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ComStock Measure Scenario Documentation:

Laboratory-Informed Modeling of Standard Performance Heat Pump Rooftop Units

Chris CaraDonna

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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Technical Report
NREL/TP-5500-95119
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Suggested Citation
CaraDonna, Chris. 2025. *ComStock Measure Scenario Documentation: Laboratory-Informed Modeling of Standard Performance Heat Pump Rooftop Units.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-95119. https://docs.nrel.gov/docs/fy25osti/95119.pdf.

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Technical Report
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List of Acronyms

CBECS	Commercial Buildings Energy Consumption Survey
COP	coefficient of performance
DX	direct expansion
EIA	U.S. Energy Information Administration
EIR	energy input ratio
HP-RTU	heat pump rooftop unit
HVAC	heating, ventilating, and air conditioning
PADD	Petroleum Administration for Defense District
PSZ-AC	packaged single-zone air conditioner
RTU	rooftop unit
URDB	Utility Rate Database

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 wide 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 subhourly energy consumption of the commercial building stock across the United States. The "baseline" model is intended 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 subhourly energy usage by fuel type and end use.

This report describes the modeling methodology for a single end-use savings shape measure—Standard Performance Heat Pump Rooftop Units Leveraging Lab-Tested Data—and briefly presents the key findings. The full public dataset can be accessed on the ComStock™ data lake or via the Data Viewer at comstock.nrel.gov. The public dataset allows users to create custom aggregations of results for their use case (e.g., filter on a specific county).

The key modeling assumptions and technical details are summarized in Table ES-1.

Table ES-1. Summary of Key Modeling Specifications

Package Title:	**Lab-Informed Modeling of Standard Performance Heat Pump Rooftop Units**
Technology Description	• This measure scenario replaces gas and electric resistance rooftop units (RTUs) in the U.S. commercial building stock with standard efficiency commercial off-the-shelf heat pump rooftop units. • This study uses performance data based on NREL laboratory testing of a 7.5-ton standard efficiency heat pump RTU. This is the main difference between this measure scenario and a similar ComStock measure scenario—Standard Performance Heat Pump Rooftop Units—that uses published manufacturer data tables to inform performance. These two scenarios are compared in this report.
Performance Assumptions	• Performance data are based on NREL laboratory testing of a standard efficiency 7.5-ton standard efficiency heat pump RTU. • Heat pumps are sized based on the design cooling load, with fully modular supplemental electric resistance heat used to address heating loads not met by the heat pump. • Heat pumps are modeled with two stages of cooling and a single stage of heating with a multispeed fan. The minimum airflow ratio is the higher of 40% or the design outdoor air flow.

Package Title:	Lab-Informed Modeling of Standard Performance Heat Pump Rooftop Units
	• Heat pump gross capacity and efficiency retention at 0°F are modeled at 36% and 42% respectively, compared to rated conditions at 47°F. • Defrosting of the outdoor coil is modeled with reverse-cycle compressor operation, following the EnergyPlus “on-demand” control scheme. Defrost operation is locked out above 40°F. • The lockout temperature is 0°F, below which the heat pump is disabled and only supplemental heating is used. • Energy efficiency features such as heat recovery, economizers, and demand control ventilation are unchanged from the corresponding baseline ComStock model.
Applicability	• This measure scenario is applied to ComStock models with existing gas or electric resistance single-zone RTUs. • This measure scenario is not applied to RTUs serving kitchens, or units where the outdoor air fraction is over 55%. • Overall, this measure is applied to models that comprise 36% of the stock floor area.
Release	2025 Release 1: 2025/comstock_amy2018_release_1/

National annual results for site energy and energy bills are summarized in Table ES-2 and Table ES-3.

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

“Applicable” buildings are those which receive the upgrade based on criteria defined for this study.

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	320.2	1524.1	21.0%	627.6	51.0%
Electricity	-1.3	3173.4	0.0%	1220.0	-0.1%

Table ES-3. Key Results for Annual Utility Cost Savings

Electricity cost 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 which receive the upgrade based on criteria defined for this study.

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	3.4	17.4	19.6%	7.0	48.6%
Electricity	0.3	107.7	0.3%	41.5	0.7%
Fuel Oil	0.3	0.7	50.8%	0.4	87.7%
Propane	0.6	1.0	56.1%	0.9	62.0%
Total	4.6	126.8	3.6%	49.9	9.3%

Acknowledgments

The authors would like to acknowledge the valuable guidance and input provided by Parveen Dhillon, Grant Wheeler, Jeff Munk, and Eric Bonnema.

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1 Introduction

Packaged rooftop units (RTUs) are one of the most prominent HVAC system types in the United States, making them an impactful segment of the building stock for energy usage, energy bill costs, and electricity grid load shape. Most existing RTUs in the U.S. building stock use gas-fired heating, with a lesser proportion using electric resistance heating (among other less common options).

Heat pumps offer a higher-performance electric option for commercial building space heating. They can deliver space heating 2–4 times more efficiently than electric resistance options. Based on the 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].

This study investigates the mass replacement of existing gas-fired or electric-resistance RTUs

in the U.S commercial building stock with heat pump RTUs (HP-RTU). The ComStock public dataset already includes several similar iterations of this scenario, including:

- Advanced performance variable-speed HP-RTUs [1]
- Advanced performance variable-speed HP-RTUs with supplemental heating matching the existing fuel type of the building [2]
- Advanced performance variable-speed HP-RTUs with exhaust air energy recovery [3]
- Standard performance HP-RTUs [4]

Like the existing ComStock measure scenario for "Standard Performance" HP-RTUs, this study models commercially available off-the-shelf HP-RTUs with electric supplemental heating. However, this study leverages NREL laboratory testing data of a 7.5-ton HP-RTU to inform performance. Alternatively, the existing "Standard Performance" ComStock measures in the ComStock public dataset use published data tables from multiple manufacturers and unit sizes. Therefore, this study serves as another option that improves our confidence in modeling the performance of HP-RTUs.

To date, there has been limited published laboratory testing data on the performance of HP-RTUs. Air-source heat pump performance is more sensitive to key assumptions compared to gas or electric resistance coils. This is because they rely on ambient air to transfer heat, which can vary in temperature substantially during heating hours, impacting both heat pump efficiency and capacity. In contrast, gas and electric resistance systems generate heat directly, making their performance less dependent on external temperature variations and thus more predictable. The testing data used in this study adds confidence to our HP-RTU energy modeling, as we can confirm performance against real operational data.

There are several available options for standard performance HP-RTUs on the market. A more detailed review of these systems is provided in [4]. Generally, these systems include multiple staged compressors, a multispeed fan, and some form of a supplemental heating coil (electric or gas, sometimes hydronic). Defrosting of the outdoor coil is usually achieved using a reverse cycle operation. There is a compressor lockout that prevents the heat pump from operating when conditions are very cold; this can be a specific minimum temperature, often between 0°F and 32°F, or some condition in the refrigerant system (e.g., a suction pressure exceeding threshold).

2 ComStock Baseline Approach

This measure replaces gas or electric resistance RTUs in the baseline ComStock models with a HP-RTU, as specified in this report. The prevalence of RTUs in the ComStock baseline is interpreted from the 2012 CBECS microdata [5]. The stock prevalence of HVAC system types in ComStock is shown in Figure 1.

RTUs in the ComStock baseline assume performance specifications and energy efficiency features based on the governing energy code during the time of the last HVAC replacement. This includes cooling efficiency, heating efficiency, and fan power as well as the prevalence of demand control ventilation, energy recovery, and economizers. For models with the “PSZ-AC [packaged single-zone air conditioner] with electric coil” HVAC system type, the ComStock baseline will use electric resistance coils with a heating coefficient of performance (COP) of 1. For models with the “PSZ-AC with gas coil” HVAC system type, the ComStock baseline will generally use a gas furnace efficiency of around 80%. More information on the baseline ComStock assumptions for RTUs can be found in the ComStock Reference Documentation [6].

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 36% of the ComStock floor area (Figure 1). ComStock HVAC distributions are informed by CBECS 2012. The methodology for interpreting CBECS data to create HVAC probability distributions for ComStock is discussed in the ComStock documentation [6]. The measure is not applicable to space types that directly serve kitchens, spaces that are unconditioned, or RTUs with outdoor air ratios above 55%.

