, defrost electricity, and crankcase heater electricity), and annual average total operating heating COP (with supplemental heating, defrost electricity, and crankcase heater electricity). Here, our data points reflect multiple aspects: 10,000 building models in total, one or more HP-RTU units per building, varying rated COPs (for both heating and cooling) depending on the size of the unit, varying COPs depending on the operating conditions (e.g., outdoor air temperature, indoor air temperature, and part-load ratio), and building models under different weather conditions (i.e., located in different states).

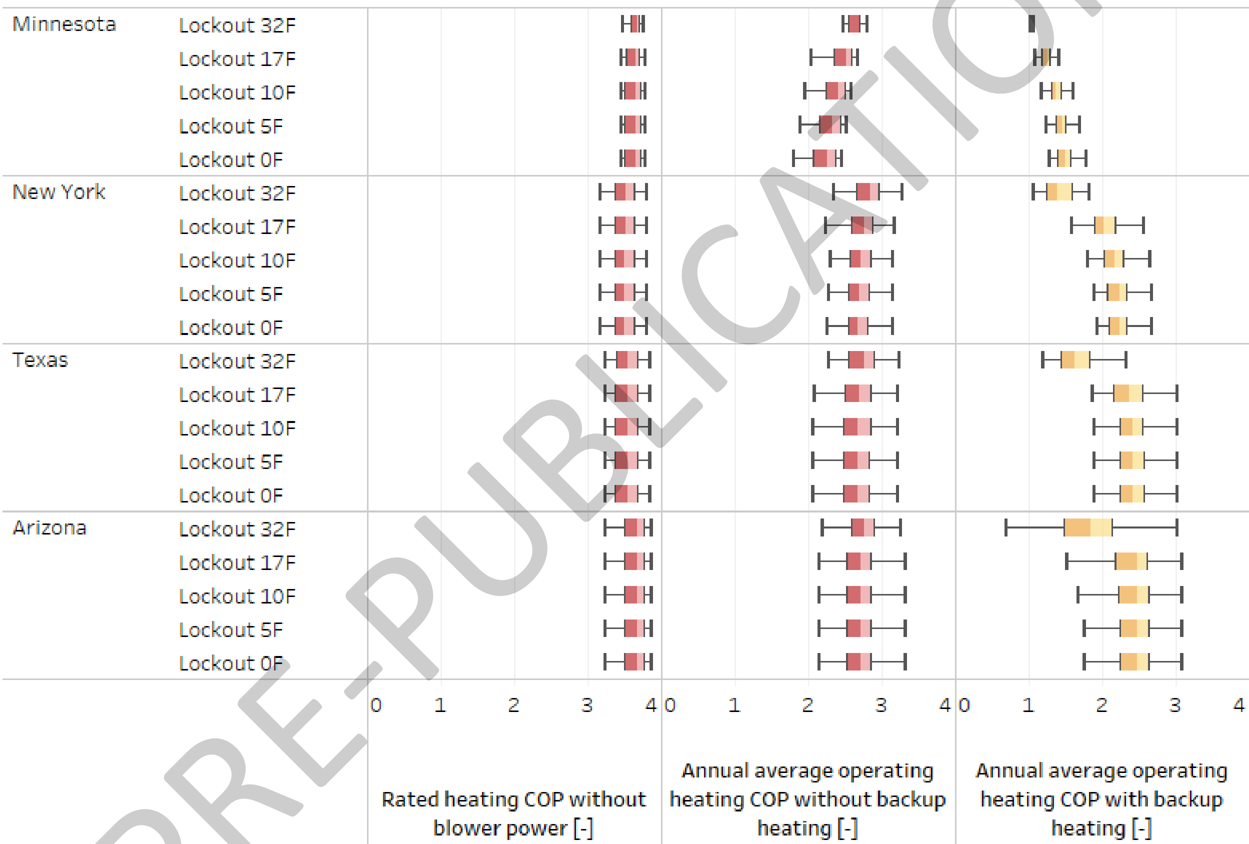


Figure 5. Lockout temperature sensitivity results: operating COP

The lockout temperature difference only affects the heating side of the operation. Thus, the operating COPs for cooling do not change between different lockout temperature scenarios. On the other hand, the operating COPs for heating (excluding the supplemental heating) increase with higher lockout temperature. For the 32°F scenario, this is because the heat pump does not operate below 32°F and, therefore, it never experiences lower operating COPs that generally occur with colder outdoor air temperature. However, when the supplemental heating is included for calculating the overall (i.e., including supplemental heating, defrost electricity, and crankcase heater electricity) operating COP for heating, the overall operating COP decreases, because the relatively inefficient electric resistance heating is handling more heating demand than the heat pump. The median operating heating COPs including supplemental heating are above 1 for all scenarios (i.e., better than electric resistance heating), but can reach 2 or higher even in the state of New York if the heat pump can handle the heating demand when the outdoor air temperature is below 32°F. For each state shown in Figure 5, the impact of different lockout temperatures is bigger in colder climates because states such as New York and Minnesota experience colder temperatures more often throughout the year. However, even in hotter states like Texas and Arizona, setting the lockout temperature to 32°F made a significant difference in the overall COP, where the median COP decreased from around 2.5 to less than 2.

Figure 6 supports the results shown above by providing the context of supplemental heating in more detail. The figure shows the fraction of the heating load met by supplemental heat and where the building data points are disaggregated, not only with the different lockout temperature scenarios but also with buildings under different weather conditions. As expected, lockout temperature variation has a bigger impact in the colder region (Minnesota). In Minnesota, the median fraction of heating load met by supplemental heat varies between 30 and 95% across the five different lockout temperature scenarios. The hotter climates show the fraction of supplemental heating as well as the differences between scenarios diminishing. However, our results show that, even in the hot and humid climates (e.g., Florida), the temperature can go below 32°F and this can increase the fraction of supplemental heating from a very small percentage to up to 10% (in terms of interquartile range). However, these plots do not show how much heating load is occurring and that a higher fraction of supplemental heating in Florida (in 32°F lockout scenario) can still be very minimal energy usage due to the low amount of heating hours.

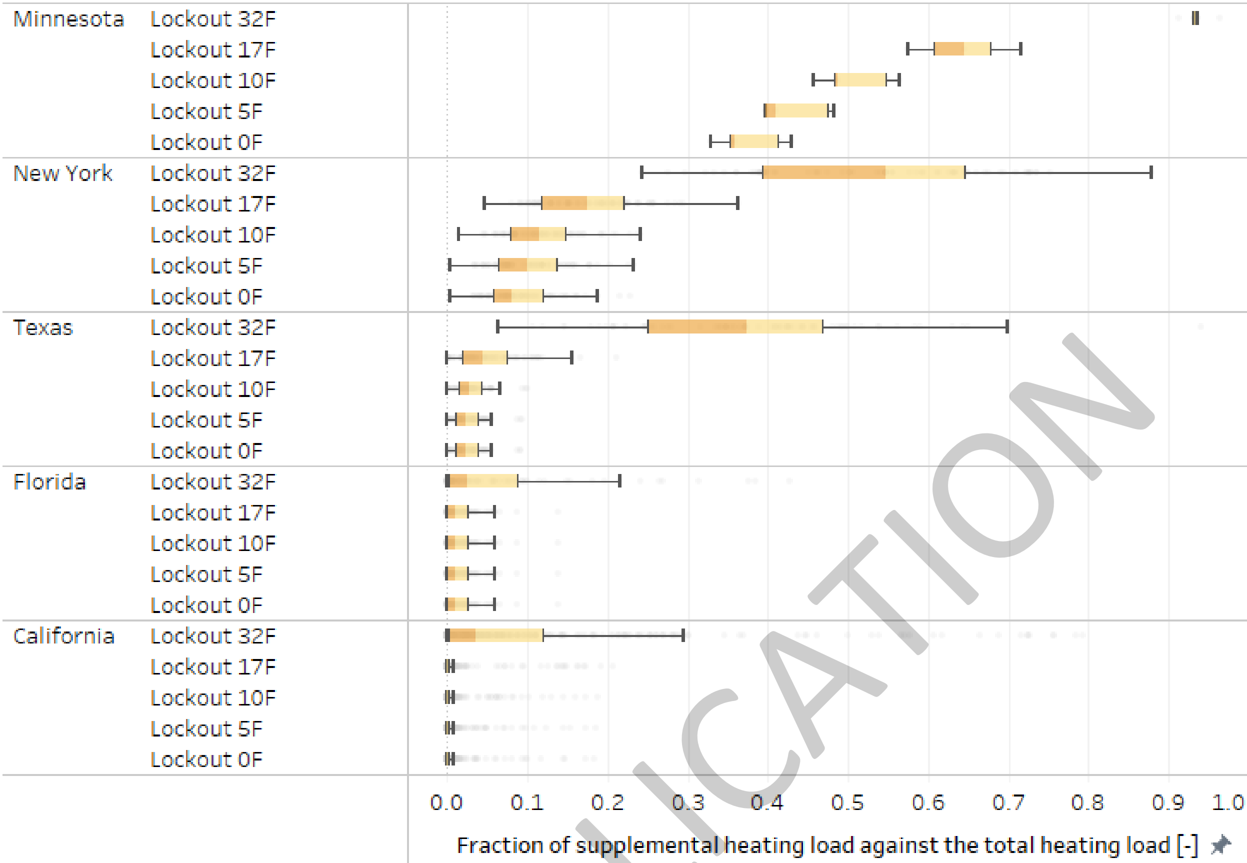


Figure 6. Lockout temperature sensitivity results: fraction of supplemental heating

