ComStock Measure Scenario Documentation:

Standard Performance Heat Pump Rooftop Unit With New Windows

Janghyun Kim and Chris CaraDonna

National Renewable Energy Laboratory

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List of Acronyms

AEDG	Advanced Energy Design Guide
CBECS	Commercial Buildings Energy Consumption Survey
CO_2e	carbon emissions equivalent
COP	coefficient of performance
DX	direct expansion
EIA	U.S. Energy Information Administration
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
PSZ-AC	packaged single-zone air conditioner
RTU	rooftop unit
SHGC	solar heat gain coefficient
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 package of two existing ComStock measure scenarios—standard performance heat pump rooftop unit (HP-RTU) with new windows—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 the combined impact of replacing (1) existing gas or electric resistance RTUs with standard performance HP-RTUs and (2) existing windows with upgraded windows. • Because we already published a dataset with many other HP-RTU measures, the data released in this analysis will be a comparable dataset to the previous dataset.
Performance Assumptions	• This scenario package combines two existing ComStock measures: standard performance heat pump rooftop units and window replacement. See previous documents for a more comprehensive overview of assumptions and interpretations. This document highlights key points of the combined impact of those two measures. • The HP-RTUs reflect typical off-the-shelf HP-RTUs often listed as "standard" efficiency. They are modeled with two stages of cooling and a single stage of heat pump heating. • Performance curves and efficiencies are entirely derived from public data across manufacturers. The capacity and efficiency retention of the heat pumps at 0°F compared to rated conditions at 47°F are 40% and 38%, respectively. Rated COPs typically range from 3.4 to 3.6 based on rated conditions. • The heat pumps are sized for cooling in this study, with electric resistance supplemental heating used to address any remaining heating loads not met by the heat pump. The heat pumps lock out below 0°F, in which case only supplemental heating is available. • The window replacement measure replaces existing windows with new windows that align with the properties proposed in the Advanced Energy Design Guide (AEDG) for each climate zone. It is applicable to all windows with assembly U-values greater than those proposed in the AEDG, and all windows with solar heat gain coefficients greater than those proposed in the AEDG.
Applicability	• The HP-RTU measure is applicable to ComStock models with either gas furnace RTUs ("PSZ-AC with gas coil," where PSZ-AC stands for packaged single-zone air conditioner) or electric resistance RTUs ("PSZ-AC with electric coil"). Buildings that do not have RTUs are not applicable, nor are kitchen spaces. • The window replacement measure is applied only to models where the HP-RTU measure is applicable and where the existing window performance is worse than the values recommended in the AEDG. • Overall, this measure is applied to models that make up 36% of the stock floor area.
Release	2025 Release 1: 2025/comstock_amy2018_release_1/

National annual results for site energy, energy bills, and carbon emissions equivalent (CO_2e) are summarized in Table ES-2 to Table ES-4. Savings shown in these tables are comparisons between the baseline and HP-RTU with new windows. The impact on electricity usage when replacing applicable heating, ventilating, and air-conditioning 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, and 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	321.5	1526.9	21.1	628.5	51.2
Electricity	0.6	3178.7	0.0	1222.0	0.0

Table ES-3. 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	3.4	17.4	19.6	7.0	48.7
Electricity	0.4	107.3	0.3	41.5	0.8
Fuel Oil	0.3	0.7	51.0	0.4	88.1
Propane	0.6	1.0	56.2	0.9	62.2
Total	4.7	126.4	3.7	49.8	9.4

Electricity bill savings in this table are calculated using the mean available electricity rate for each building. Other electricity rate structures are available in this report and in the public dataset.

Table ES-4. Key Results for Annual CO_2e 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	21.5	102.0	21.1	42.0	51.2
Electricity	-2.3	240.0	-1.0	93.5	-2.5
Fuel Oil	0.9	1.8	50.9	1.0	88.1
Propane	1.6	2.8	57.2	2.5	63.0
Total	21.6	346.5	6.2	139.0	15.5

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.

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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. 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 rooftop unit 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.

Heat pumps sometimes require the use of supplemental (or backup) heating systems, depending on the heating design conditions where they must operate, and the sizing scheme used. Supplemental heating types can vary, but electric resistance is a common choice for many applications. However, gas supplemental heating is also an option.

This study combines two existing ComStock™ measure scenarios as a package to understand the combined impact: standard performance heat pump rooftop units and window replacement. The combined impact of an enhanced building envelope (with new windows) and an HP-RTU will provide measurable data on load reduction and inform decisions on the potential downsizing of heat pumps. For a more comprehensive review of the individual measure scenarios that make up this package, reference the documentation for each individual measure.

The standard performance HP-RTUs used in this study are meant to reflect existing products and are often referred to as “standard efficiency” and are therefore not necessarily top-of-the-line products. However, they often have a lower initial cost, which can make them more attractive. The term “standard efficiency” is somewhat ambiguous, especially when generalizing across different product lines. Based on information gathered from nine products across five major manufacturers, we used the following shared characteristics to define “standard performance”:

- Two stages of heat pump cooling and a single-stage heat pump heating (i.e., all compressors running at the same time during heating); compressors are generally not variable-speed
- Backup electric resistance heating that can run simultaneously with the heat pump
- A heat pump minimum lockout temperature of 0°F (-17.8°C), below which only supplemental heating is available
- Seasonal energy efficiency rating of 14 and heating seasonal performance factor of 8 (for units with a capacity of 5 tons or less), integrated energy efficiency ratio between 10.8

and 14.1, and a coefficient of performance (COP) (at 47°F) between 3.2 and 3.5 (for units with a capacity of 6 tons or more).

2 ComStock Baseline Approach

The following sections provide high-level summaries of the ComStock baseline approach for RTUs and windows. These components of the baseline model are influential to the results of the applied measure scenario package. For more detail about how these systems are modeled in the ComStock baseline, including data sources, reference the ComStock documentation [2].

2.1 Existing Rooftop Units

The state of the existing RTUs in ComStock is based on a combination of when the buildings were built and how the equipment has been updated over time, which is described in detail in the *ComStock Reference Documentation: Version 1* report by the National Renewable Energy Laboratory [2]. Equipment performance is assumed to meet the energy code requirements in force at the time and place of installation. For this reason, most of the existing RTUs are modeled as constant air volume with single-speed compressors. This assumption is influential to the results in this analysis because energy savings will be calculated by comparing the energy performance of the ComStock baseline models to an updated version of the ComStock models that use the proposed HP-RTUs.