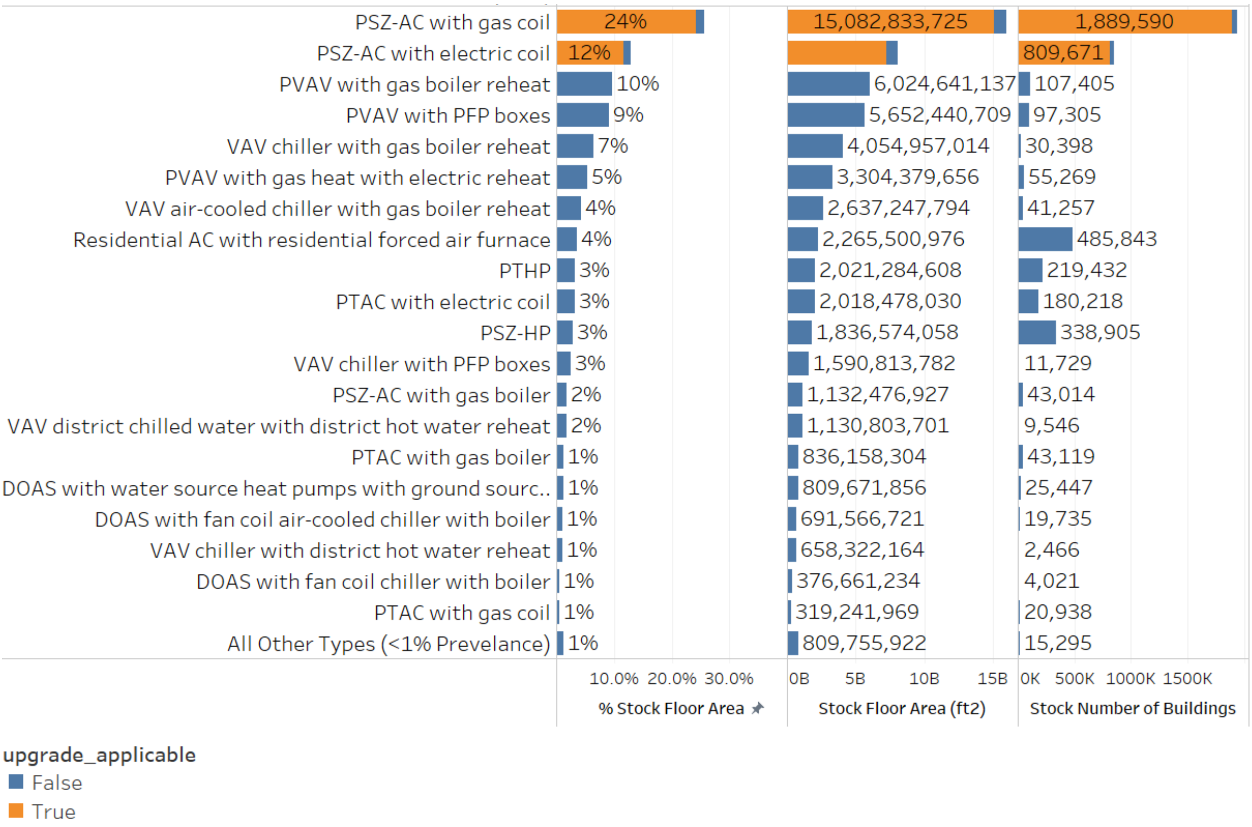

Figure 1. ComStock HVAC system type prevalence by stock floor area.

This measure scenario is applicable to the “PSZ-AC with gas coil” and “PSZ-AC with electric coil” system types. PSZ-AC= packaged single zone air conditioner; PVAV = packaged variable air volume; PFP = parallel fan powered box; PTHP = packaged terminal heat pump; DOAS = dedicated outdoor air system

3.2 Measure Scenario Modeling Methodology

In this measure scenario, existing gas-fired or electric resistance RTUs are replaced with HP-RTUs modeled to align with typical standard performance HP-RTUs on the market today. The key performance metrics are largely based on NREL laboratory testing of a 7.5-ton “standard performance” HP-RTU. The application of this data, and other key assumptions, are described in this section.

3.2.1 Heat Pump Sizing

The HP-RTUs in this study are sized to meet the design cooling load, following the same methodology as [4]. Sizing to the design cooling load is not necessarily optimal, but it is common practice [1].

The sizing of heat pumps is nontrivial because the same refrigerant system is used for both heating and cooling. Heat pumps in very cold climates often require a source of supplemental heat, which is often sized to meet the entirety of the heating load. This is because heat pump capacity generally decreases as outdoor ambient temperature decreases, which generally corresponds to the highest heating loads for the building. Furthermore, compressor lockout controls are often implemented in heat pump systems, which disable heat pump operation below a certain temperature. This requires the supplemental heat source to be sized to meet the full load below this temperature.

Because the supplemental heat source in colder climates is often sized to meet the design heating load, the system can then be sized based on the required cooling capacity with the assumption that the supplemental heat source will address any heating load exceeding the corresponding capacity of the heat pump, avoiding the need to purchase a larger-capacity unit. Supplemental heat is less of a concern in warmer climates where the design cooling load exceeds the design heating load, even when accounting for heat pump capacity degradation at lower temperatures, and where the design heating temperature is well above any minimum compressor lockout temperature.

3.2.2 Heat Pump Heating

The modeling methodology used in this study intends to align with the performance data from NREL laboratory testing of a standard efficiency 7.5-ton HP-RTU, and other assumptions from typical commercial off-the-shelf HP-RTUs on the market today. The RTUs are modeled with one stage of direct expansion (DX) heat pump heating. Although these RTUs often have two compressor stages, the default operation of the tested unit as well as other available products [4] use both compressors as the first and only stage of heat pump heating.

Table 1. Heat Pump Rated Heating COP and Capacity by Heating Stage

Gross COP and capacity values shown in this table are at rated conditions and therefore do not include the impact of performance modifier curves. Rated values are at 47°F ambient air temperature and 70°F at the indoor coil.

Heating Stage	Stage Name	Capacity Fraction of Rated	Fan Flow Fraction	COP Fraction of Rated	Applied Rated COP[1]	Minimum Lockout Temperature
1	High (rated)	1	1	1	4.0	0°F

[1] Rated COP is the gross COP, which does not include indoor fan heat or fan power

As discussed in Section 3.2.1, the rated heating capacity is sized to match the required rated cooling capacity, which is determined for every individual RTU in ComStock. If the required heating load is greater than what the heat pump can provide for a timestep, or the heat pump is locked out, then supplemental heating is used to address any unmet heating loads.

Heat pump performance and capacity can vary substantially based on operating conditions, including indoor/outdoor temperature, fan flow fraction, and part load ratio. These interactions are accounted for in the simulation through performance modifier curves. This performance curve set was constructed using NREL laboratory testing data of a 7.5-ton standard performance HP-RTU.

1. **Heating capacity as a function of temperature**: Indoor and outdoor drybulb temperature are used at each timestep to determine a capacity modifying factor that is multiplied against the gross rated capacity for each stage. The data fits are illustrated for each heating stage in Figure 2, with each data point reflecting the result of laboratory testing. During simulation, the ratios (right plot) are multiplied by the nominal heat pump heating capacity for each time step to determine the actual available capacity for the time step.

2. **Heating efficiency as a function of temperature**: Indoor and outdoor drybulb temperature are used at each timestep to determine an efficiency modifying factor that is multiplied against the gross rated energy input ratio (EIR) (EIR = 1/COP) for each heating stage. The curves are illustrated for each heating stage in Figure 3 with each data point reflecting the results of laboratory testing. During simulation, the ratios (right plot) are multiplied by the gross heat pump heating efficiency for each time step to determine the realized COP for the time step.

3. **Heating efficiency as a function of part load ratio:** Part load ratio, which is defined as the fraction of load required for the timestep divided by the total available heating capacity, is used at each timestep to determine an efficiency modifier factor that is divided by the gross rated EIR. This performance curve essentially reduces equipment efficiency due to cycling losses. The curve is illustrated in Figure 4.

4. **Defrost power as a function of temperature**: Indoor wetbulb and outdoor drybulb temperature are used at each timestep to determine a power modifying factor that is multiplied by the rated heating capacity. This performance curve dictates compressor power usage during reverse cycle defrost operation and is only active during timesteps where defrost occurs. The curve is illustrated in Figure 5. Defrost operation is discussed further in Section 3.2.4.

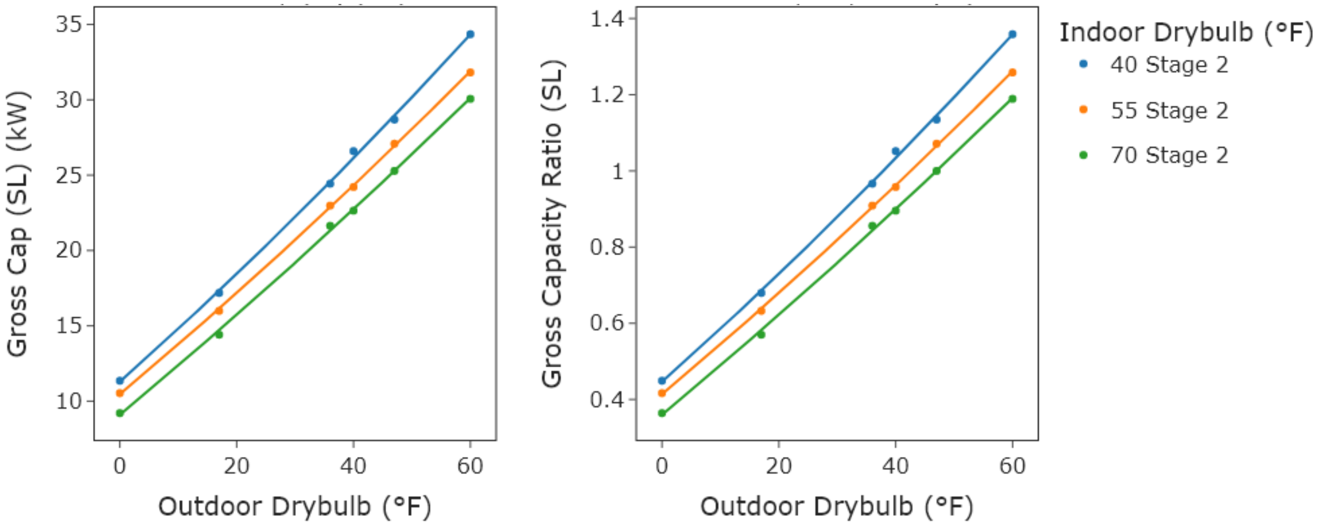

Figure 2. Heat pump gross heating capacity as a function of temperature performance map.