Figure 7 and Figure 8 show the impact of different lockout temperatures on the stock-level energy consumption and utility bills, respectively. The stock-level energy consumption shown in Figure 7 is site energy, which does not equate to the impact on primary energy use. As shown in that figure, because natural gas removal (with fuel switching) outweighs the increased electricity usage, the total site energy is always smaller (in all lockout temperature scenarios) compared to the baseline scenario. However, if we calculate the total energy cost, which somewhat reflects the differences in primary energy for each energy type, we can see from New York results that the total cost of using HP-RTU under a certain lockout temperature scenario (e.g., 32°F) can increase the annual utility bills compared to the baseline scenario. Thus, for individual buildings, if the heat pump can maintain reasonable performance under colder outdoor air temperatures, the lockout temperature setting should be carefully considered because of its impact on utility bills. Also, although the aggregated bill impacts for the state of New York show an increase, there are some increases and some decreases in terms of individual buildings.

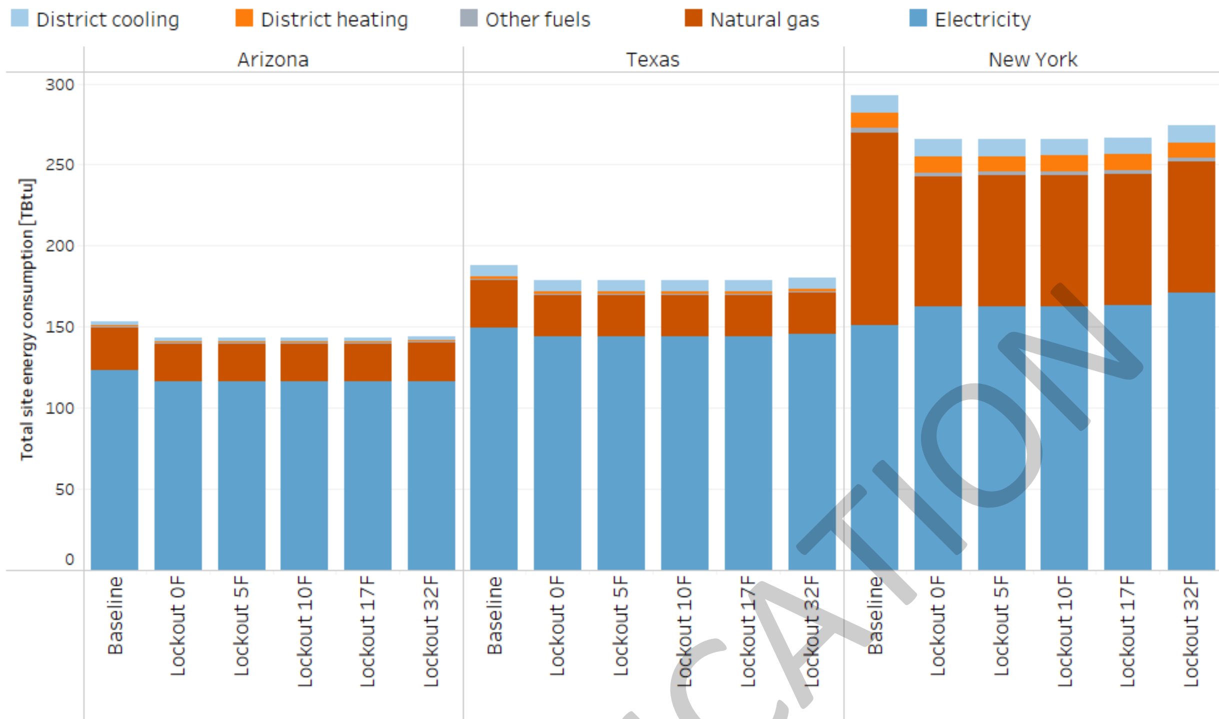


Figure 7. Lockout temperature sensitivity results: stock-level site energy consumption

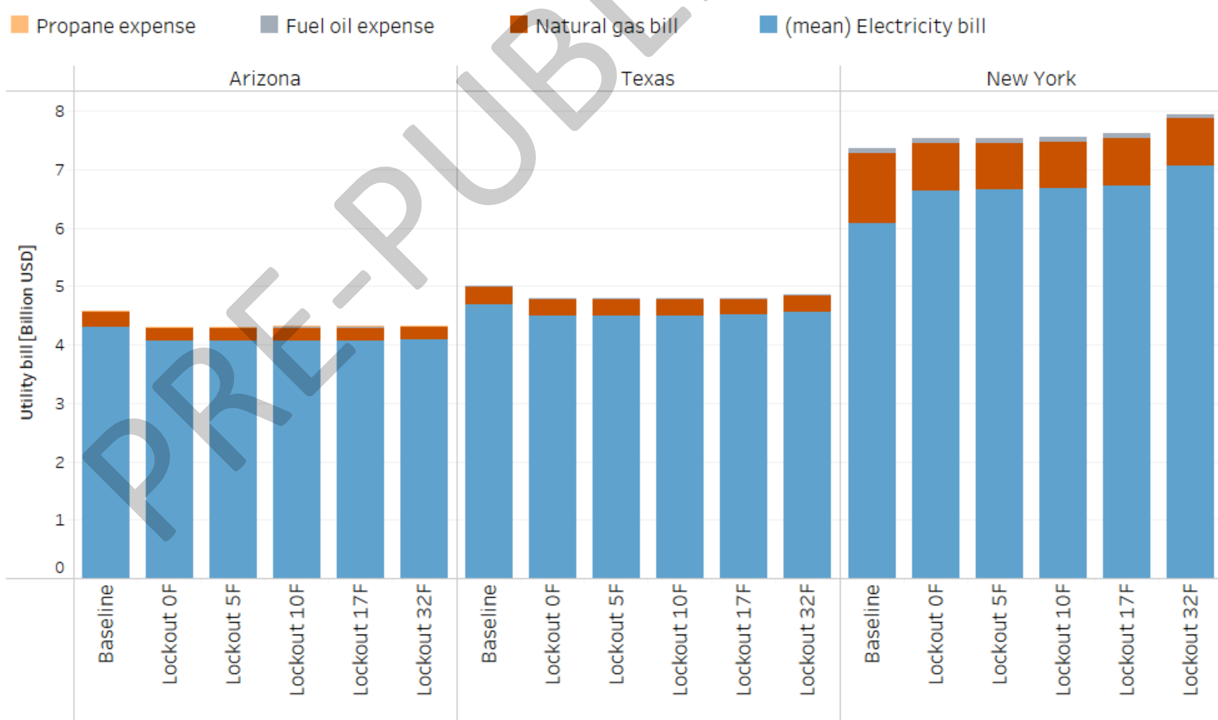


Figure 8. Lockout temperature sensitivity results: stock-level utility bills

5.3 Stock Energy Impacts

Figure 9 and Figure 10 show the comparison of annual site energy consumption between the baseline and upgrade scenarios for the entire building stock and buildings that are only applicable to the upgrade, respectively. The HP-RTU reflecting the standard performance with higher lockout temperature (32°F) measure demonstrates 4% total site energy savings (206 trillion British thermal units [TBtu]) for the U.S. commercial building stock modeled in ComStock. Figure 9 and Figure 10 also show the same plot with the HP-RTU with 0°F lockout temperature from the previous analysis as a comparison. The HP-RTU with higher lockout temperature consumes 2% (82 TBtu) more site energy compared to the HP-RTU with 0°F lockout temperature. To put this number in context, Figure 9 shows the entire commercial building stock, even including buildings that did not receive the upgrade (i.e., only 34% of the entire stock floor area received the upgrade). The savings of the HP-RTU standard performance are primarily attributed to:

- 28.4% stock heating natural gas savings (277.6 TBtu)
- 11.0% stock fan electricity savings (61.3 TBtu)
- 3.4% stock cooling electricity savings (23.9 TBtu)
- 24.8% stock heating other fuel savings (21.7 TBtu)
- -101.8% stock heating electricity savings (-178.7 TBtu)