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 for the particular model. The ComStock workflow checks the necessary characteristics of each RTU to determine if 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 will use electric resistance coils with a COP of 1. For models with the "PSZ-AC with gas coil" HVAC system type, the ComStock baseline will use a gas furnace efficiency of generally around 80%.

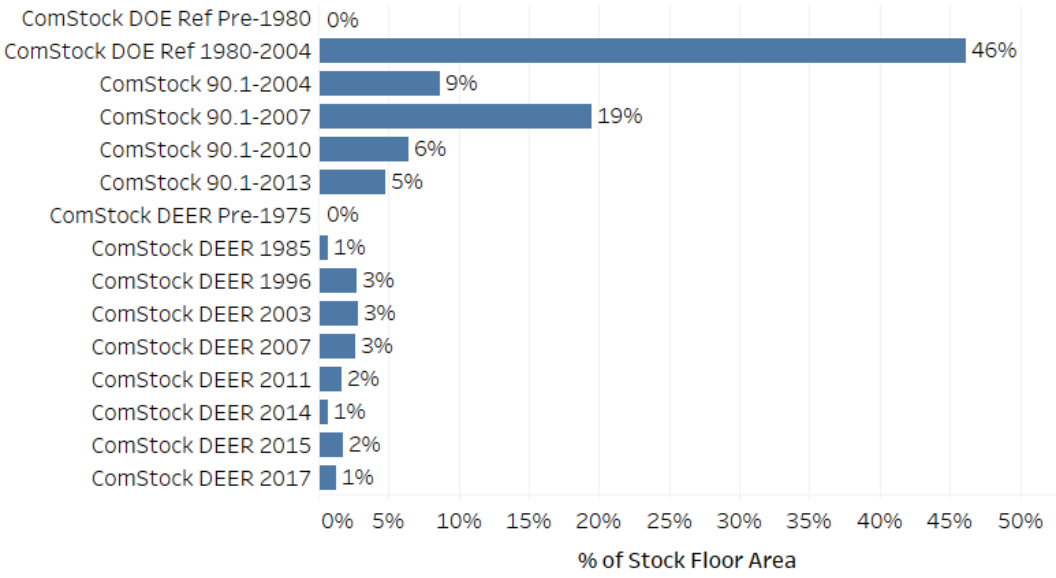

Figure 1. Percentage of ComStock floor area by HVAC energy code followed during last HVAC replacement.

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.

2.2 Existing Windows

The ComStock baseline uses a mix of wood-framed and aluminum-framed windows with or without a thermal break. They range from single pane to triple pane and can be clear/tinted or low-emissivity (low-e). The properties were informed by a variety of data sources, described in the ComStock documentation [2]. Each ComStock model is assigned a window type through a sampling process. Each window type has a probability for which it will be assigned to a model. These probabilities are primarily informed by the National Fenestration Rating Council Commercial Fenestration Market Study, which was conducted by Guidehouse in collaboration with the National Fenestration Rating Council, with input from various other sources [3]. Triple-pane windows will not be considered for replacement in this measure because they are already high-performing. Figure 2 shows percentages of stock floor area assigned to each window type in the ComStock baseline. More details of the window replacement measure can be found in the original measure documentation.

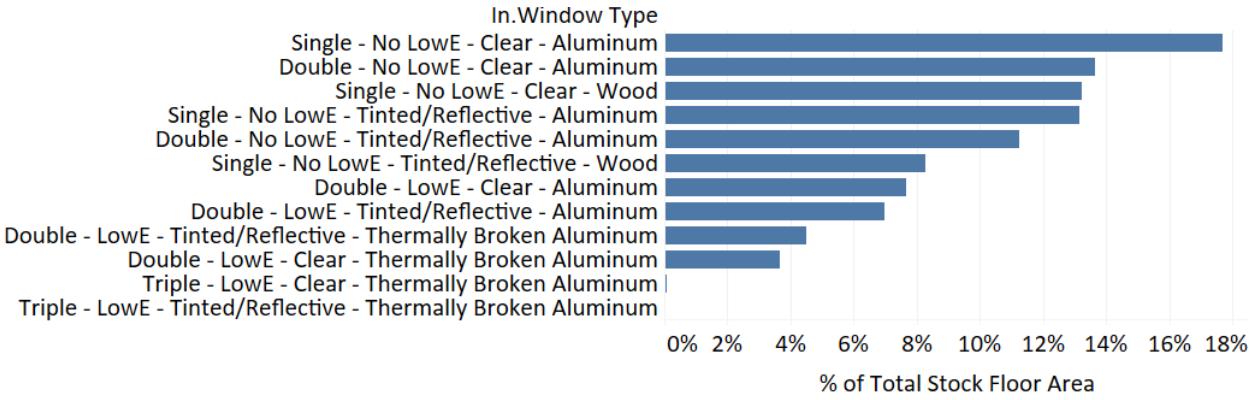

Figure 2. Percentage of stock floor area assigned to each window type in the ComStock baseline

3 Modeling Approach and Applicability

The following sections briefly summarize the modeling approach and applicability for the standard performance heat pump rooftop units and window replacement measure scenarios included in this upgrade package. For more detailed review, refer to each individual upgrade documentation.

3.1 Standard Performance Heat Pump Rooftop Units

3.1.1 Modeling Approach

The methodology and assumptions used to develop the model for the standard efficiency HP-RTU are discussed in depth in the original documentation for that measure scenario. Below are a few key assumptions:

- HP-RTUs are sized to the design cooling load, with electric resistance supplemental heating used to meet any heating load not met by the heat pump.
- Supplemental heating is modeled as fully modular and can operate simultaneously with heat pump heating when needed.
- Performance curves and efficiencies are entirely derived from public data across manufacturers. The capacity and efficiency retention of the heat pumps at 0°F compared to rated conditions at 47°F are 40% and 38%, respectively.
- The heat pump operates with two stages of cooling and a single stage of heat pump heating (both compressors operating simultaneously) plus supplemental heat.
- The supply fan operates at multiple speeds dictated by the heating or cooling stage.
- The compressor lockout temperature is 0°F; below this temperature, only supplemental heating is available.