The left plot shows the raw gross heating capacity of the tested unit, while the right plot shows the generalized ratios applied in modeling.

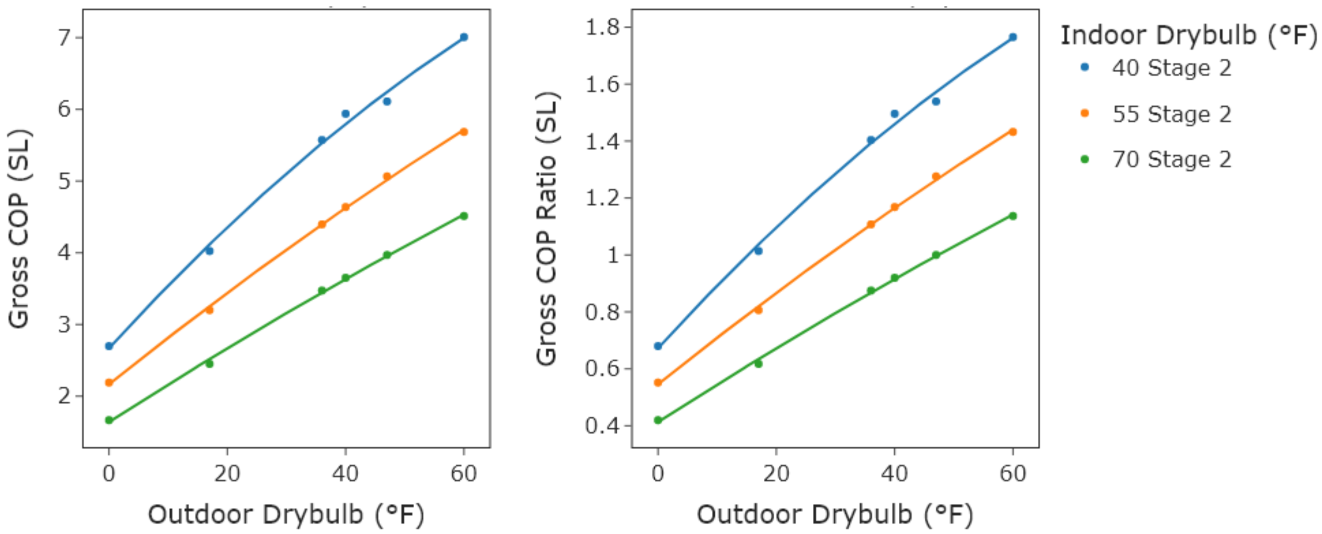

Figure 3. Heat pump gross heating COP as a function of temperature performance map.

The left plot shows the raw gross heating COP of the tested unit, while the right plot shows the generalized ratios applied in modeling.

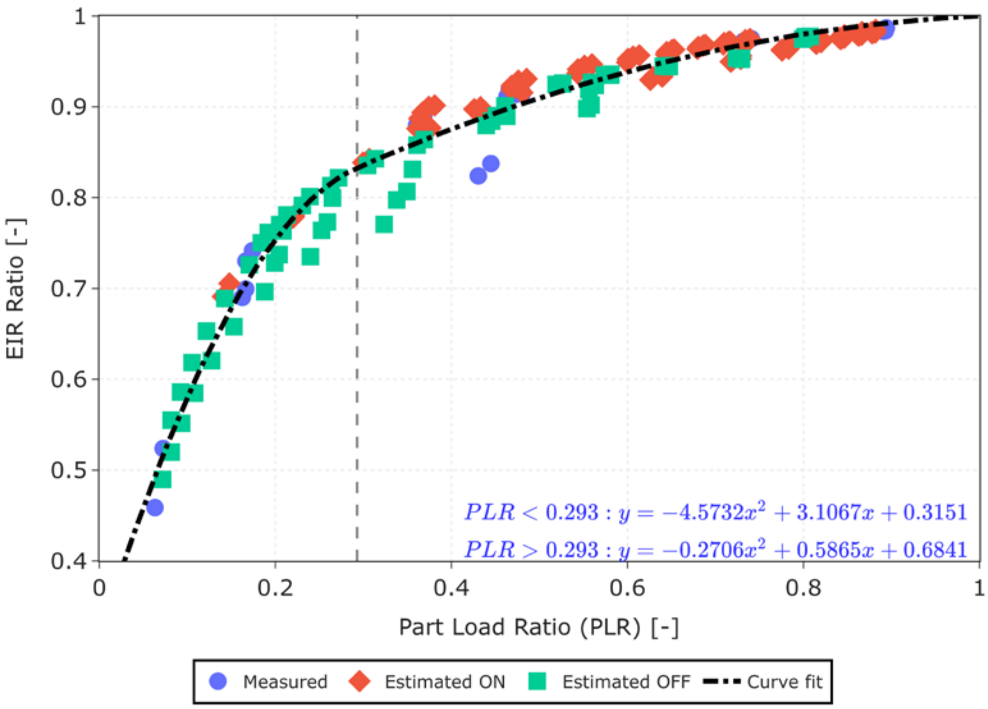

Figure 4. Energy input ratio (EIR) as a function of part load ratio.

The output of this curve is divided by the EIR (1/COP) at each timestep, effectively reducing efficiency due to cycling losses. EnergyPlus does not currently support performance curves in the form of piecewise regressions functions, therefore, the above functions are implemented in the models through lookup tables generated with these functions.

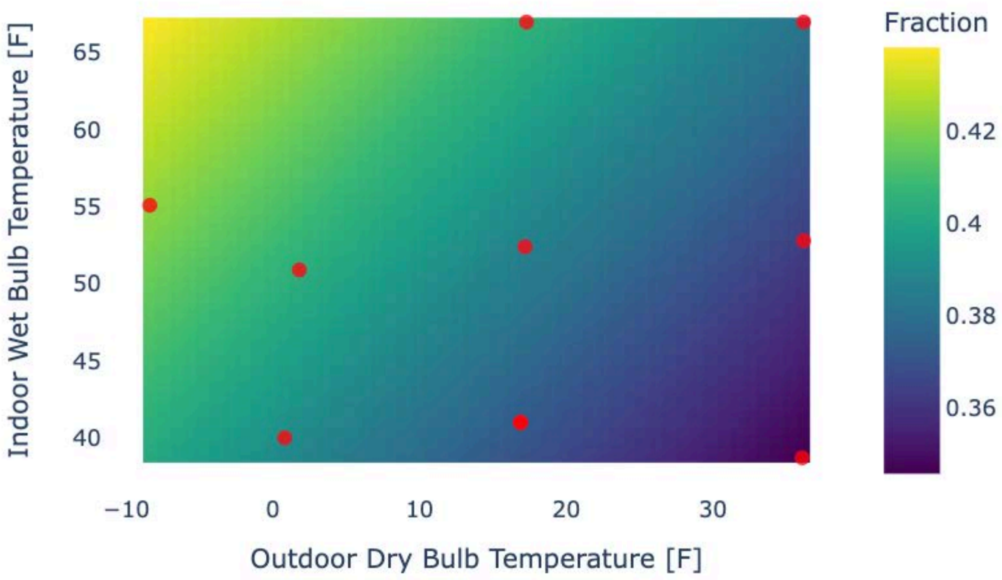

Figure 5. Defrost power modifier curve as a function of indoor wetbulb and outdoor drybulb temperature.

The output of this curve is multiplied by the rated heating capacity, the fractional defrost time and the runtime fraction of the heating coil to give the defrost power for the timestep. The red dots are the testing points.

3.2.3 Supplemental Heating

This study uses variable capacity electric supplemental coils with a COP of 1 (100% efficiency). Supplemental heating is used to address any heating load not met solely by the heat pump. The supplemental heating coil operates simultaneously with the heat pump as needed to minimize usage of the relatively less efficient supplemental coil. In other words, heat pump heating is prioritized over supplemental heating to maximize system efficiency.

Supplemental heating, both in the models and in real buildings, occurs for multiple reasons. First, RTUs, both in this analysis and often in real buildings, are sized to the design cooling load, which means there is no guarantee that it will meet the design heating load. Often, when sized for cooling loads, the heat pump heating capacity is insufficient to meet the heating load, and thus supplemental heating is necessary. Additionally, heat pump heating capacity decreases with lower outdoor air temperatures, which can be further exacerbated by increased heat pump defrost operation during colder outdoor periods. Buildings in colder climates are generally expected to show higher prevalence of supplemental heat on average due to higher heating loads, colder temperatures that decrease available heat pump capacity, and insufficient heat pump capacity when sized to cooling loads because in cold climates the cooling load is typically smaller than the heating load.