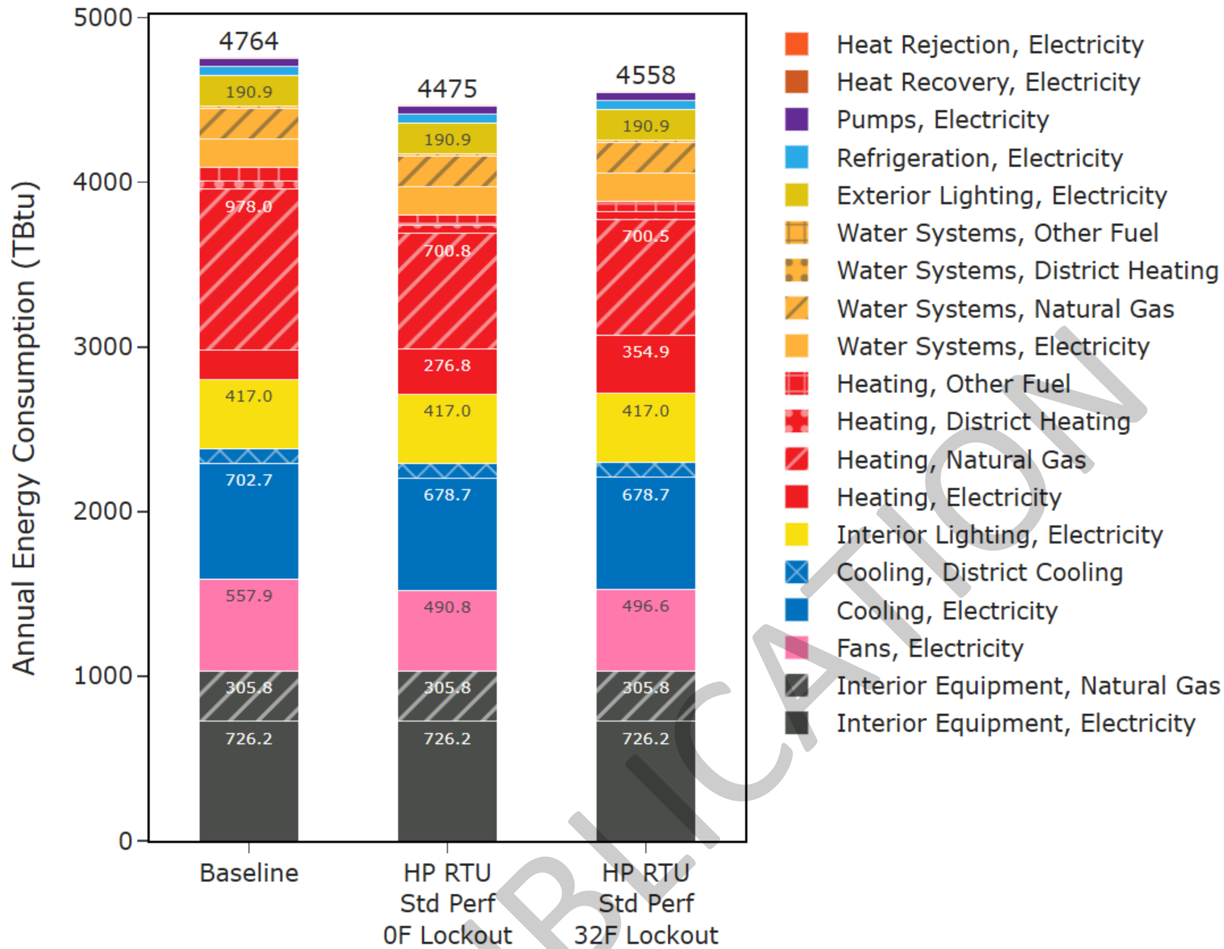


Figure 9. Comparison of annual site energy consumption between the ComStock baseline and the HP-RTU measure scenarios for the entire building stock

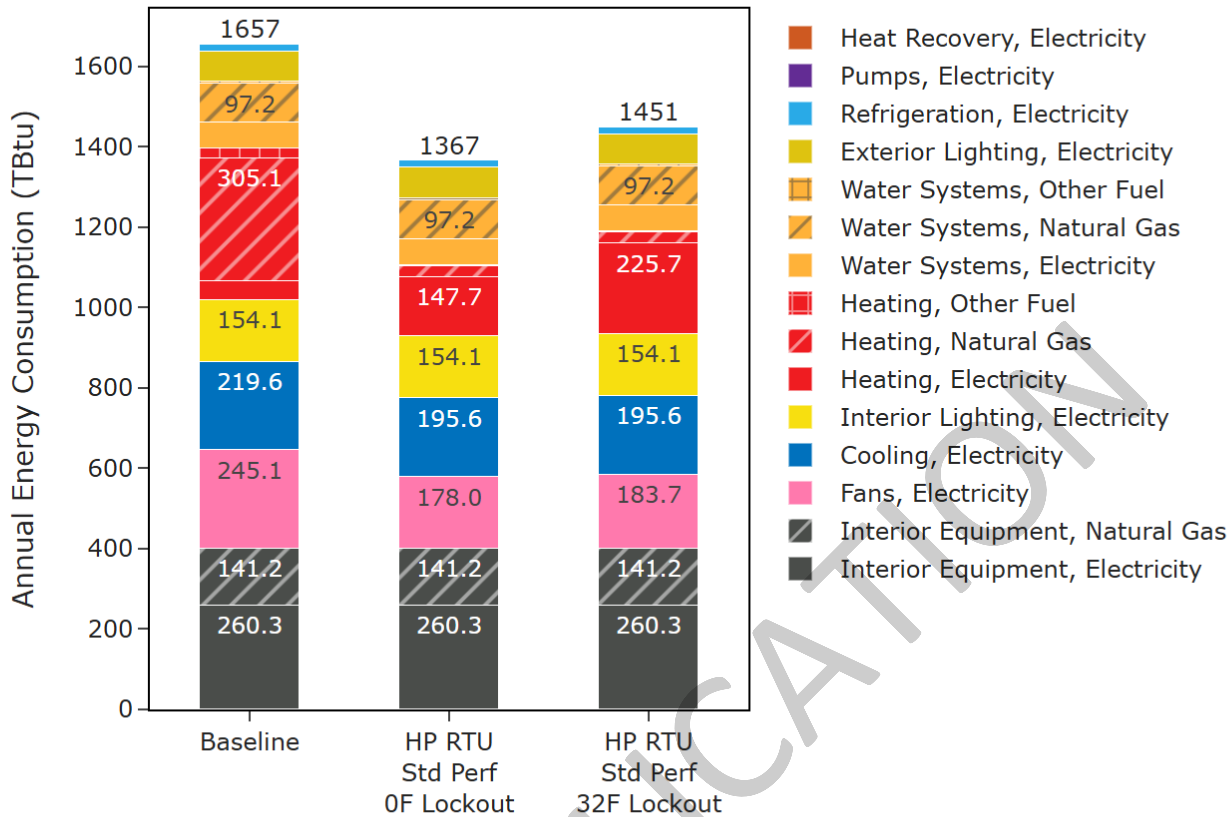


Figure 10. Comparison of annual site energy consumption between the ComStock baseline and the HP-RTU measure scenarios only for buildings that are applicable to the upgrade

As expected (and as highlighted in Figure 4 with an example model), the HP-RTU scenario with higher lockout temperature uses more energy than the HP-RTU scenario with 0°F lockout temperature. Figure 9 and Figure 10 also show this trend in terms of total site energy use; however, the HP-RTUs with a higher lockout temperature still show savings potential compared to the ComStock baseline. In other words, these simulation results show that converting gas-fired heating systems to electric heat pumps results in a 138% increase in electric heating, but a savings of 38% natural gas heating. Leveraging more efficient heating (with the heat pump) and even achieving reasonable heating performance in colder regions are the key factors for this savings potential. The results here assume electric resistance supplemental heat when the heat pump capacity is insufficient to meet the building load. More detailed findings are presented in Sections 5.5 and 5.8.

5.4 Stock Greenhouse Gas Emissions Impacts

Figure 11 shows ComStock simulation results for greenhouse gas emissions avoided across all electricity grid scenarios and on-site combustion fuel types. Additionally, Table 3 (in the Executive Summary section) also tabulates avoided emissions between different end use types and against the entire building stock and applicable building stock. Overall, the HP-RTU with higher lockout temperature (32°F) demonstrates between 7 and 10 million metric tons (MMT) of greenhouse gas emissions avoided (for all fuel types) for the three electricity scenarios presented. The 10 MMT number is determined using a 4% reduction for the LRMER Low RE Cost 15 scenario, while the 7 MMT number is determined using a 2% reduction for the eGRID 2021 scenario. These results are mostly attributed to 1) reduced electricity consumption from cooling and fans, 2) increased electricity usage from fuel switching gas heating systems, and 3) reduced natural gas usage with fuel switching gas heating systems. The 18% emissions avoided from on-site combustion are attributable to fuel switching some of these combustion-based heating systems. Compared to the lower lockout temperature (0°F) scenario, the overall emissions increase by 2%–3% for the higher lockout temperature scenario due to use of more electric resistance supplemental heating when the temperature falls below 32°F.