3.1.2 Applicability

The HP-RTU upgrade is applicable to ComStock models with either gas furnace RTUs (PSZ-AC with gas coil) or electric resistance RTUs (PSZ-AC with electric coil). ComStock HVAC distributions are informed by the CBECS (2012 and 2018 data combined). The methodology for interpreting CBECS data to create HVAC probability distributions for ComStock is discussed in the ComStock documentation [2]. This methodology is especially impactful to aggregated results as it determines how many buildings are applicable to the upgrade and therefore how much stock potential the upgrade has. The upgrade does not apply to space types that directly serve kitchens, spaces that are unconditioned, or RTUs with outdoor air ratios above 55%. Overall, this upgrade applies to about 36% of the ComStock floor area (Figure 3).

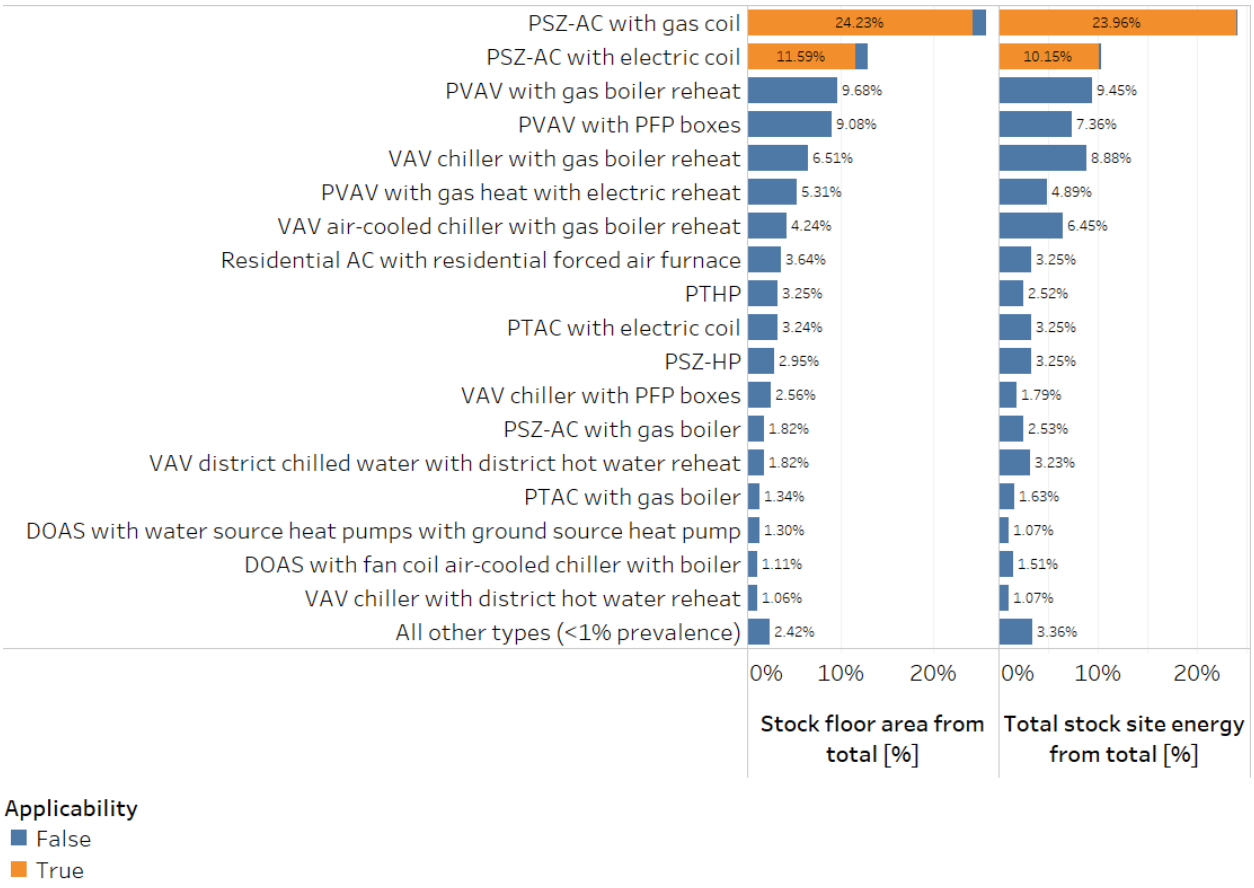

Figure 3. ComStock HVAC system type distribution. The measure scenario in this study applies to PSZ-AC with gas coil and PSZ-AC with electric coil.

Note: PTHP stands for packaged terminal heat pump, PVAV stands for packaged variable air volume, DOAS stands for dedicated outdoor air system, PSZ-AC stands for packaged single zone air conditioner, and PFP stands for parallel fan-power.

3.2 Window Replacement

3.2.1 Modeling Approach

Window performance depends on frame material, glass panes, gas fill, and coatings. Aluminum frames are common in commercial windows for their strength and cost but have high U-values, which can be improved with thermal breaks. Glazing options include single, double, and triple panes, with double-pane offering a good balance of cost and performance and triple-pane reserved for high-performance needs. Gas fills like air, argon, or vacuum also affect U-values, with vacuum achieving the lowest. Solar heat gain coefficient (SHGC) varies by tint and should balance cooling and heating benefits per climate zone. Upgrades will use aluminum frames with properties aligning to ASHRAE Advanced Energy Design Guide (AEDG) guidelines [4]. These properties are summarized in Table 1, along with some informal window characteristics that may achieve these properties. More details can be found in the original measure documentation.

Table 1. Target Properties for Window Replacements

	ASHRAE Climate Zone								
	0	1	2	3	4	5	6	7	8
Number of Panes	Double							Triple	
Fill	Air				Argon or vacuum				
Thermal Breaks	1				>1				
Maximum Assembly U-Factor	0.48	0.48	0.43	0.40	0.34	0.34	0.32	0.28	0.25
Maximum SHGC	0.21	0.22	0.24	0.24	0.34	0.36	0.36	0.38	0.38

3.2.2 Applicability

The window replacement upgrade applies to (1) all window assemblies with performance worse than the target AEDG values and (2) (for this measure package) buildings that apply to the HP-RTU measure. Triple-pane windows are excluded from this analysis because they are already high-performing. However, triple-pane windows make up a very low percentage of windows in the commercial building stock. Thus, this measure effectively replaces most of the windows in ComStock baseline models, even after the building model is applicable for the HP-RTU upgrade.

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 [10]. Summary statistics from this implementation are shown in Table 2. Note that ComStock does not currently estimate utility bills for district heating and cooling.