3.2.4 Defrost

Defrost occurs in heat pumps to remove frost buildup on the outdoor coil that inhibits proper heat transfer. Defrost in this study is modeled as reverse cycle, meaning the heat pump goes into cooling mode to heat up and melt the frost buildup on the outdoor coil. This operation adds cooling to the indoor airstream, effectively adding additional heating load, and eliminates the availability of the heat pump for heating. Both factors can increase the need for supplemental heating.

The electricity consumption of the refrigeration cycle during defrost is determined by the performance curve shown in Figure 5, which is a function of outdoor drybulb and indoor wetbulb temperature. The output of this curve is multiplied by the coil rated heating capacity, the fractional defrost time and the runtime fraction of the heating coil which yields the defrost power for the timestep. Note that this power does not include the system supply fan, or any required supplemental heating, which are considered separately in the model.

When engaged, a reverse-cycle defrost strategy eliminates the heating capability of the heat pump system, which often requires the use of lower-efficiency supplemental heating during these times to maintain building comfort. Additionally, reversing the cycle of the heat pump causes additional heating load, as the system is effectively in cooling mode, supplying cold air to the building. EnergyPlus adds this additional load to the total effective heating load during defrost timesteps [7], [8]. However, one key distinction between defrost operation in most real units and EnergyPlus is that EnergyPlus will only use supplemental heat if the available heating capacity minus the cooling during defrost for the timestep is not sufficient to meet the load. This can underestimate the need for supplemental heat in cases where defrost is enabled but the heat pump capacity is still sufficient to meet load.

Control of the defrost cycle can also vary. Some units use a set time fraction, where the unit operates in defrost mode for a specified time at regular time intervals when outdoor air temperatures are below a specified temperature threshold. This analysis uses the EnergyPlus "on-demand" defrost operation, which estimates the amount of time needed for defrost based on a set of empirical calculations dependent on outdoor air wetbulb temperature, coil temperature, and other parameters. These calculations are described in more detail in the EnergyPlus documentation [7], [8].

3.2.5 Crankcase Heater

Crankcase heater power in this workflow is modeled per [9] and are active when the compressors are not running and ambient temperatures are below 40°F. Note that this temperature threshold can vary with some equipment turning on crankcase heaters anytime the compressors are not active. Crankcase heaters are electric resistance heating elements that strap around a compressor and are used to prevent refrigerant migration to the compressors when the compressors are off. Equipment damage can occur if the compressors try to start and there is a buildup of liquid refrigerant in the compressor. This is generally a concern at outdoor temperatures below 40°F, so manufacturers often specify a maximum temperature threshold for crankcase heater operation around this temperature; the crankcase heaters do not operate when the outdoor air temperature is above this threshold.

Equation 1: Formula for calculating crankcase heater (CCH) power from [9].

$$CCH\ Power = 60 * \left(\frac{Nominal\ tonnage\ per\ compressor}{10}\right)^{0.67}$$

3.2.6 Cooling Performance

The cooling system is modeled with two stages: the first using one compressor and the second using both compressors simultaneously. The performance curves and other performance assumptions are described thoroughly in [4]. These performance assumptions represent commercially available standard performance RTUs. The staging assumptions are summarized in Table 2.

Table 2. Heat Pump Rated Cooling COP and Capacity by Cooling Stage

COP and capacity values shown in this table are at rated conditions and, therefore, do not include the impact of performance modifier curves. Rated values are at 95°F ambient air temperature.

Cooling Stage	Stage Name	Capacity Fraction of Rated	Fan Flow Fraction	COP Fraction of Rated	Applied Rated COP[1]	Sensible Heat Ratio Fraction
2 (Rated)	High	1.00	1.00	1	3.97	0.77
1	Low	0.50	0.59	1	3.97	0.82

[1] Rated COP is the gross COP, which does not include indoor fan heat or fan power

3.2.7 Fan Power and Operation

Here, the modeled HP-RTUs utilize a multispeed fan system. During ventilation-only mode, when no heating or cooling is required but the building still requires outdoor ventilation air, the fan defaults to a speed that is either the higher of (1) the design outdoor air flow rate or (2) 59%

of the maximum. The design outdoor air flow rate is prescribed by ANSI/ASHRAE Standard 62.1 in ComStock and therefore varies substantially across the stock. This can result in a fan speed greater than 59% for systems with especially high outdoor air requirements.

Fan power varies as a function of fan speed and is modeled using a fan power as a function of flow fraction curve in EnergyPlus. The output of this curve is multiplied by the design fan power, lowering fan power with flow rate. The fan power curve modeled in this work is illustrated in Figure 6.

Table 3. Fan Flow Fractions for Various Heat Pump Operation Stages

Stage	Stage Mode	Stage Name	Fan Flow Fraction
1H	Heating	High	1
2C	Cooling	High	1
1C	Cooling	Low	0.59
1V	Ventilation-only	Vent	Max(design OA fraction, 0.40)

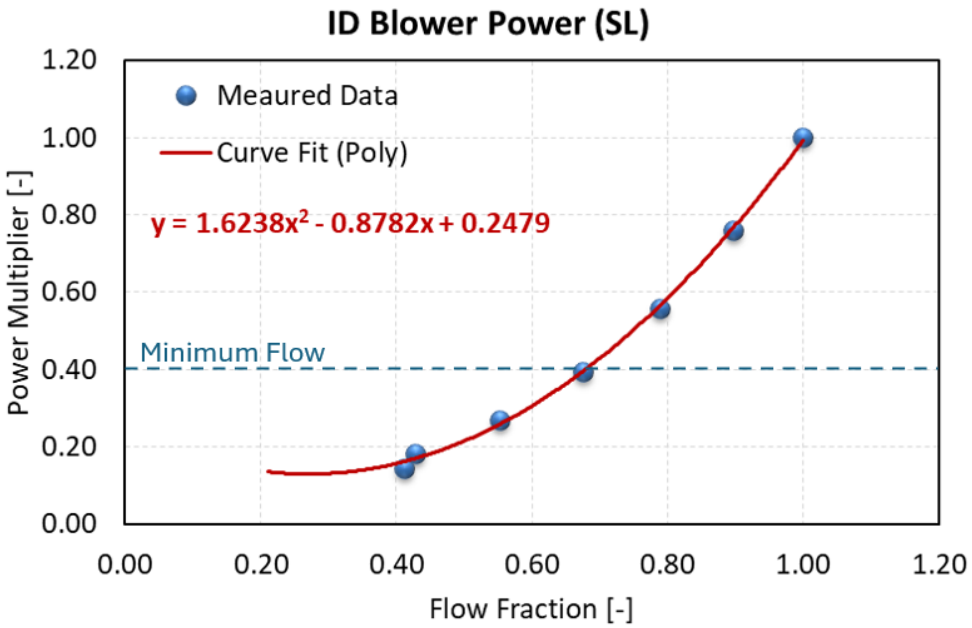

Figure 6. Fan power curve as a function of flow fraction. The output of this curve is multiplied by the design fan power to determine the realized fan power for each time step.

3.2.8 Cycling Losses

The operating efficiency of a heat pump system can be reduced when the unit runs for short periods of time. This is often referred to as short cycling, which occurs primarily because the useful system thermal output lags power input during the start-up and warm-up of compressors. The impact of the warm-up period becomes nearly negligible when the unit has long run times but can be notable if the system experiences frequent short run cycles. Proper sizing of equipment can mitigate the prevalence of short cycling, although complete elimination is sometimes unavoidable due to the wide variation in building loads.

To model the efficiency impacts of short cycling, we use the EIR as a function of part load ratio EnergyPlus performance curve. This curve uses the calculated part load ratio for the timestep to determine an EIR modifier to represent efficiency loss due to compressor short cycling. The curve used in this work is shown in Figure 4, which is derived from NREL lab data for a multispeed HP-RTU. The output of this curve is divided by the EIR; therefore, a lower curve output represents reduced efficiency.

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 [6]. Summary statistics from this implementation are shown in Table 4. ComStock does not currently estimate utility bills for district heating and cooling.

Table 4. 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)	$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)

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 [14].

Propane and fuel oil bills are estimated using 2022 EIA averages by state. Residential No. 2 Distillate Prices by Sales Type, 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 [15]. 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 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 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

- Although this study uses performance data from a commercially available RTU, it still represents one of many standard efficiency HP-RTUs on the market. The intent is that this study generalizes the performance to represent units of this class, but it is unclear how similarly they perform without testing many of them. Similarly, the testing was performed on a 7.5-ton unit. It is most likely that different sizes have slightly different performance.
- This study assumes an electric resistance supplemental heating coil that can modulate its output to exactly match the required load not met by the heat pumps. Many units on the market used two stage electric heating coils which may cause additional demand spikes.
- EnergyPlus does not model discrete defrost cycles and instead uses a time fraction of defrost. This time fraction is applied to the simulation timestep regardless of its length. This results in a small amount of defrost operation in every timestep where conditions for defrost are met. Additionally, many units will run the supplemental heat during defrost cycles to prevent "cold blow." This is not a feature of EnergyPlus, and the heat pump will run longer in the heating mode to offset cooling delivered during defrost. Supplemental heat will only be used to offset cooling during defrost if the heat pump cannot meet the combined load of the building and the cooling delivered during defrost. These limitations can underestimate the peak demand impact of defrost and underestimate the amount of supplemental heating required to prevent cold blow during defrost.