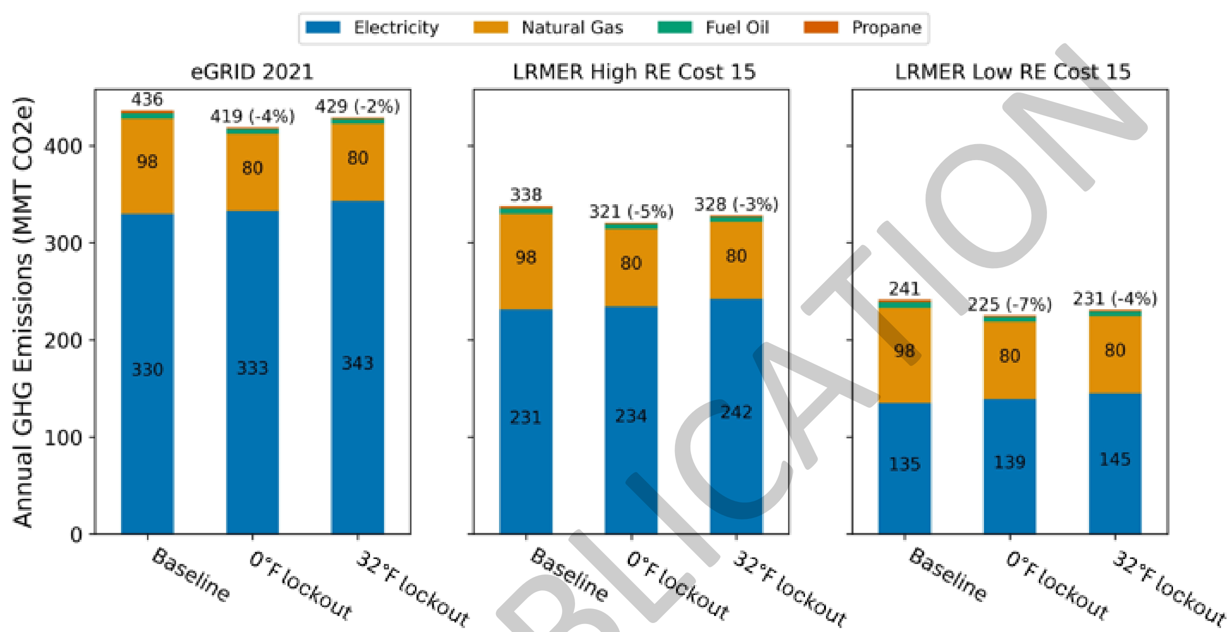


Figure 11. Greenhouse gas emissions comparison of the ComStock baseline and the HP-RTU scenario

5.5 Stock Utility Bill Impacts

This section includes a comparison of annual utility bills for buildings using different energy sources (i.e., electricity, natural gas, propane, fuel oil). Because we apply many electricity utility rate structures that are available for a building located in a certain geographical location, our data includes many annual utility bills per building model. Figure 12 shows a comparison among three scenarios (i.e., baseline, 0°F lockout, and 32°F lockout), including three different electricity utility bill statistics. The comparison highlights three statistics (i.e., maximum, mean, and minimum) across all electric utility bill costs. For detailed information regarding utility rate implementation, refer to the ComStock Reference Documentation [20]. Figure 9 showed aggregated "site" energy consumption, which does not reflect the "primary" energy perspectives. The cost of electricity and natural gas not only reflects the difference among energy costs, but also reflects the primary energy conversion factor differences. Thus, the annual aggregated cost comparisons, shown in Figure 12, can also tell us the primary energy consumption comparisons between different scenarios.

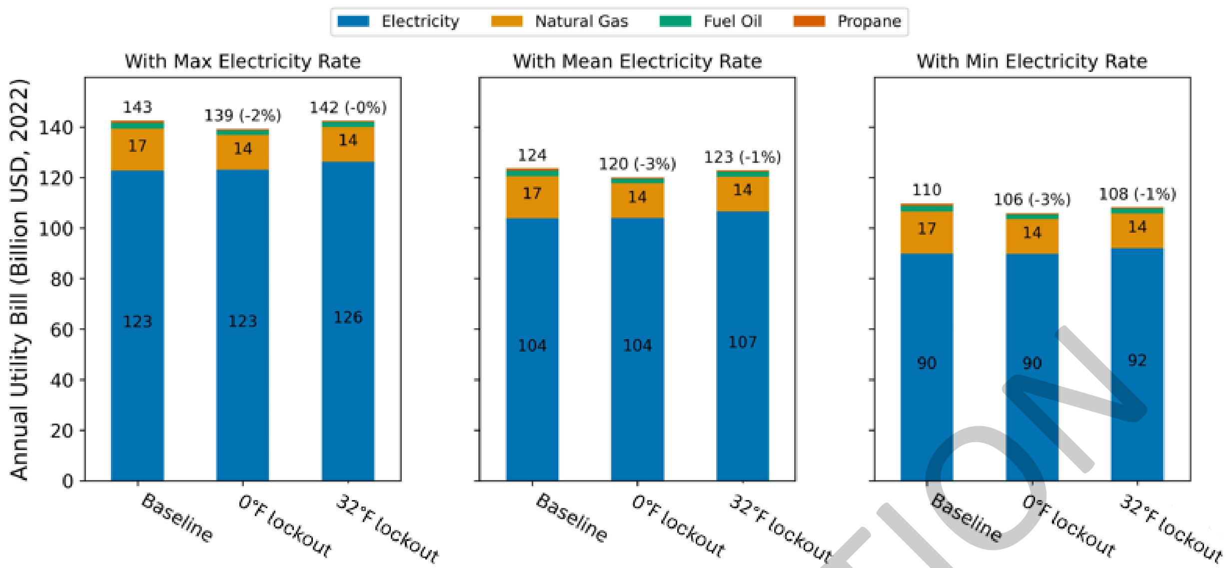


Figure 12. Utility bill comparison of the ComStock baseline and the HP-RTU scenario

The major difference between the 0°F and 32°F lockout temperature scenarios considered in this study is simply how much heating load is covered by heat pump heating compared to the electric resistance supplemental heating. Our models assume that heat pumps maintain reasonable (i.e., better than electric resistance) performance below 32°F and because of compressor lock out (and heat pump heating) at 32°F, they will lose the ability to provide heat pump heating (which has higher efficiency compared to electric resistance supplemental heating) under lower temperatures. Thus, when compared to the baseline scenario, usage choices between electricity (in the heat pump scenario) and natural gas (in the baseline scenario) can make a difference in terms of utility bills and primary energy usage.

Figure 13 shows a comparison of two HP-RTU scenarios (0°F versus 32°F lockout temperature) with average utility bill savings intensity across different U.S. states. The bill savings intensity represents the percentage savings calculated from the total utility bill intensities of the baseline model compared to HP-RTU models with higher lockout temperatures. The total utility bill intensity is a metric that divides the utility bill (in dollars) by the total floor area (in square feet) to provide a floor-area-normalized impact for comparing buildings of different sizes. Now the usage choice between electricity used for heat pumps and electricity used for electric resistance supplemental heating is responsible for the difference between the two scenarios. As can be expected, the differences between the two scenarios intensify toward the colder climates. Colder climates perform worse because the outdoor air temperature can often fall below 32°F, and supplemental heating covers all the heating load below that temperature for the 32°F lockout temperature scenario.

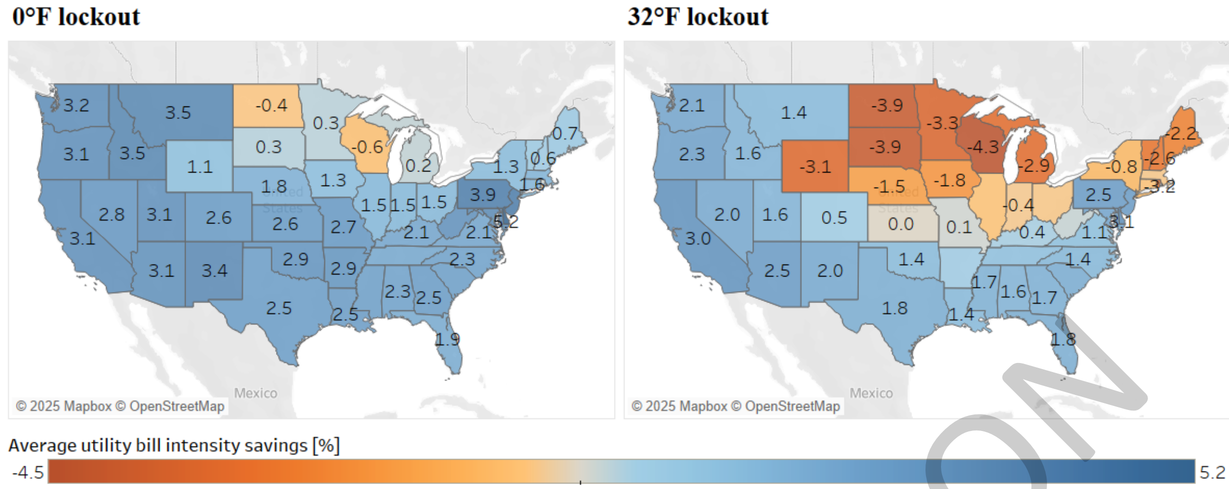


Figure 13. Average utility bill intensity savings among different U.S. states for two lockout scenarios

As shown in previous results, a higher lockout temperature scenario negatively affects colder climates, and this will also negatively impact utility bills in the colder climate zones. Figure 14 shows the distribution of utility bill savings (normalized by building floor area) across all climate zones. Because this figure is comparing the baseline scenario against the HP-RTU scenario with 32°F lockout temperature, we still see utility bill savings by leveraging more efficient cooling in hotter climates (e.g., climate zone 1A). However, as the weather gets colder (e.g., climate zone 8), switching many gas-fired furnaces to heat pumps while using electric resistance heating when the outdoor air is colder than 32°F results in increased utility bills in many of the cases (in terms of interquartile range). Thus, it is important to understand the cost implications when deciding on the lockout temperature setting.