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

Fuel Type	Minimum Price ($)	Average Price ($)	Maximum Price ($)
Natural gas	$0.007/kBtu ($0.70/therm)	$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. The 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 [11]. 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 [12]. 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 is 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 [13]. 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 [14]. 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. The utility bill implementation described in this section does not include possible future rate changes, specifically those designed for electric heating.

3.4 Carbon Emissions Equivalent

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 third scenario uses the eGrid dataset [6], [7]. 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 [8]. Emissions due to on-site combustion of fossil fuels use the emissions factors shown in Table 3, which are from Table 7.1.2(1) of draft American National Standards Institute/Residential Energy Services Network/International Code Council 301 [9]. 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 3. 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

3.5 Limitations and Concerns

Although this study was initially intended to capture the potential downsizing of heat pump systems resulting from the installation of higher-performance windows, this effect was not reflected in the current iteration of the simulation workflow. Efforts are underway to incorporate a robust HVAC re-sizing mechanism, and this aspect will be addressed in future iterations of the dataset and subsequent publication releases.

The limitations and concerns for each measure scenario in this package can be found in the individual documentation for each respective measure.

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 this packaged measure. 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 4. Output Variables Calculated from the Measure Application

Upgrade	Variable Name	Description
HP-RTU	out.params.hvac_count_dx_cooling_XX_to_XX_kbtuh	Total number of direct expansion (DX) cooling units within a size bin. XXs are values which vary.
	out.params.hvac_count_dx_heating_XX_to_XX_kbtuh	Total number of DX heating units within a size bin. XXs are values which vary.
	out.params.hvac_count_heat_pumps_XX_to_XX_kbtuh	Total number of heat pump units within a size bin. XXs are values which vary.
	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. XXs are values which vary.
	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). XXs are values which vary.
	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.

Upgrade	Variable Name	Description
	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. XXs are values which vary.
	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
Window replacement	out.params.ext_window_area	Total external window area in m^2.
	out.params.average_window_shgc	Average solar heat gain coefficient of all the windows in the building model.
	out.params.average_window_u_value	Average thermal conductance (in Btu/hr-ft^2-°F) of all the windows in the building model.
	out.params.average_window_vlt	Average visual light transmission.
	out.params.window_to_wall_ratio	Window-to-wall ratio.

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 carbon emissions equivalent (CO_2e) 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

A small office model located in Atlanta, Georgia, was selected to demonstrate the building-level impact of combining an HP-RTU (with standard performance) and a window upgrade. Table 5 presents the annual end-use electricity consumption for three scenarios with color coding representing higher (red) to smaller (blue) values in each row: (1) a ComStock baseline model with a packaged single-zone system using an electric heating coil, (2) an upgraded model with an HP-RTU, and (3) an upgraded model incorporating both the HP-RTU and window upgrades. As expected, the HP-RTU upgrade leads to electricity savings in heating (in this example, the baseline uses electric resistance for heating), cooling, and fan operation compared to the baseline due to the improved performance of the heat pump system.

Table 5. Single-Building Model Test Results: Annual Aggregate Consumptions

	Annual Electricity Consumption [GJ]		
	Baseline	HP-RTU (Std Perf)	HP-RTU (Std Perf) + Window
Heating	74.02	10.75	10.09
Cooling	20.57	17.32	16.97
Interior Lighting	3.39	3.39	3.39
Exterior Lighting	10.64	10.64	10.64
Interior Equipment	15.65	15.65	15.65
Fans	20.51	17.46	17.05
Water Systems	3.51	3.51	3.51
Total	148.29	78.72	77.3

To assess the impact of combining new windows with an HP-RTU, Figure 4 presents daily profiles (averaged over 365 days) for six key parameters: compressor power for heating and cooling, crankcase heater power, defrosting power, heat pump cycling ratio, and solar radiation transmitted into the spaces. The improved building envelope provided by the new windows slightly reduced heating and cooling demands, leading to energy savings in heat pump operation for space heating and cooling.

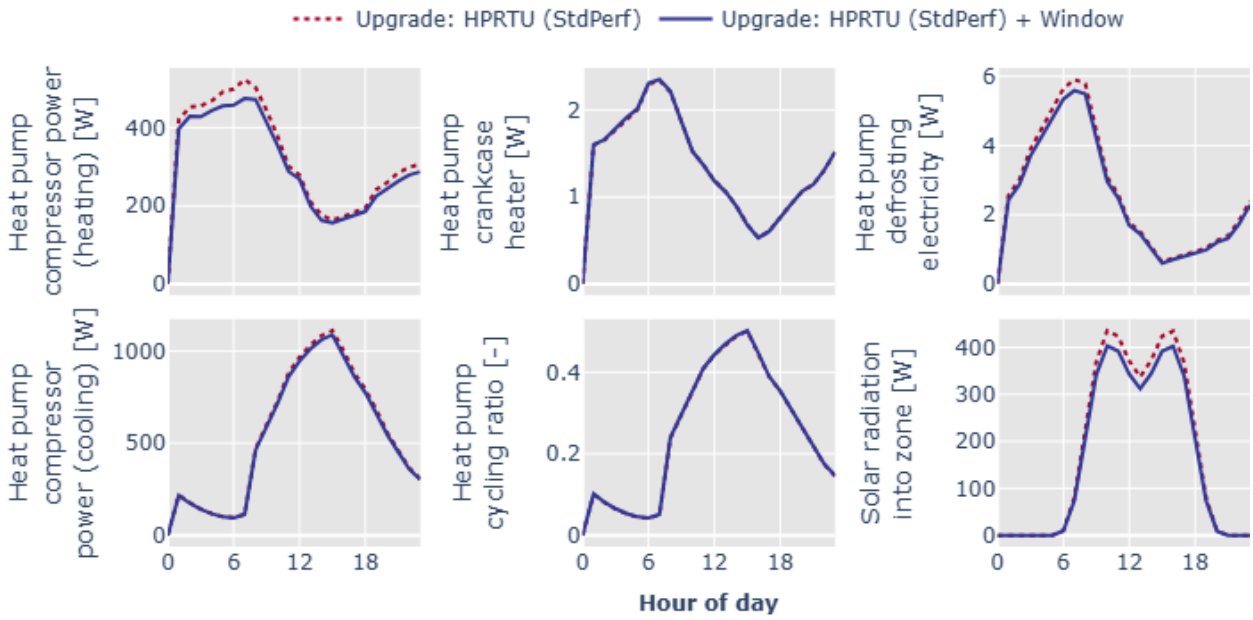

Figure 4. Single-building model test results: time series profiles

5.2 Stock Energy Impacts

Figure 5 and Figure 6 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. While Figure 6 only includes applicable building model results, Figure 5 shows the entire commercial building stock, even including buildings that did not receive the upgrade (i.e., only 36% of the entire stock floor area received the upgrade). While this study focuses on HP-RTU with new windows, we also present comparable scenarios such as the HP-RTU (standard performance) upgrade only and HP-RTU with new roofs based on the existing upgrade measure that was developed previously.