4 Output Variables

Table 5 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 Lab Data measure applied. These output variables can also be used for understanding the economics of the upgrade (e.g., return on investment) if cost information (e.g., material, labor, and maintenance costs for technology implementation) is available.

Table 5. Output Variables Calculated From the Measure Application

Upgrade	Variable Name	Description
Roof Insulation	Energy Code Followed During Last Roof Replacement	The energy code followed during the last roof replacement (or installation) for a building model, which dictates the roof performance properties for the ComStock baseline models
HP-RTU	stat.hvac_count_dx_cooling_XX_to_XX_kbtuh	Total number of direct expansion (DX) cooling units within a size bin
	stat.hvac_count_dx_heating_XX_to_XX_kbtuh	Total number of DX heating units within a size bin
	stat.hvac_count_heat_pumps_XX_to_XX_kbtuh	Total number of heat pump units within a size bin
	stat.dx_cooling_average_cop..COP	Average operational COP (compressor only) of DX cooling models during simulation
	stat.dx_cooling_capacity_tons..tons	Total tons of DX cooling modeled
	stat.dx_cooling_design_cop..COP	Average rated (compressor only) COP of DX cooling units at rated conditions
	stat.dx_heating_average_cop..COP	Average operational COP (compressor only) of DX cooling models during simulation
	stat.dx_heating_average_minimum_operating_temperature..C	Average compressor minimum heating lockout temperature, below which the heat pump heating will be disabled (°C)
	stat.dx_heating_average_total_cop..COP	Average effective COP of DX heating. This includes energy from the defrost cycle and any supplemental heating
	stat.dx_heating_capacity_at_XXF..kBtu_per_hr	Average available heat pump capacity at a given temperature (kBtu/h)
	stat.dx_heating_capacity_at_rated..kBtu_per_hr	Average available heat pump capacity at rated temperature (47°F)

Upgrade	Variable Name	Description
	stat.dx_heating_design_cop..COP	Average design COP of heat pumps
	stat.dx_heating_design_cop_XXf..COP	Heat pump COP at a given temperature, or rated conditions (47°F)
	stat.dx_heating_fraction_electric_defrost	Fraction of heat pump electric defrost energy to DX heating energy
	stat.dx_heating_fraction_electric_supplemental	Fraction of heat pump electric supplemental heating energy to DX heating energy
	stat.dx_heating_supplemental_capacity_electric..kBtu_per_hr	Electric coil supplemental heating capacity (kBtu/h)
	stat.dx_heating_supplemental_capacity_gas..kBtu_per_hr	Gas coil supplemental heating capacity (kBtu/h)
	stat.dx_heating_supplemental_capacity..kBtu_per_hr	Total (gas or electric) supplemental heating capacity (kBtu/h)
	stat.dx_heating_fraction_supplemental	Fraction of heat pump heating energy from supplemental heating
	stat.dx_heating_total_dx_electric..J	Total heat pump heating electric load (J)
	stat.dx_heating_total_dx_load..J	Total heat pump heating load (J)
	stat.dx_heating_total_load..J	Total heat pump system heating load (J)
	stat.dx_heating_total_supplemental_load_gas..J	Total heating output energy from gas supplemental coil (J)
	stat.dx_heating_total_supplemental_load_electric..J	Total heating output energy from electric supplemental coil (J)
	stat.dx_heating_defrost_energy..kBtu	Total heat pump electricity energy for defrost (kBtu)
	stat.dx_heating_ratio_defrost	Ratio of heat pump defrost electricity to heat pump heating energy
	stat.hours_below_XXF..hr	Number of hours below given outdoor air temperature during simulation

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 energy bill 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 strategy, depending on the use case.

Results focus on comparing the ComStock baseline to the HP-RTU with lab testing data measure scenario. However, comparisons are also made to a similar measure scenario published in the ComStock public datasets: HP-RTU with standard performance. These two scenarios represent the same class of HP-RTU and therefore should ideally perform similarly. The only difference is that the HP-RTU with lab data uses NREL laboratory testing data to represent heating performance curves (as described in this report), while the HP-RTU Standard Performance measure instead uses publicly available performance data provided by manufacturers.

5.1 Single Building Measure Tests

In this section, we describe the operation of a small office building in Alamosa County, Colorado, climate zone 6B, to demonstrate the measure scenario application on a single building. The baseline model uses packaged RTUs with direct expansion cooling and gas furnace heating. Outdoor ventilation air is provided directly through the RTUs.

Two HP-RTU scenarios are simulated and compared. The first represents a standard efficiency unit (“Std Perf”) available today, with single-stage heat pump heating and two-speed DX cooling. The minimum lockout temperature is 0°F, and the capacity retention at 0°F is around 42%. The performance for the Std Perf unit is derived from public manufacturer performance tables. The second scenario is similar to Std Perf but uses NREL laboratory testing data of a HP-RTU for heating performance instead of manufacturer data tables. All other assumptions, including cooling performance, are consistent between the two.

Table 6 summarizes the heating and cooling COPs between the two HP-RTU scenarios. Cooling performance is identical, as expected, since both scenarios use the same efficiencies and performance curves for cooling. Comparing heating performance, the scenario using laboratory testing data shows slightly lower annual average COPs. However, the difference is very minimal which suggests the manufacturer performance maps are reasonable compared to realized performance, at least in a laboratory setting.

Table 7 compares annual energy consumption by HVAC end use. Cooling and fan usage are comparable, as expected. The laboratory data shows a 2% increase in heating energy annually, and roughly 1% increase in annual site energy for the HVAC end uses shown. Overall, the differences are minimal, underscoring the alignment between the NREL laboratory testing data and the manufacturer performance tables.

Table 6. Heat Pump Heating and Cooling Performance Comparison for Single Building Between the Standard Performance and Lab Tested Performance HP-RTU Measure Scenarios

	Standard Performance	Lab Data Performance
dx heating average total cop	2.12	2.08
dx heating average cop	2.50	2.47
dx heating design cop	3.84	3.84
dx cooling design cop	3.80	3.80
dx cooling average cop	3.87	3.87

Table 7. Comparison of Annual Energy Consumption for HVAC End Uses for Test Model Between the Standard Performance and Lab Tested Performance HP-RTU Measure Scenarios

End Use	Standard Performance	Lab Data Performance	% Difference
Heating (kBtu)	16,644	16,919	-2%
Cooling (kBtu)	4,701	4,701	0%
Fans (kBtu)	7,564	7,564	0%
Total (kBtu)	28,909	29,184	-1%

5.2 Stock Energy Impacts

The HP-RTU with lab performance data measure scenario demonstrates 7.2% total site energy savings (348 trillion British thermal units [TBtu]) for the baseline U.S. commercial building stock modeled in ComStock (Figure 7). This comparison includes buildings not applicable to the HP-RTU measure scenario. A similar comparison that only includes buildings applicable to the upgrade scenario is included in the Appendix (Figure A-1).

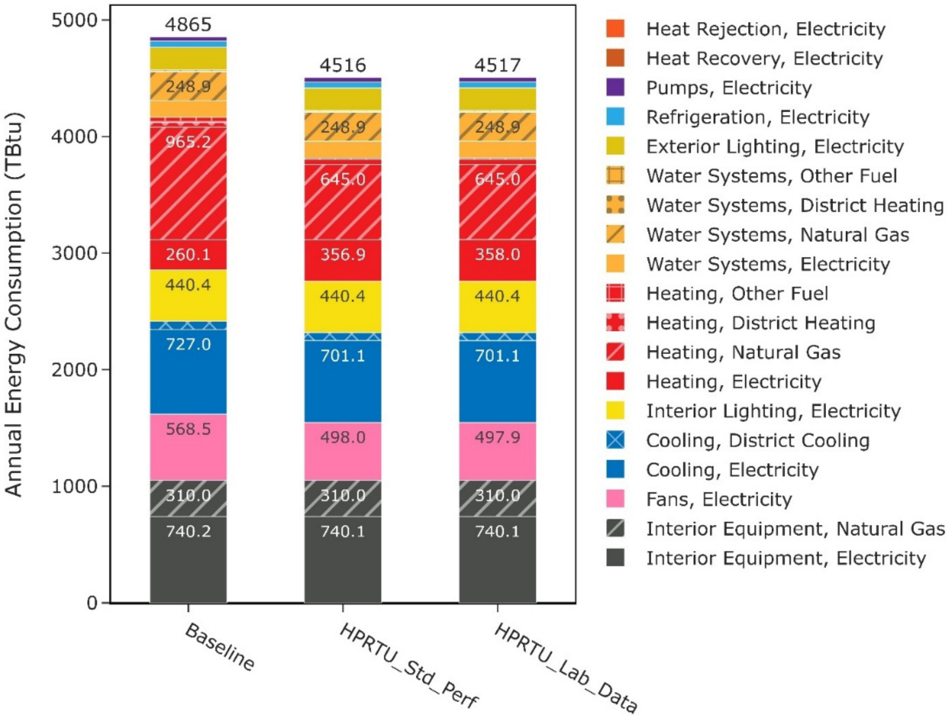

Figure 7. Comparison of annual site energy consumption between the ComStock baseline the HP-RTU Standard Performance and HP-RTU Lab Data measure scenarios.