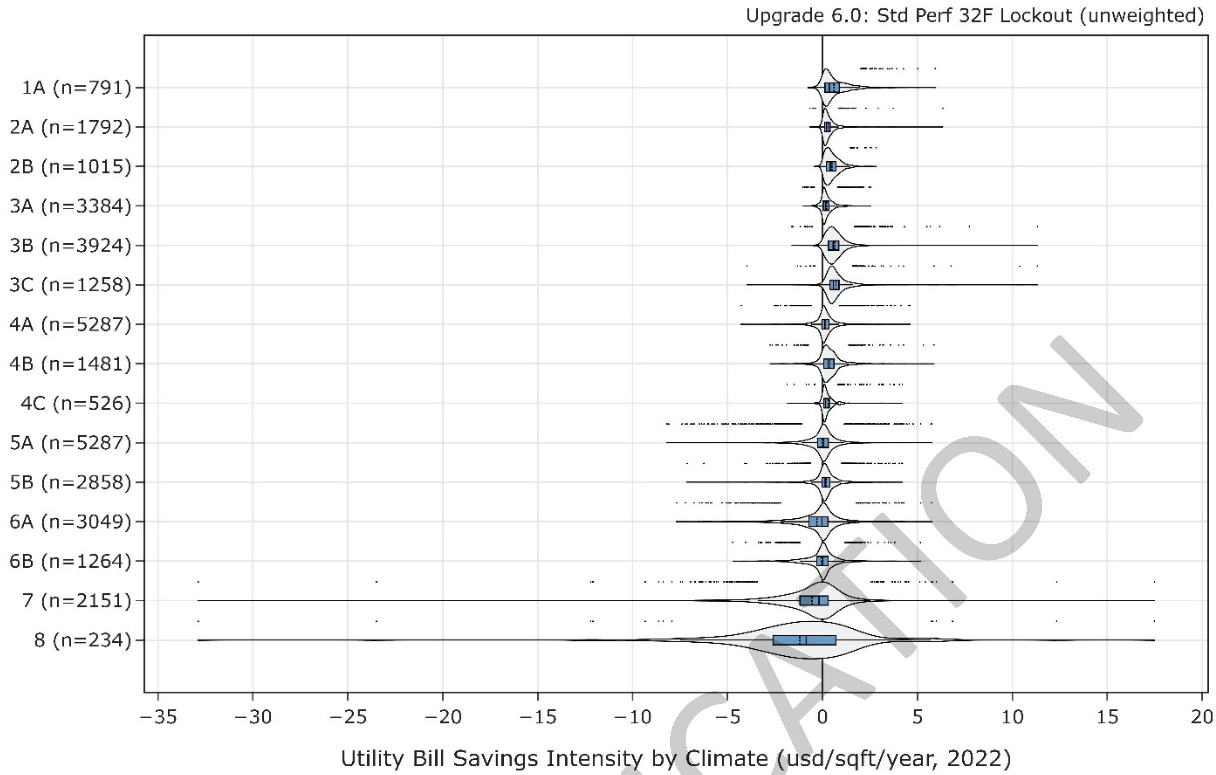


Figure 14. Utility bill savings (compared to baseline) distribution for ComStock models with the HP-RTU measure applied by climate zone

5.6 Site Energy Savings Distributions

This section discusses site energy consumption for quality assurance/quality control purposes. Site energy savings can be useful for these (and possibly other) purposes, but additional factors should be considered when drawing conclusions, as site energy savings do not necessarily translate proportionally to source energy savings, greenhouse gas emissions avoided, or energy costs, which vary widely across the United States. Savings shown in this section is based on comparisons between the baseline and 32°F lockout temperature scenarios.

Figure 15 through Figure 17 show distributions of the applicable baseline ComStock models versus the upgrade scenario for percent site energy or site end use intensity (EUI) savings with different end uses, fuel types, or climate zones. Percent savings provide relative impact of the measure at the individual building level, while site EUI savings provide absolute (or aggregated) scale of impact. 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. It should also be noted that these pairwise comparisons represented with distributions only calculate percent savings for buildings where the baseline included some prevalence of end use/fuel type. Thus, the electric heating savings only shows buildings that originally used some amount of electric heating, and does not represent buildings where natural gas was the only heating fuel.

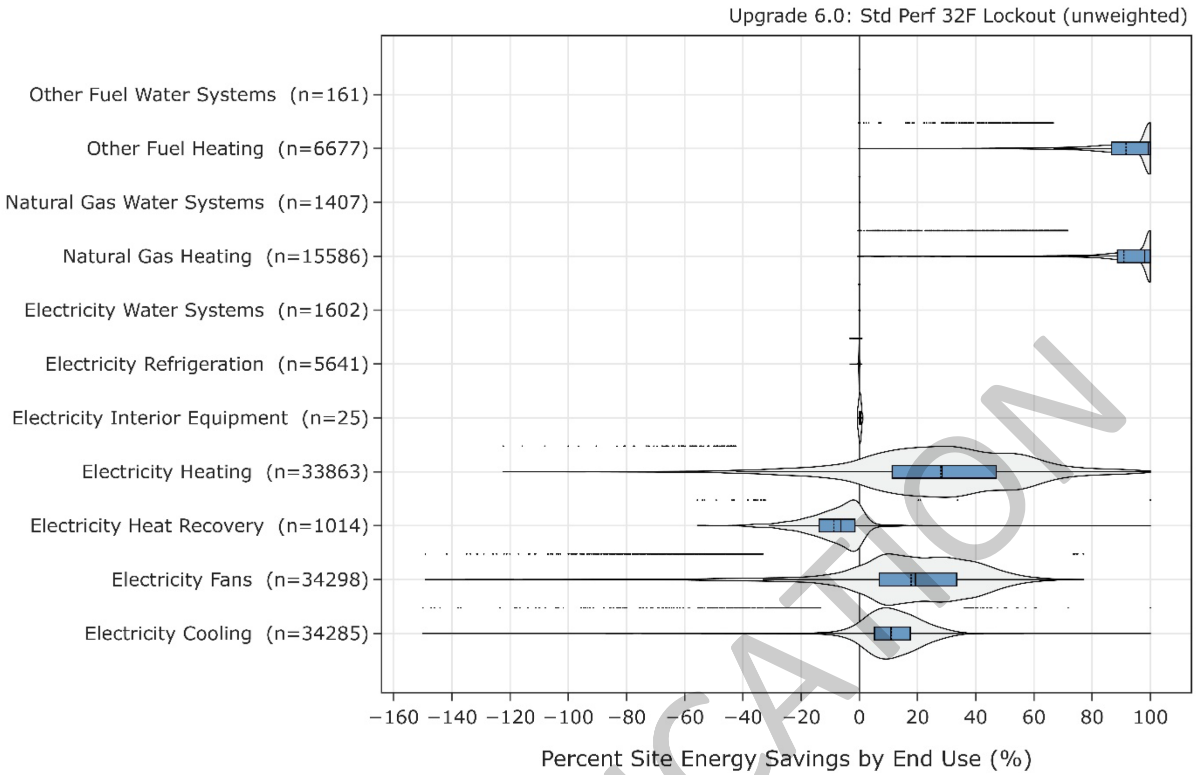


Figure 15. Percent site energy savings (compared to baseline) distribution for ComStock models with the HP-RTU measure applied by end use and fuel type