The HP-RTU reflecting the standard performance with window upgrade measure demonstrates 7% total site energy savings (351 trillion British thermal units [TBtu]) for the U.S. commercial building stock modeled in ComStock versus the existing baseline. To put the number in context, the savings of the HP-RTU standard performance with new windows are primarily attributed to:

- 33.2% stock heating natural gas savings (320.9 TBtu)
- 11.9% stock fan electricity savings (67.8 TBtu)
- 5.8% stock cooling electricity savings (42.0 TBtu)
- 69.2% stock heating other fuel savings (29.5 TBtu)
- -42.0% stock heating electricity savings (-109.2 TBtu).

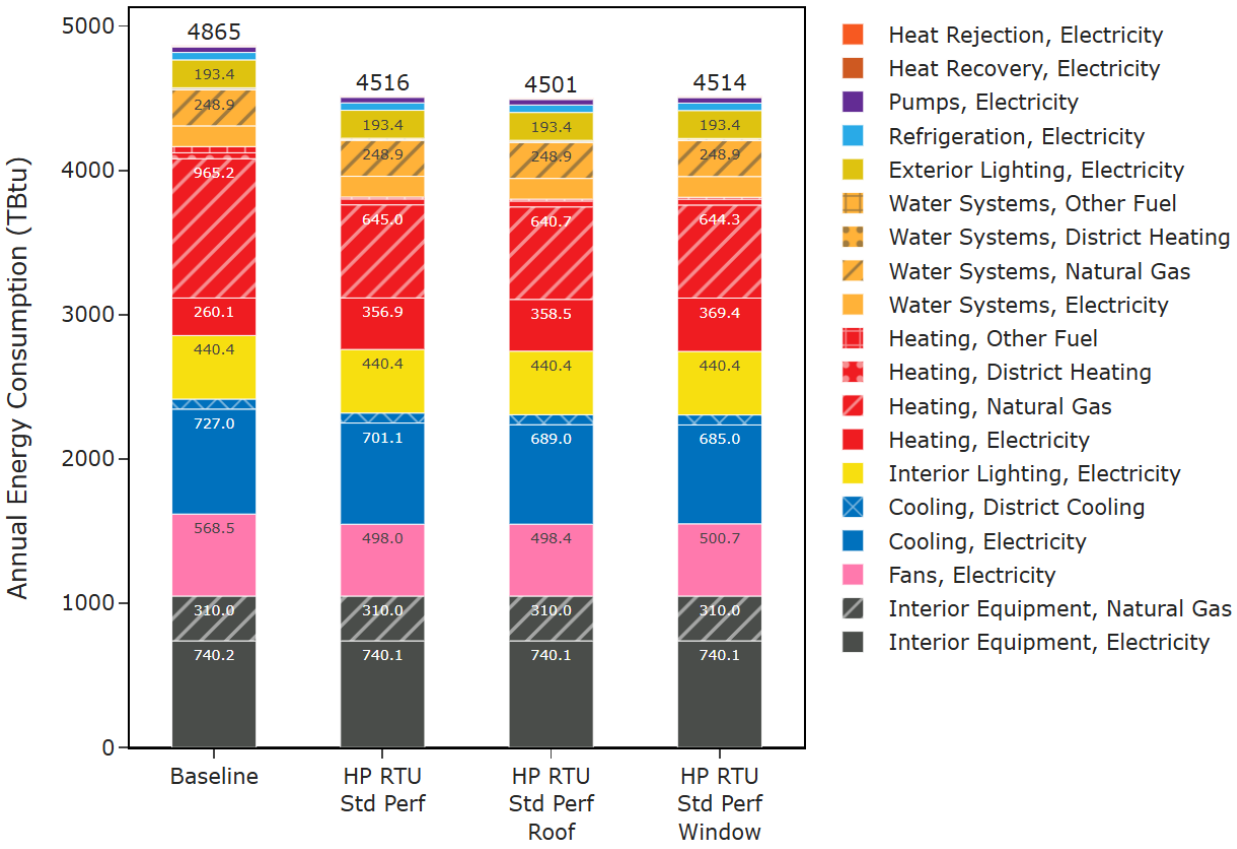

Figure 5. Comparison of annual site energy consumption between the ComStock baseline and the HP-RTU measure scenarios for the entire building stock