The plot includes all buildings modeled in ComStock, including those not applicable to the measure scenarios.

Results between the HP-RTU Lab Data and HP-RTU Standard Performance scenarios show minimal difference of ~1 TBtu annually for the stock, which is well within the margin of error for this type of study (<0.1%). These two scenarios both represent a similar class of standard performance HP-RTUs available today. However, the former uses heat pump heating performance data from NREL laboratory testing as described in this report, while the latter uses publicly available performance data from manufacturers. This result demonstrates close alignment between manufacturer data tables versus what was found in the lab. Note that all other performance data besides heating is constant between the two scenarios (e.g., cooling, fans).

Results on an end-use basis compared to the baseline are similar to those presented in the HP-RTU with Standard Performance measure documentation [4]. Some key highlights:

- Natural gas heating is reduced, and electric heating increased, due to switching gas RTUs to electric heat pump RTUs. The overall site heating end use across all fuel types is reduced since electric heat pumps generally have higher on-site COPs than combustion fuels. However, other factors like utility bill impacts should be considered since these savings may not translate proportionally.
- Cooling and fan energy is reduced since we are replacing older, less efficient RTUs with newer, more efficient multistage systems.
- All other end uses show minimal to no change.

5.3 Stock Utility Bill Impacts

The HP-RTU Lab Data scenario shows 3%–4% (~$3–4 billion, 2022) annual utility bills savings for the U.S. commercial building stock modeled in ComStock (Figure 8). This comparison includes buildings not applicable to the measure scenario and therefore should not be interpreted as the average savings of any building. The range of electricity cost outcomes reflects the range of applicable/available electricity rate structures modeled for each building. Other fuel types only use a single rate structure per building based on the state and therefore do not change between the scenarios presented.

Savings are primarily attributable to reductions in natural gas bills. Electricity bills see minimal change. This is because of the balance between increased electricity usage by adding more electric heating with heat pumps and reduced fan/cooling electricity usage by switching out older, less efficient RTUs in the U.S. commercial building stock. Note that outcomes can vary substantially based on factors like building type, climate, operations hours, etc., and annual cost savings may not be achieved for all buildings. The ComStock public dataset should be used to investigate specific stock segments as needed.

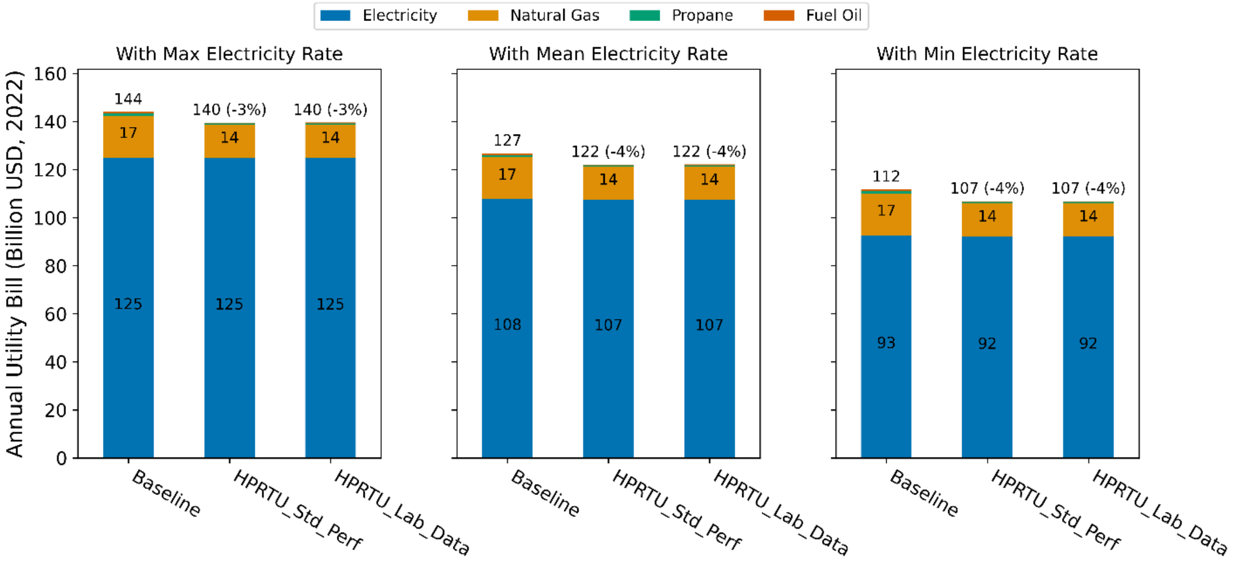

Figure 8. Annual utility bill impacts using the max, mean, and minimum bills across available rate structures for buildings for both the HP-RTU Standard Performance and Lab Data measure scenarios.

Includes buildings not applicable to the HP-RTU measure scenarios.

The HP-RTU Lab Data scenario shows comparable annual stock cost results to the HP-RTU Standard Performance scenario. Again, this underscores the agreement between the published manufacturer data tables used to inform performance curves in the previously published Standard Performance scenario to the performance found in lab testing for the Lab Data scenario discussed in this report.

5.4 Site Energy Savings Distributions

This section discusses site energy consumption for quality assurance/quality control purposes. Note that site energy savings can be useful for these purposes, but other factors should be considered when drawing conclusions, as they are not necessarily proportional to source energy savings or energy cost. When presenting the pairwise distribution of percentage savings, only samples that contain a non-zero value for the corresponding baseline ComStock model are included.

Figure 9 shows the annual percentage site energy savings broken down by end use and fuel type for the HP-RTU Lab Data measure scenario compared to the corresponding models in the ComStock baseline before the measure is applied. The highest savings are for combustion fuel heating, as these systems are replaced by electric heat pump systems. Many buildings save 100% of the energy for this combination of end use and fuel type. Buildings that save less than 100% include some systems that are not applicable to the HP-RTU measure scenario, such as gas unit heaters.

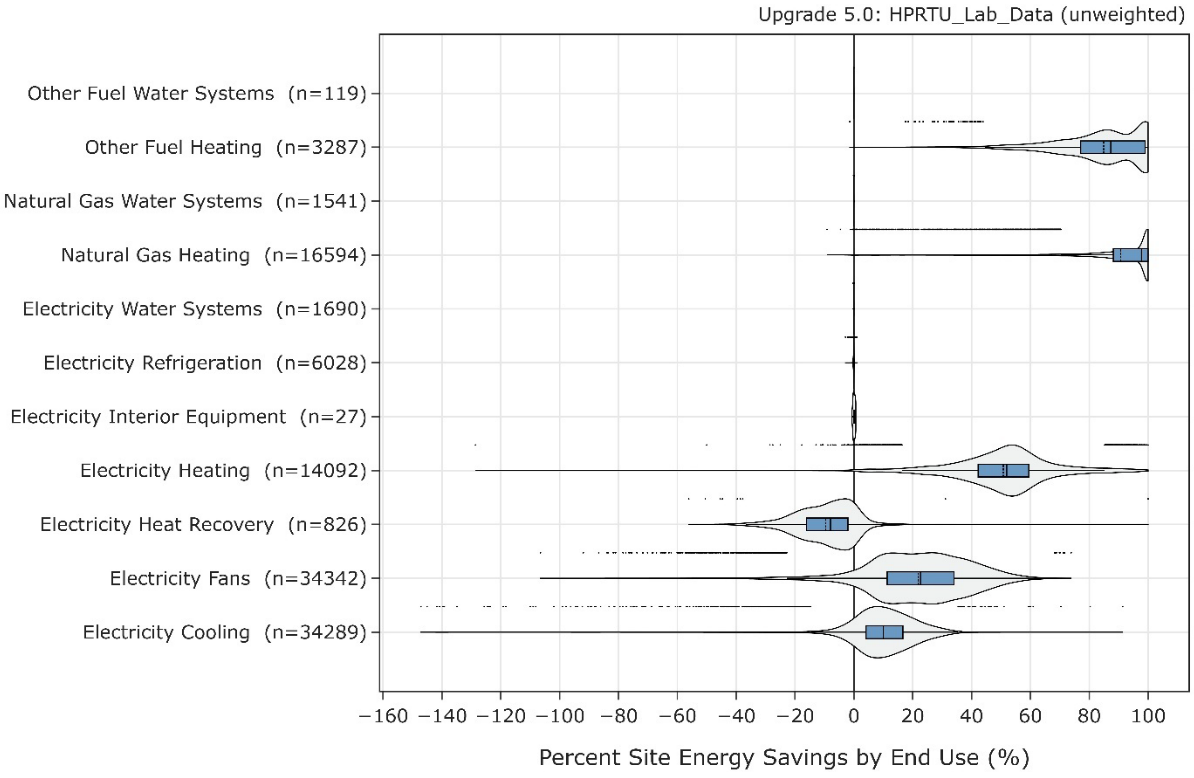

Figure 9. Percent site energy savings distribution for ComStock models with applied measure scenario by end use and fuel type.