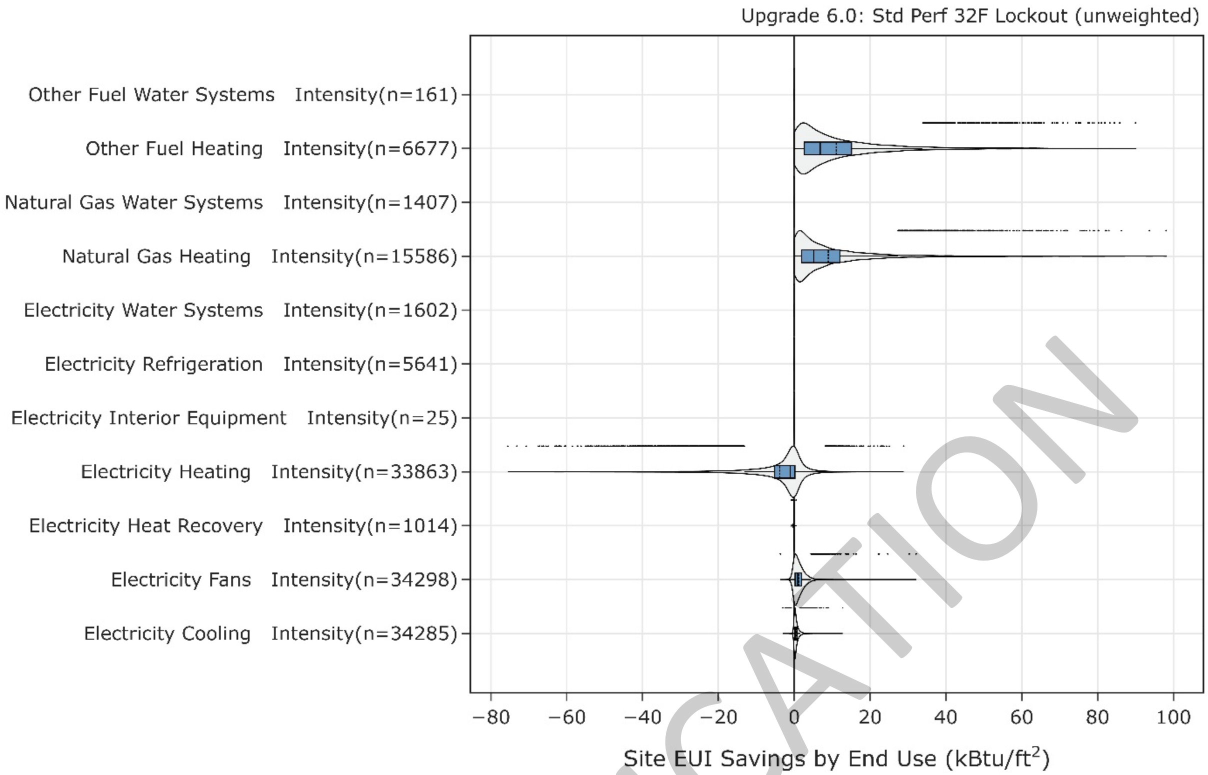


Figure 16. Site EUI savings (compared to baseline) distribution for ComStock models with the HP-RTU measure applied by end use and fuel type

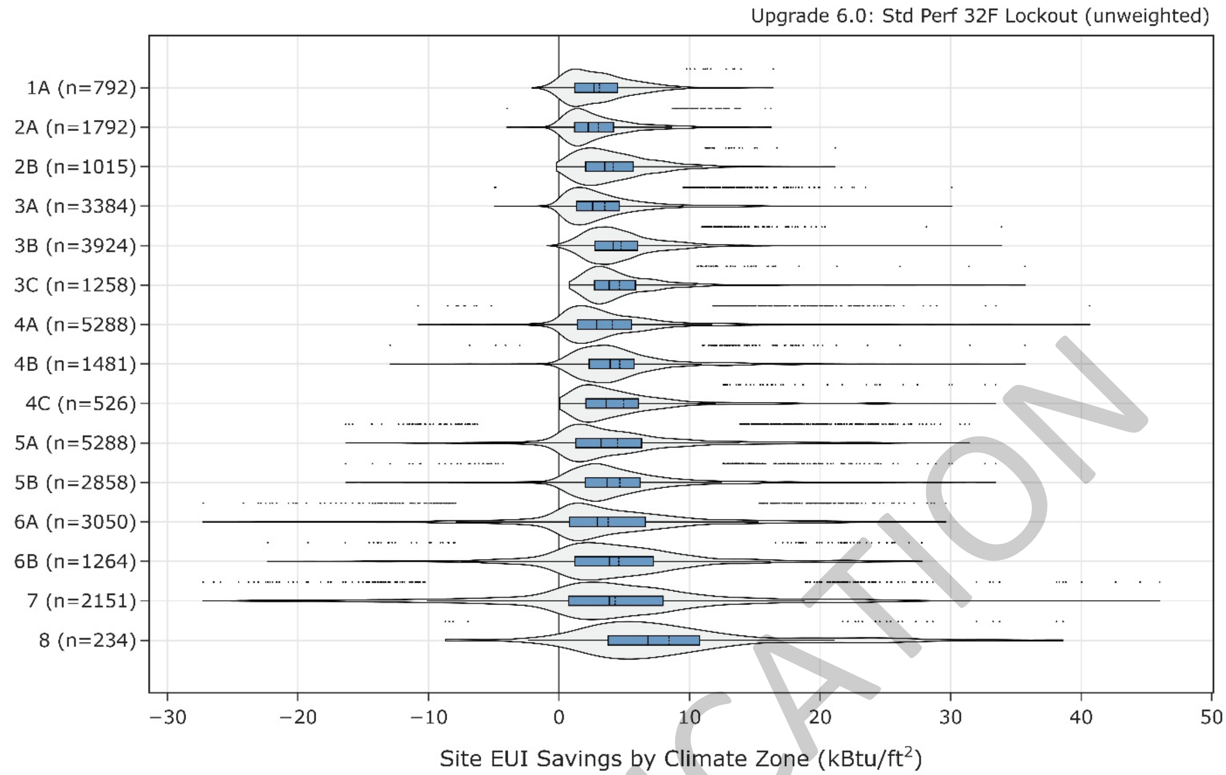


Figure 17. Site EUI savings (compared to baseline) distribution for ComStock models with the applied HP-RTU measure by climate zone

Highlights of conclusions drawn from Figure 15 through Figure 17 include:

- Fuel switching of combustion fuel-based heating:
    - Up to 100% savings on combustion fuel used for heating, as shown in Figure 15. Data points showing savings less than 100% are buildings with multiple HVAC systems and where the upgrade is only applicable to some of those systems.
    - Absolute or aggregated impact of heating savings (using natural gas or other fuel) is more noticeable compared to the other end uses, as shown in Figure 16.
    - Absolute or aggregated increase in electricity for heating due to fuel switching is well depicted in Figure 16. This was especially noticeable in the colder climates.
- Conversion of electric resistance heating to HP-RTU heating:
    - Positive savings on electricity used for heating, as shown in Figure 15.
- Higher cooling COP of HP-RTU compared to old buildings with older equipment:
    - Positive savings on electricity used for cooling and fans, as shown in Figure 15.
    - Absolute or aggregated savings scale is depicted in Figure 16.
- Staled savings potential in colder climates:
    - By locking out a heat pump at 32°F (0°C), savings potential does not noticeably increase with colder climates, as shown in Figure 17.

- Others:
    - Data points showing extreme (e.g., -120% electricity heating savings) positive/negative savings, shown in Figure 15, are (1) buildings in either very hot or very cold climates, (2) where absolute heating or cooling demand is small, and (3) where even a small change (due to upgrades) in heating or cooling demand (e.g., MWh) results in large relative (e.g., %) savings. The absolute impact of these data points should be understood with site EUI savings distributions.
    - More detailed findings related to the standard performance HP-RTU can be found in the original documentation "Heat Pump Rooftop Units With Standard Performance."

5.7 Other Key Findings

This section includes additional and more detailed findings specific to the HP-RTU with higher lockout temperature measure not covered in the previous sections.

Figure 18 illustrates the median annual operating COPs for heating across the contiguous U.S. states under two lockout scenarios. These values represent the median heating COPs of HP-RTUs for the building stock in each state, accounting for supplemental heating, defrosting, and crankcase heater electricity use. The variation reflects performance differences driven by regional weather characteristics. COP reductions of 30%–40% are common across the country. It's important to note that these COP values exclude the electrical consumption of the blower fan; including this load would further reduce the COPs. Additionally, since the reported COPs incorporate the impact of backup heating, the COP of the heat pump system alone (i.e., the vapor compression cycle) would be relatively higher, as shown in Figure 5.