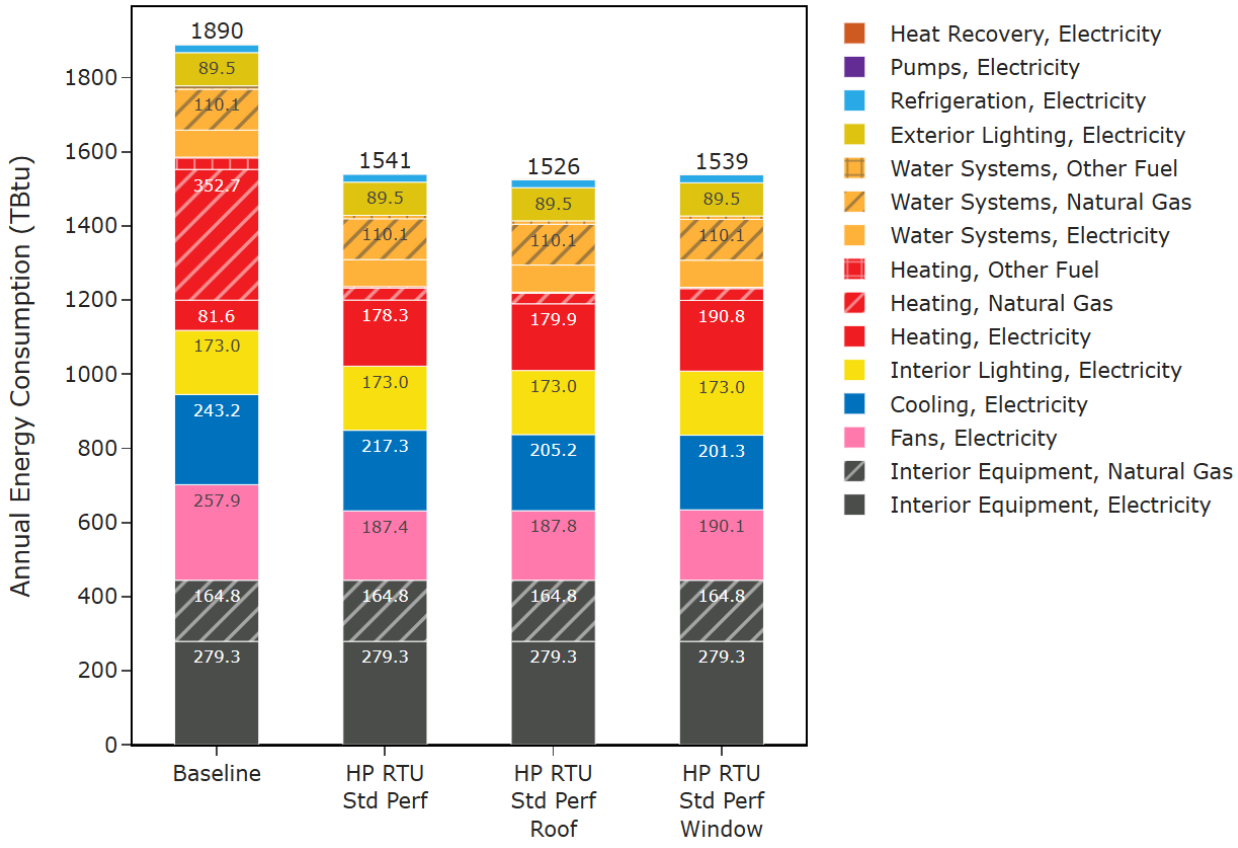

Figure 6. Comparison of annual site energy consumption between the ComStock baseline and the HP-RTU measure scenarios only for buildings that are applicable to the upgrade

Figure 5 and Figure 6 also show other HP-RTU with envelope upgrades as a comparison. As expected, the HP-RTU with window upgrade consumes (1) slightly less site energy compared to the HP-RTU without window upgrade, (2) slightly more compared to HP-RTU with new roof, and (3) slightly more compared to HP-RTU with new roof and window.

The HP-RTU scenario with upgraded windows exhibits increased electricity consumption for space heating relative to the HP-RTU scenario in Figure 5 and Figure 6. This is primarily due to a reduction in the SHGC in some stock building models compared to baseline values. The lower SHGC reduces passive solar heat gains, particularly in colder climates, thereby increasing the heating load that must be met by the HVAC system.

These simulation results also reflect that converting gas-fired heating systems to electric heat pumps results in a 45% increase in electric heating but a 34% reduction in natural gas heating. This shift leads to overall site energy savings, primarily due to the higher efficiency of heat pumps and their ability to provide reasonable heating performance even in colder regions. However, it is important to note that these energy savings may not directly translate to cost savings, as they depend on the relative prices of electricity and natural gas. The results presented here assume electric resistance supplemental heat when the heat pump capacity is insufficient to meet the building load.

5.3 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 include many annual utility bills per building model. Figure 7 shows a comparison of scenarios 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 [10].

Site energy savings and utility bills savings do not necessarily align due to cost differences between fuel types as well as primary energy conversion factor differences. Figure 5 shows aggregated "site" energy consumption, which does not reflect the "primary" energy perspectives. Thus, the annual aggregated cost comparisons, shown in Figure 7, can also tell us the primary energy consumption comparisons between different scenarios.

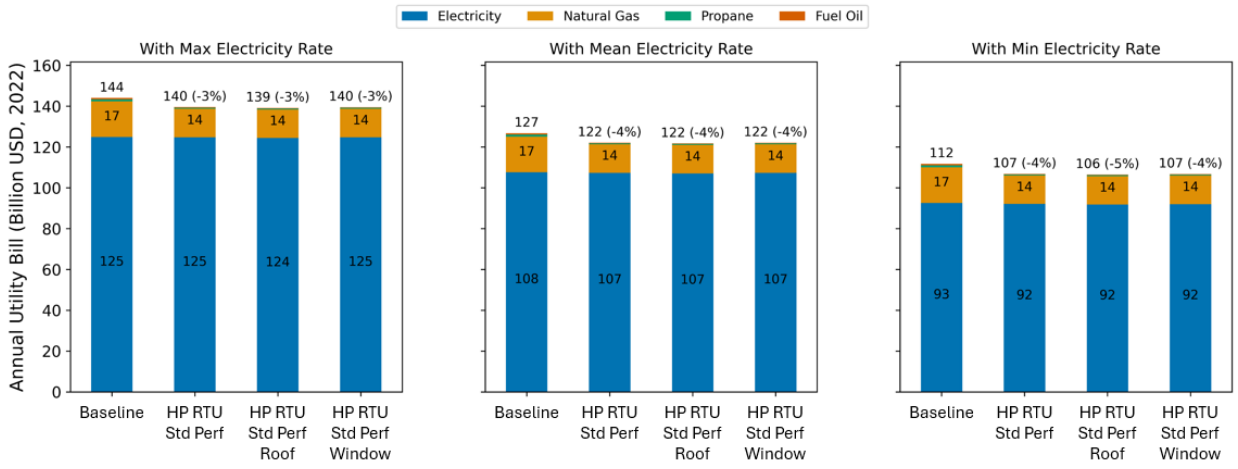

Figure 7. Utility bill comparison of the ComStock baseline and the HP-RTU scenario

5.4 Stock CO_2e Impacts

Figure 8 shows ComStock simulation results for CO_2e avoided across all electricity grid scenarios and on-site combustion fuel types. Additionally, Table ES-4 (in the Executive Summary) also tabulates avoided emissions between different end use types and against the entire building stock and applicable building stock. Overall, the HP-RTU with new windows demonstrates between 20 and 22 million metric tons (MMT) of CO_2e avoided (for all fuel types) for the three electricity scenarios presented. The 20 MMT number is determined using an 8% reduction for the LRMER Low RE Cost 15-Year scenario, while the 22 MMT number is determined using a 5% 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 22% emissions avoided from on-site combustion are attributable to fuel-switching some of these combustion-based heating systems.