The data points that appear above some of the distributions indicate outliers in the distribution, meaning they lie 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. Each data point represents the pairwise comparison between a ComStock baseline model and the corresponding model after the measure scenario is applied.

A few outliers show increased gas usage, mostly in buildings that still have some non-applicable gas systems and very small overall heating loads. In these cases, even minor changes in gas heating energy can lead to large fluctuations in percent savings. Figure A-2 in the Appendix shows the same plot using EUI savings instead of percentage savings, with no building showing a notable increase in gas use.

The electricity heating end use also shows savings in Figure 9, representing buildings with some electric resistance heating replaced with more efficient electric heat pump heating. However, it is important to note that this does not include buildings that start with no electric heating. Buildings that did not have electric heating in the baseline are not shown because the percent savings calculation would be invalid from a starting point of 0. These buildings result in increased electric heating, although this is not depicted in the plot.

The cooling and fan end uses also show savings for the median building around 10%–20%. This is due to replacing older, less efficient RTUs in the existing building stock with higher efficiency multispeed fan and cooling systems. A small portion of the distribution shows increases usage (negative savings) in these categories. The energy increases are mostly buildings showing increased fan and outdoor air usage during night cycling, or buildings with very low HVAC usage that are sensitive to change in a percent savings calculation.

Figure 10 shows the annual percentage site energy savings by fuel type for the HP-RTU Lab Data measure scenario compared to the corresponding models in the ComStock baseline before the measure is applied. Most on-site combustion fuel is removed in applicable buildings, but some remains due to non-applicable HVAC systems as well as other end uses that use combustion fuels (e.g. kitchen equipment).

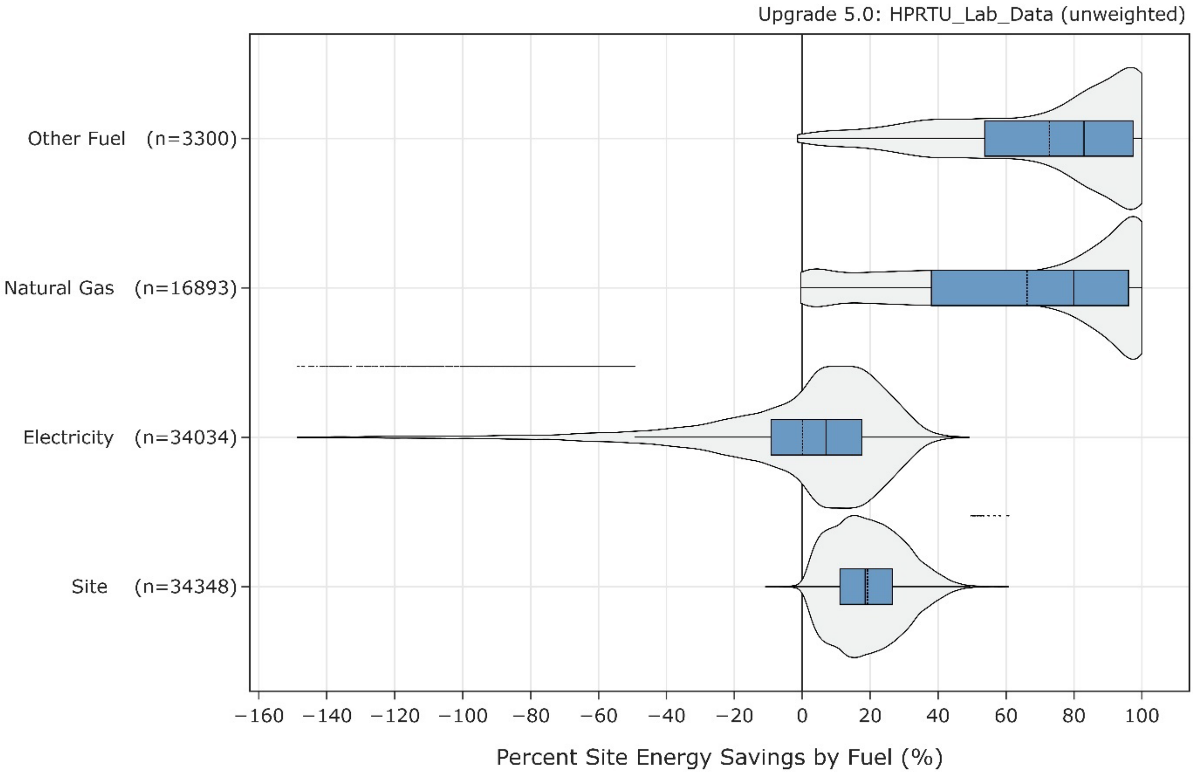

Figure 10. Percent site energy savings distribution for ComStock models with the applied measure scenario by fuel type.

The data points that appear above some of the distributions indicate outliers in the distribution, meaning they lie 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. Each data point represents the pairwise comparison between a ComStock baseline model and the corresponding model after the measure scenario is applied.

The electricity end use shows mixed results with notable portions of the distribution showing both savings and increases. Buildings that save electricity with this measure scenario generally do so by replacing less efficient electric resistance RTUs with HP-RTUs, and/or in cases where the reduction in fan/cooling electricity use outweighs the increased electricity use for heating when transitioning from a gas unit (e.g., buildings in warmer climates). Buildings that show increased electricity are generally those that start with primarily gas heating, where transitioning to electric heating outweighs any fan/cooling savings associated with the newer units.

The median building shows 20% site energy savings, which is expected when switching from electric resistance or gas heating to relatively more efficient heat pumps. However, site energy savings do not consider the energy used to generate and distribute electricity to the site and may not translate proportionally to utility bill savings or source energy savings. These other factors should be considered depending on the priorities of the application.

Figure 11 shows the annual percent site energy savings by climate zone for the HP-RTU Lab Data measure scenario compared to the corresponding models in the ComStock baseline before the measure is applied. Higher percent site energy savings are seen in colder climate zones. This result is driven by the heating end use representing a higher prevalence of the total site energy usage, and this measure scenario implements relatively higher efficiency heating systems. But again, site energy savings may not translate directly to other important considerations such as utility bills.

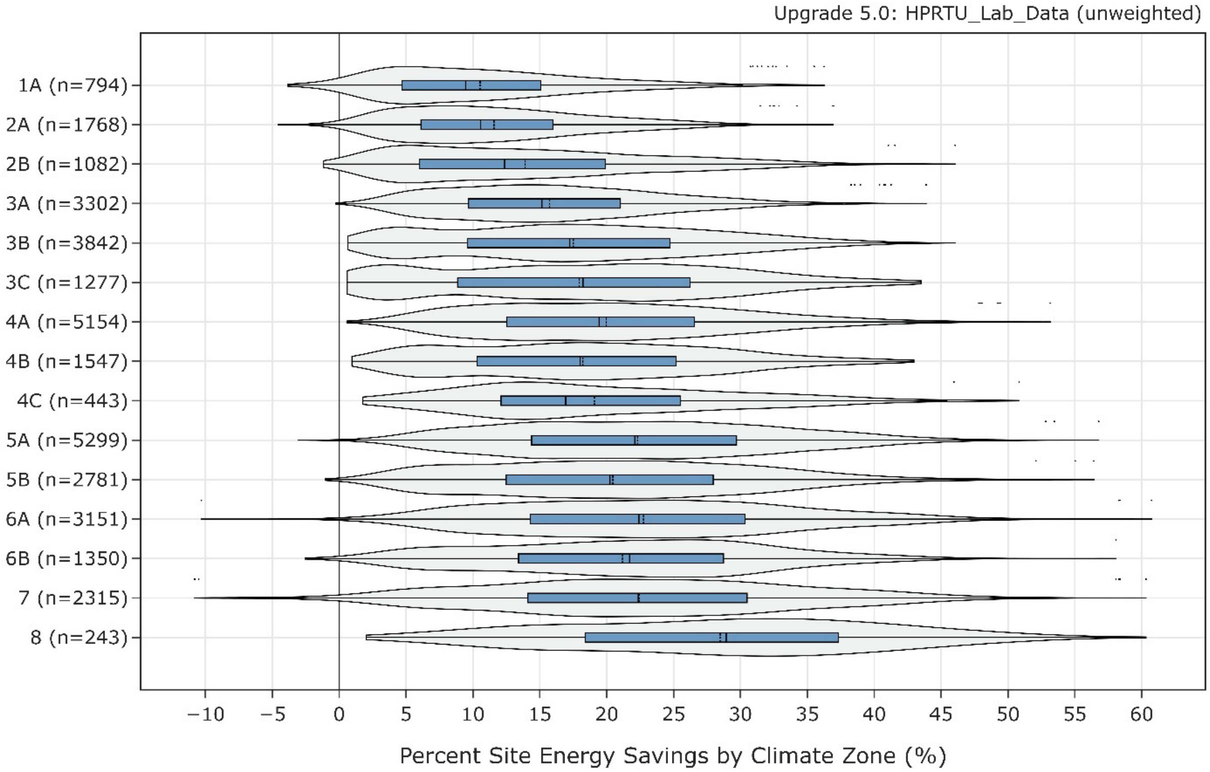

Figure 11. Percent site energy savings distribution for ComStock models with the applied measure scenario by climate zone.