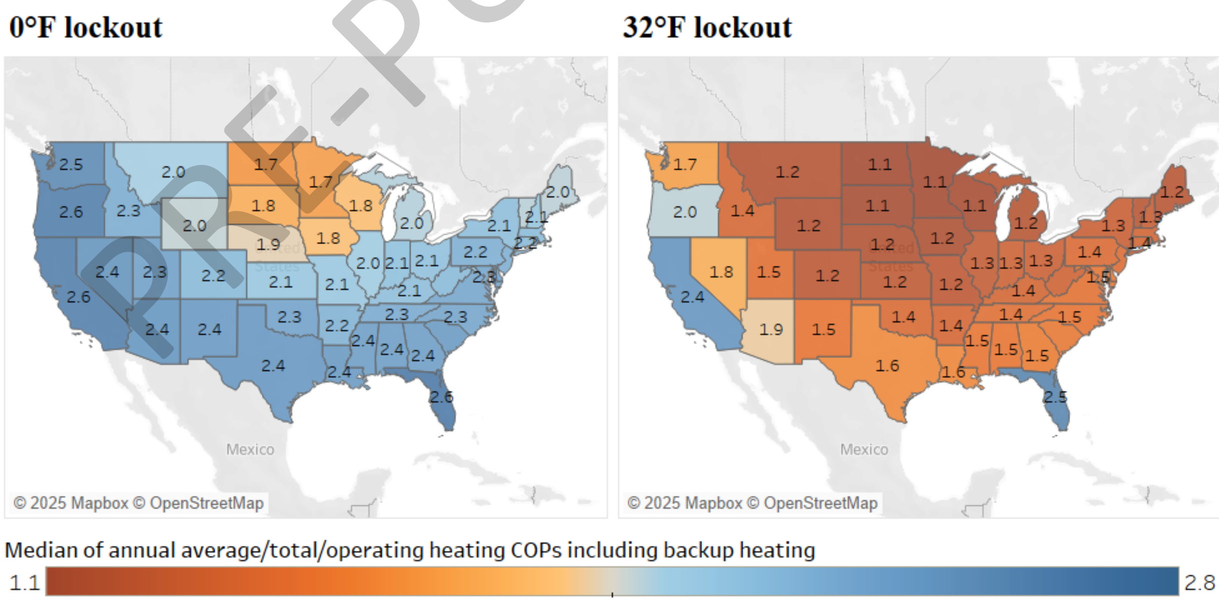


Figure 18. Annual operating median heating COP between contiguous U.S. states

Figure 19 illustrates the state-level peak power implications (using a normalized peak metric of W/ft²) for two lockout scenarios compared to the baseline scenario for sample models in four different states.. As expected, an increased winter peak due to fuel switching of gas heating systems is illustrated in Figure 19. A consistent decrease in summer peak leveraging relatively higher COP (compared to older units in reality) is also shown in Figure 19. A slight increase in winter peak in colder states by using more supplemental heating than the heat pump heating with higher lockout temperature is also shown. Note that these building-level peak load impacts should not be extrapolated to aggregate coincident peak load impacts; that analysis would need to be based on summing the time-series results across all buildings.

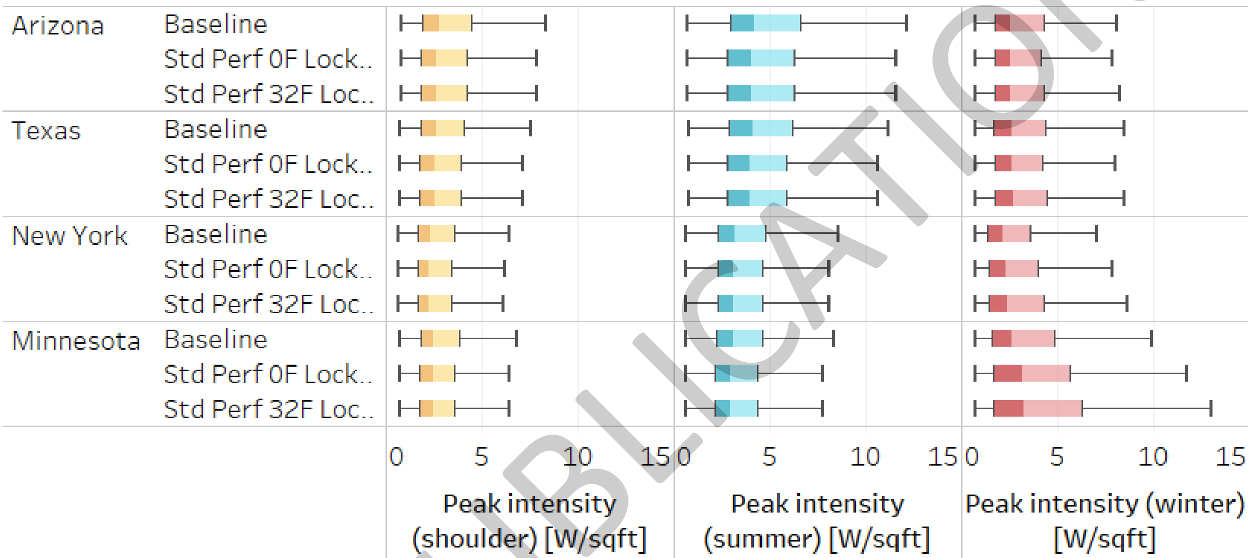


Figure 19. Distributions between all scenarios: peak power intensity

Figure 20 shows the peak power timing implications between two lockout scenarios and the baseline scenario. Fuel switching of the gas heating system shifts the peak to an earlier time in colder states, which is often when outdoor air temperatures are coldest and when commercial buildings are warming up in the morning from unoccupied evening times with setback temperature set points. Peak timing differences in the shoulder and summer seasons are less noticeable compared to the winter peak timing shift. In addition, the impact of different lockout temperatures is also minimal.

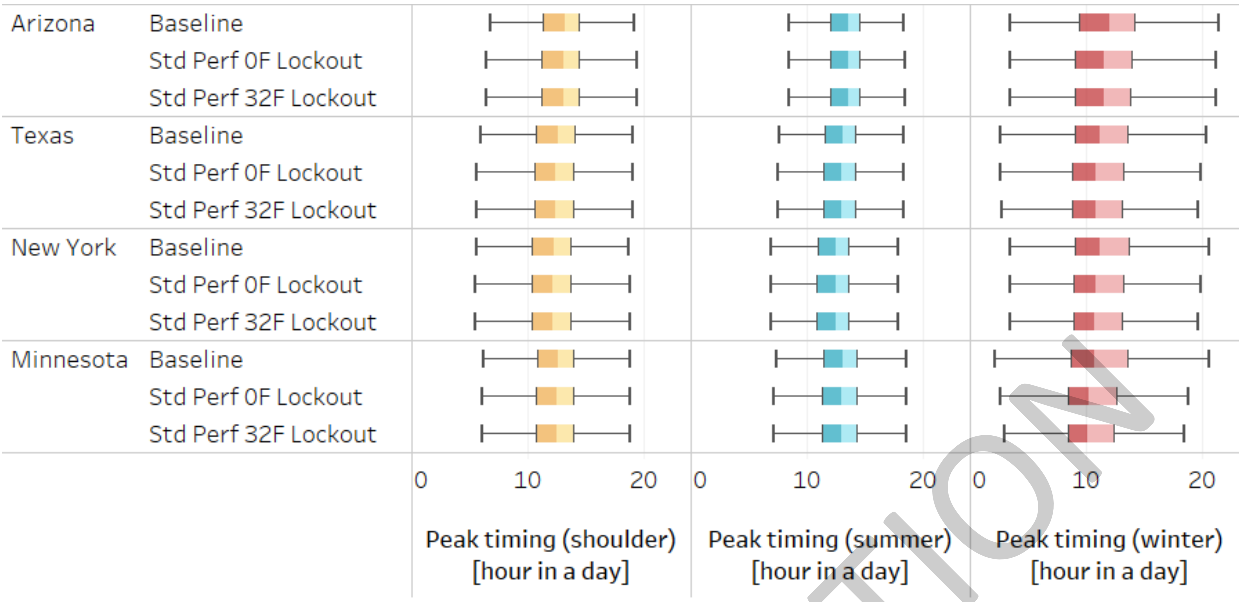


Figure 20. Distributions between all scenarios: peak power timing

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Appendix A. Supplementary Figures