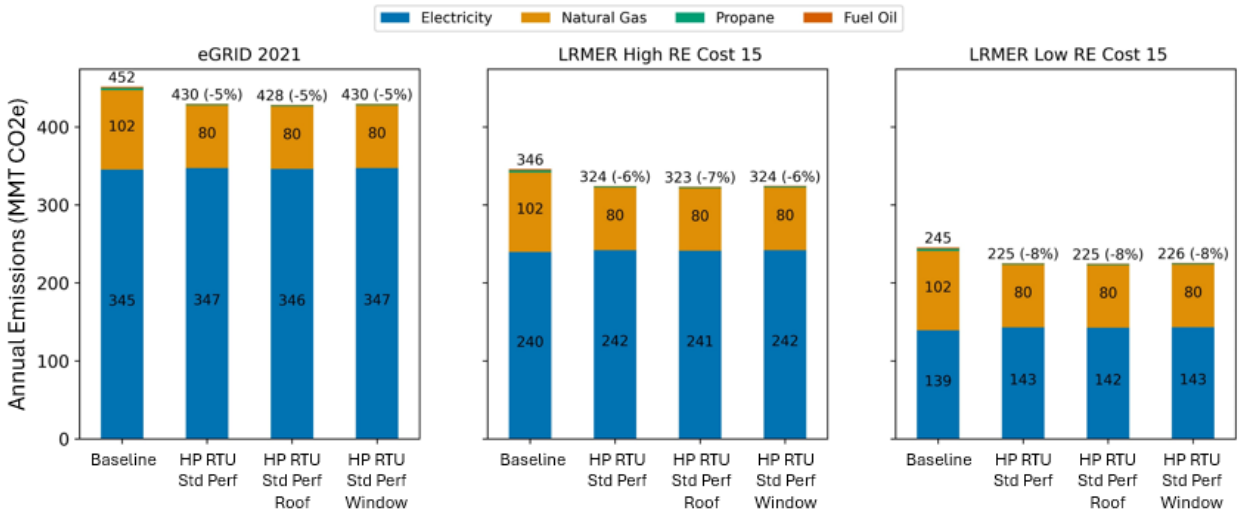

Figure 8. CO_2e comparison of the ComStock baseline and the HP-RTU scenario

5.5 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, CO_2e avoided, or energy costs, which vary widely across the United States. Savings shown in this section are based on comparisons between the baseline and HP-RTU with new windows scenario.

Figure 9 through Figure 11 show distributions of the applicable baseline ComStock models versus the upgrade scenario for percent site energy or site energy 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.

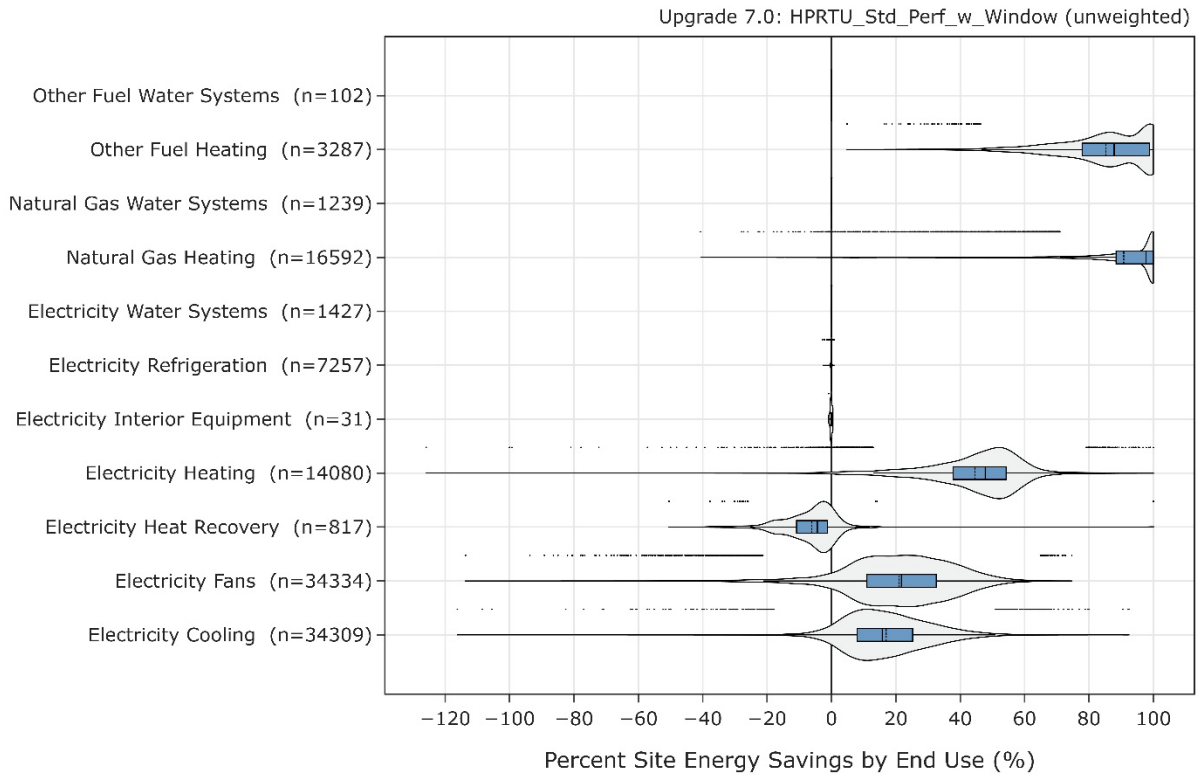

Figure 9. Percent site energy savings (compared to baseline) distribution for ComStock models with the HP-RTU measure applied by end use and fuel type