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. Each data point represents the pairwise comparison between a ComStock baseline model and the corresponding model after the measure scenario is applied.

5.5 Other Findings

The HP-RTU Standard Performance and Lab Data measure scenarios show similar average total COPs by state, with only a few states showing any difference at this aggregation level (Figure 12). This again highlights the consistency between the two data sources used to model similar class HP-RTUs. The COPs show lower average values in colder climates where more supplemental heating is required given the performance and sizing scheme used in this work. Electric supplemental heat has a COP of 1, so a higher prevalence of supplemental heat would bring the total average COPs closer to 1 in this calculation.

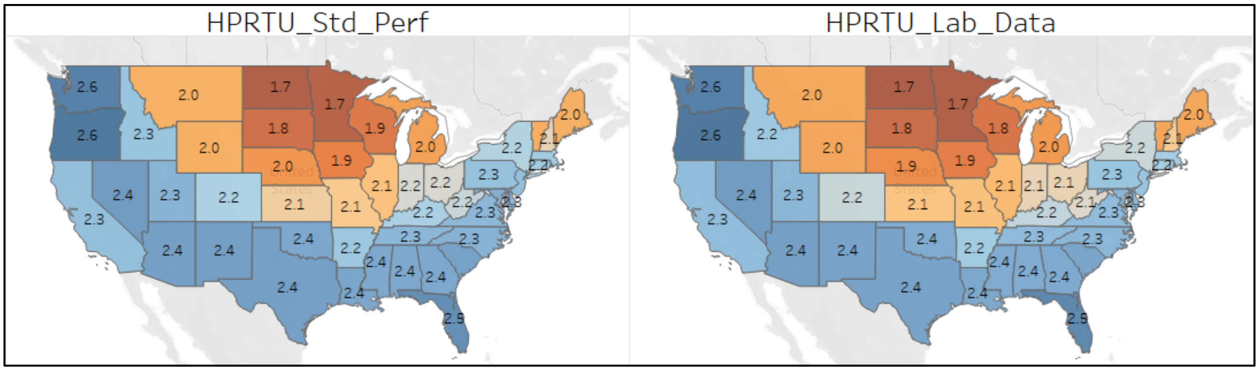

Figure 12. Annual average total heating COP for the median building between the HP-RTU Standard Performance and Lab Data measure scenarios.

COPs presented include impacts of supplement heat, crankcase heat, and reverse-cycle defrost, but not supply fan.

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Appendix A.

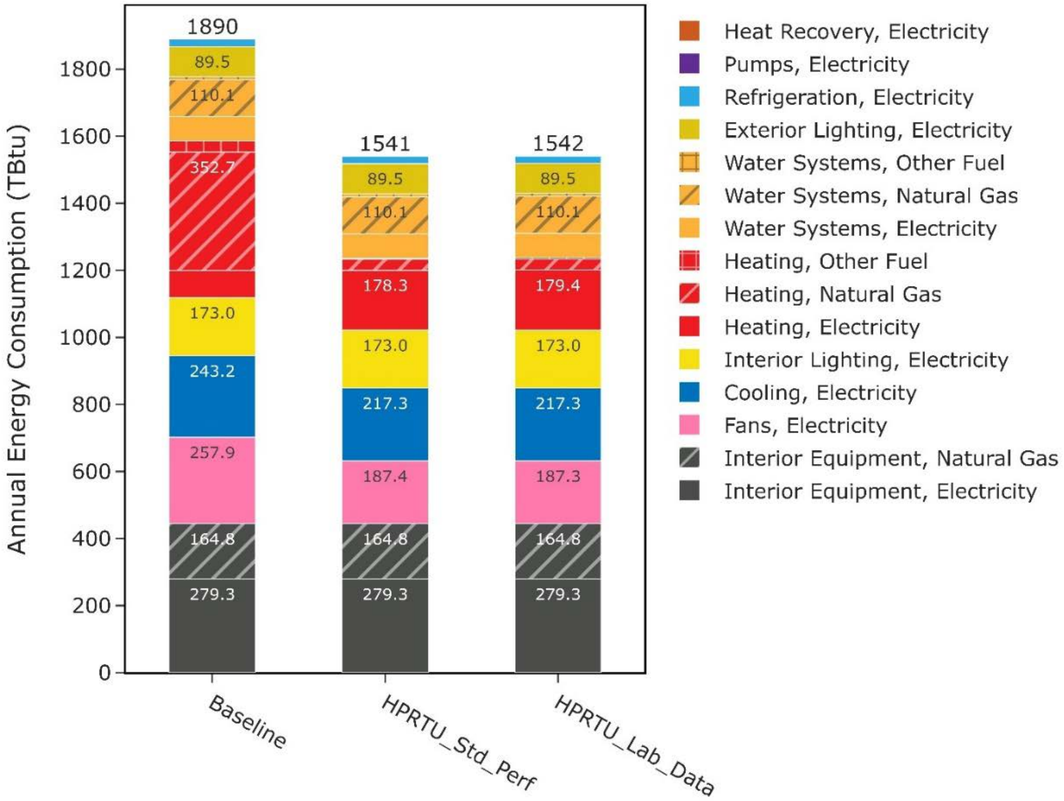

Figure A-1. Comparison of annual site energy consumption between the ComStock baseline the HP-RTU Standard Performance and HP-RTU Lab Data measure scenarios.

The plot only includes buildings applicable to the HP-RTU measure scenarios.

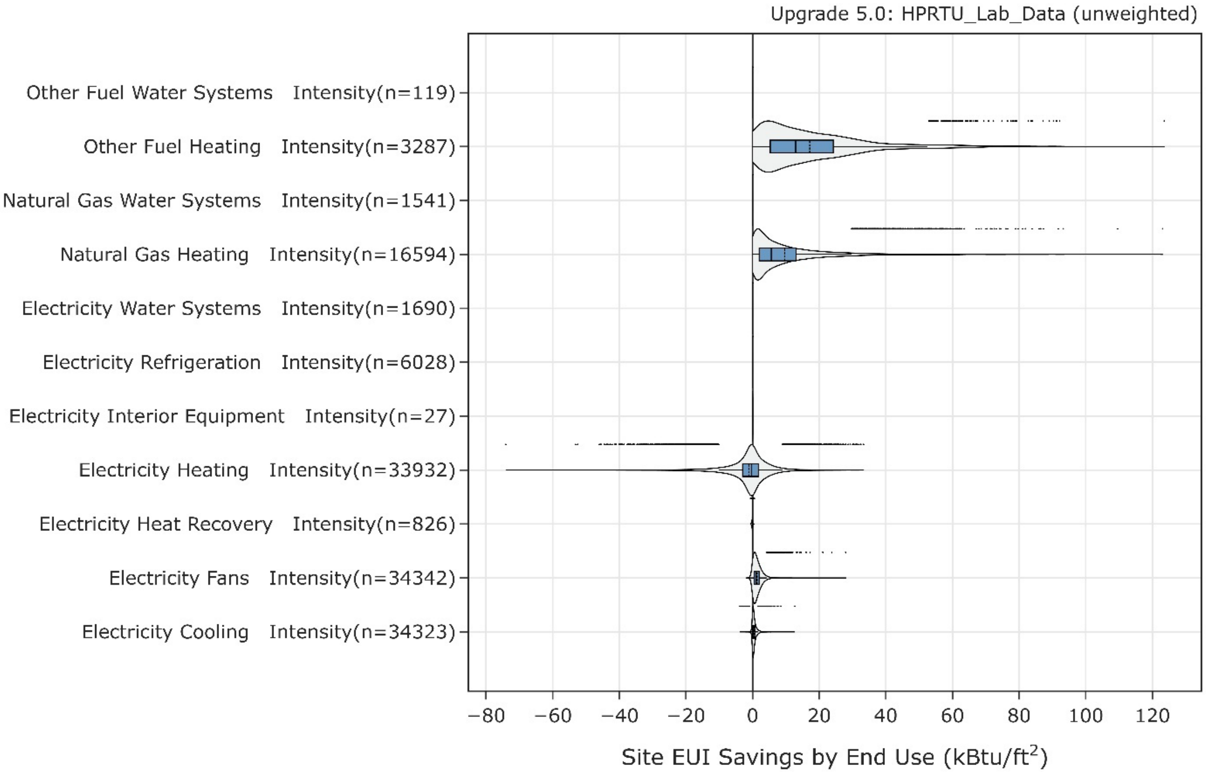

Figure A-2. Site energy use intensity (EUI) savings distribution for ComStock models with applied measure scenario by end use and fuel type.

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. Each data point represents the pairwise comparison between a ComStock baseline model and the corresponding model after the measure scenario is applied.