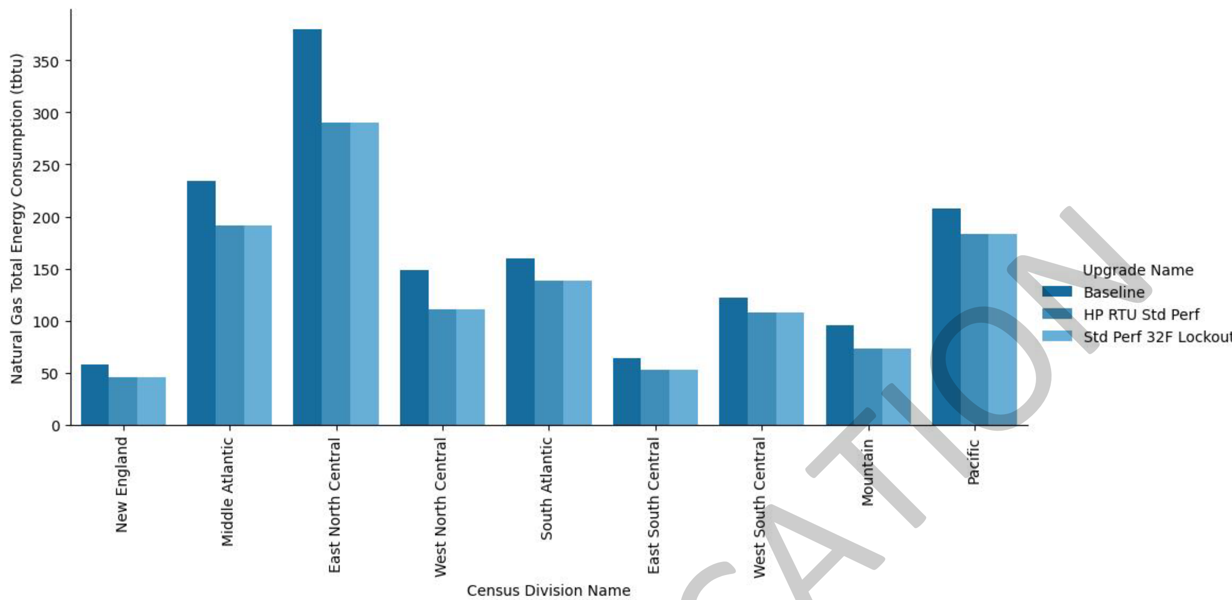

Figure A-1. Site annual natural gas consumption of the ComStock baseline and the measure scenario by census division

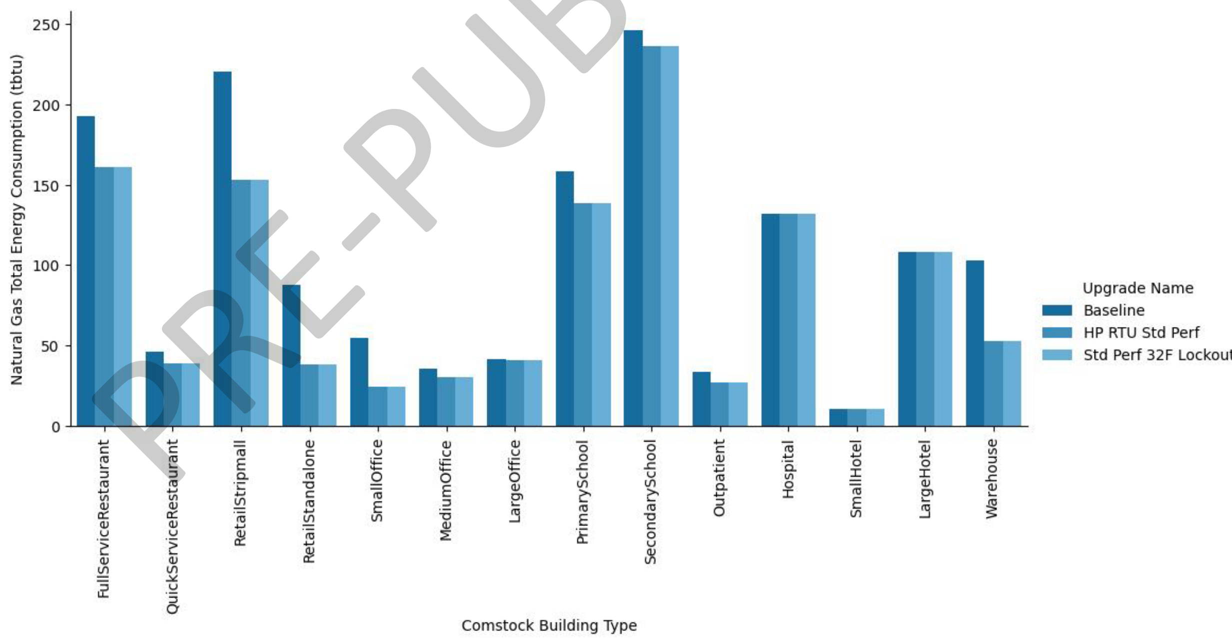

Figure A-2. Site annual natural gas consumption of the ComStock baseline and the measure scenario by building type

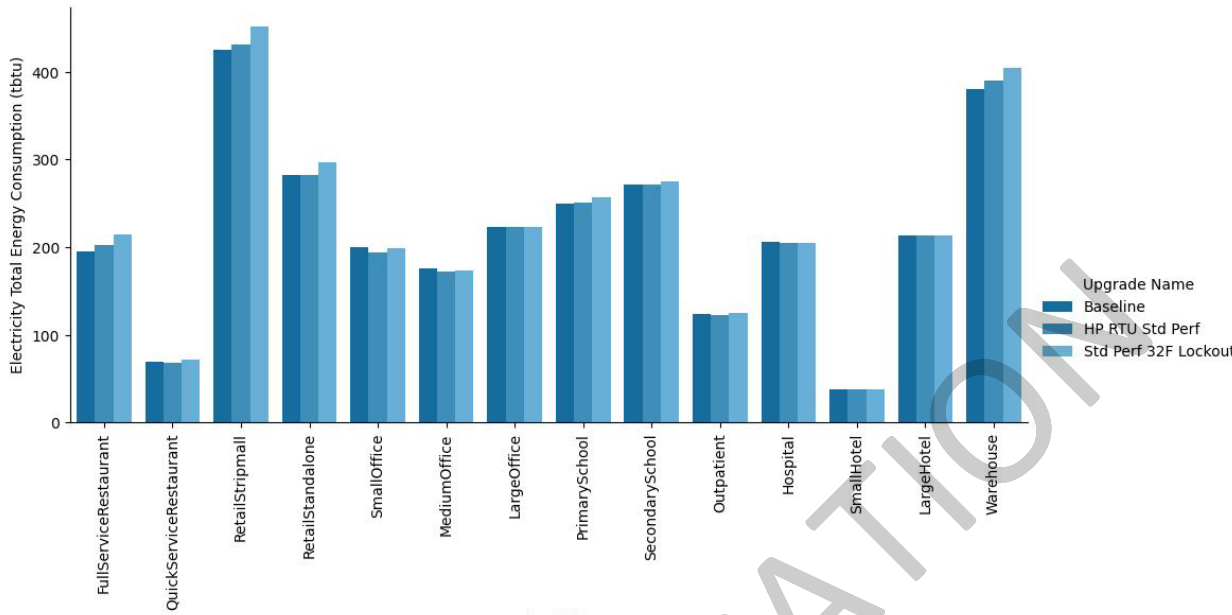

Figure A-3. Site annual electricity consumption of the ComStock baseline and the measure scenario by building type

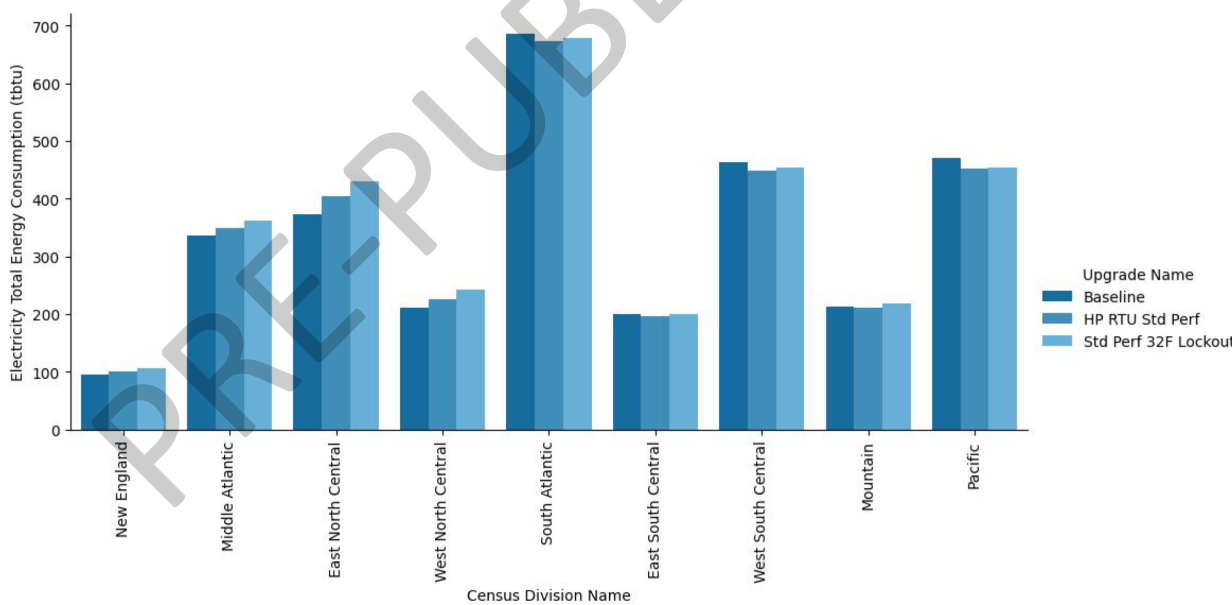

Figure A-4. Site annual electricity consumption of the ComStock baseline and the measure scenario by census division