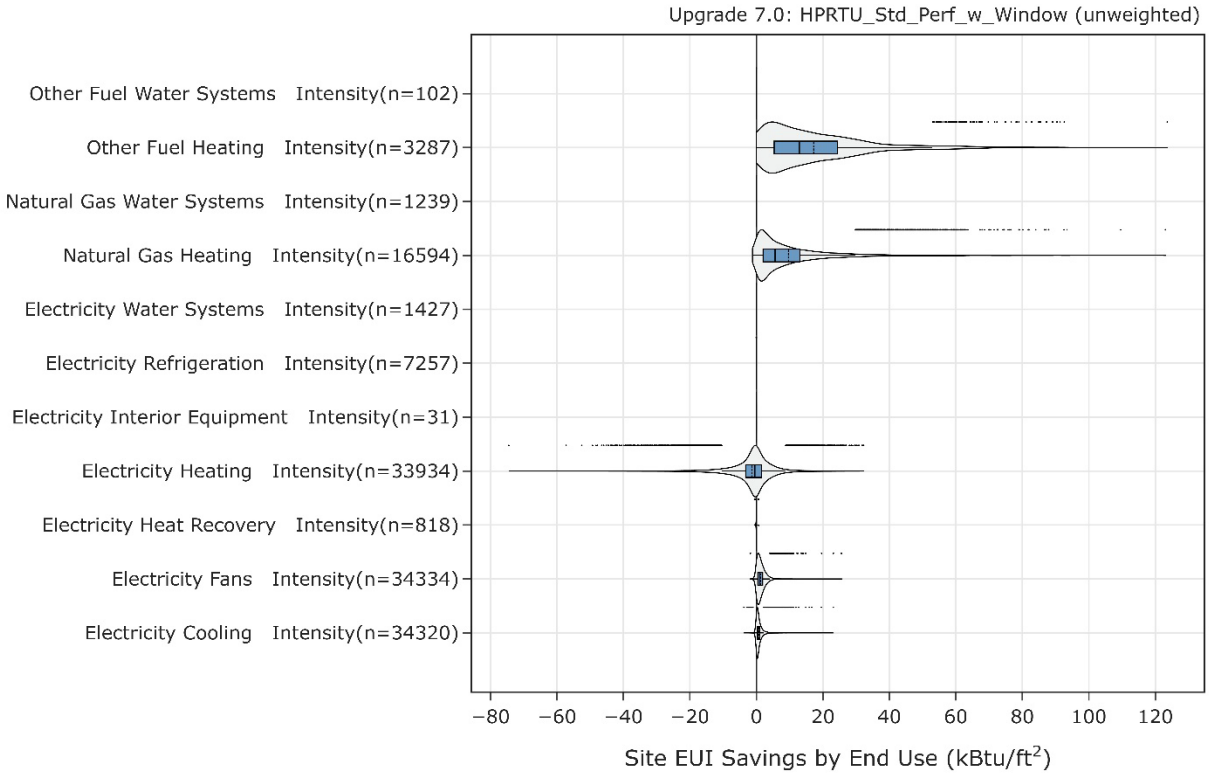

Figure 10. Site EUI savings (compared to baseline) distribution for ComStock models with the HP-RTU measure applied by end use and fuel type

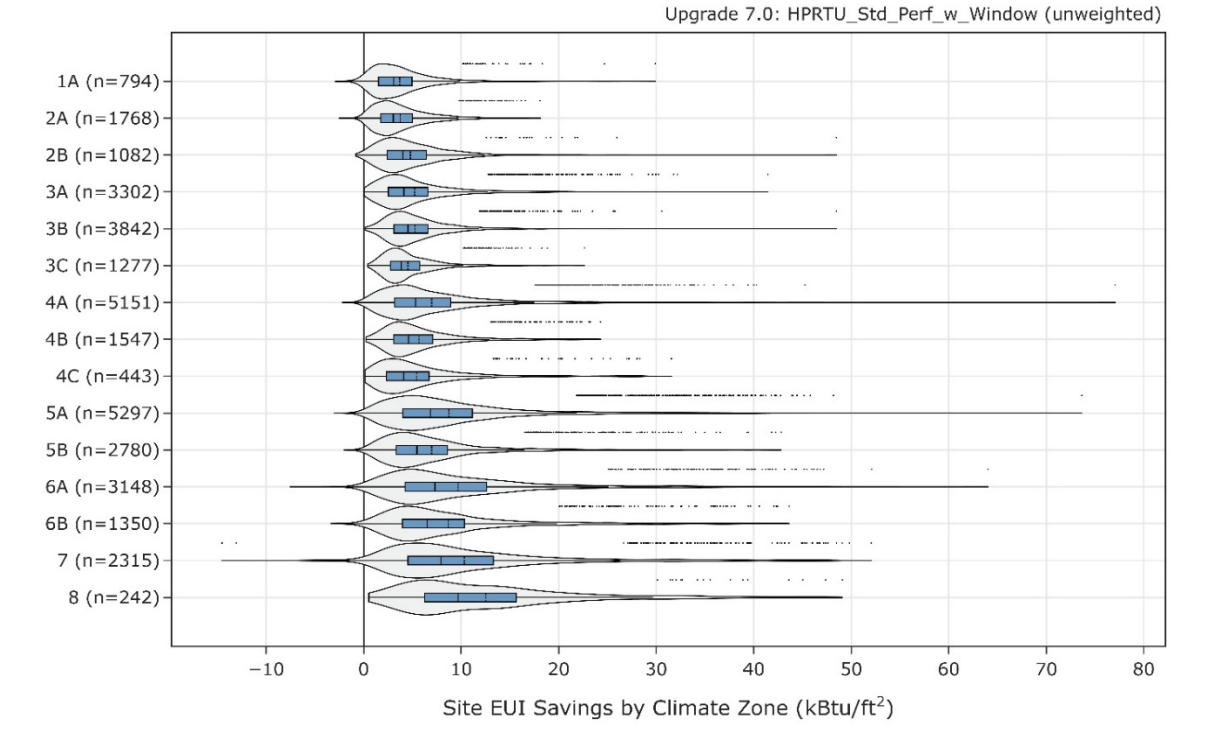

Figure 11. Site EUI savings (compared to baseline) distribution for ComStock models with the applied HP-RTU measure by climate zone

Highlights of conclusions drawn from Figure 9 through Figure 11 include:

- Fuel-switching of combustion fuel-based heating:
    - Up to 100% savings on combustion fuel used for heating, as shown in Figure 9. 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 10.
    - Absolute or aggregated increase in electricity for heating due to fuel-switching is well depicted in Figure 10. This was especially noticeable in the colder climates.
- Conversion of electric resistance heating (in baseline) to HP-RTU heating:
    - Positive savings on electricity used for heating, as shown in Figure 9.
- 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 9.
    - Absolute or aggregated savings scale is depicted in Figure 10.
- Most of these distribution trends are driven by the HP-RTU upgrade and where the impact from new windows is relatively less.
- Others:
    - Data points showing extreme (e.g., -110% electricity cooling savings) positive/negative savings, shown in Figure 9, 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.

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