End-Use Savings Shapes Measure Documentation:

Heat Pump Rooftop Units With Exhaust Air Energy Recovery

Chris CaraDonna

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
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Technical Report
NREL/TP-5500-89481
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List of Acronyms

AEDG	Advanced Energy Design Guide
AHU	air handling unit
CBECS	Commercial Buildings Energy Consumption Survey
COP	coefficient of performance
DOAS	dedicated outdoor air system
GHG	greenhouse gas
HP-RTU	heat pump rooftop unit
HVAC	heating, ventilating, and air conditioning
LRMER High RE	Long-Run Marginal Emissions Rate High Renewable Energy
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
PSZ-AC	packaged single-zone air conditioner
RTU	rooftop unit

Executive Summary

Building on the successfully completed effort to calibrate and validate the U.S. Department of Energy's ResStock™ and ComStock™ models over the past several years, the objective of this work is to produce national data sets that empower analysts working for federal, state, utility, city, and manufacturer stakeholders to answer a broad range of analysis questions.

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

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

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 subhourly energy consumption of the commercial building stock across the United States. The baseline model intends to represent the U.S. commercial building stock as it existed in 2018. The methodology and results of the baseline model are discussed in the final technical report of the End-Use Load Profiles project.

This documentation focuses on a package of two end-use savings shape measures—Heat Pump Rooftop Unit (HP-RTU) and Exhaust Air Heat/Energy Recovery. This study combines the modeling methodologies from the "HP-RTU With Electric Supplemental Heat" measure from the Commercial End-Use Savings Shapes 2023 Release 1 data set and the "Add Exhaust Air Heat/Energy Recovery" measure from the 2023 Release 2 data set. This document will primarily discuss the addition of heat/energy recovery to the HP-RTU system. For a more comprehensive understanding of the background and modeling methodology of the HP-RTU or Heat/Energy Recovery measures, please refer to the respective documents dedicated to each measure.

This measure replaces gas furnace and electric resistance rooftop units with high-efficiency variable-speed HP-RTUs that include exhaust air heat or energy recovery. Energy recovery with sensible and latent exchange gets added in humid climate zones, whereas heat recovery with sensible-only exchange gets added in drier climate zones. Energy recovery is modeled as a fixed membrane plate counterflow heat exchanger, and heat recovery is modeled as a sensible-only fixed aluminum plate counterflow heat exchanger. Both systems include a bypass (for temperature control and economizer lockout) and minimum exhaust air temperature control for frost prevention.

The measure uses the same assumptions and technology as the variable-speed HP-RTU measure from the End-Use Savings Shapes 2023 release 1, but adds energy recovery to precondition outdoor ventilation air to reduce HVAC loads. The HP-RTU compressor lockout temperature is modeled as 0°F; below this temperature, the heat pump is set to shut off. The unit is sized based on the design cooling loads, with backup electric resistance heating addressing any remaining loads including heating hours below the compressor lockout temperature when there is no heat pump heating.

The HP-RTU with heat/energy recovery measure is applicable to buildings comprising 33% of the stock floor area and demonstrates 9% total site energy savings (382 trillion British thermal units [TBtu]) for the U.S. commercial building stock modeled in ComStock. The savings are primarily attributed to:

- **28%** stock **heating gas** savings (235 TBtu)
- **-22%** stock **heating electricity** savings (-39 TBtu)
- **13%** stock **cooling electricity** savings (85 TBtu)
- **15%** stock **fan + heat recovery** savings (81 TBtu)
    - Fan static pressure increases due to heat/energy recovery are categorized under the “heat recovery” end use.

The HP-RTU with heat/energy recovery measure shows 7%–9% annual greenhouse gas emissions avoided (219 to 372 MMT CO_2e) against the baseline building stock depending on the electricity grid scenario.

Acknowledgments

The authors would like to acknowledge the valuable guidance and input provided by the ComStock team, Shanti Pless, and Eric Bonnema.

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Heat Pump Rooftop Units With Energy Recovery

Accessing Results

This documentation covers the “Heat Pump Rooftop Unit With Energy Recovery” upgrade methodology and briefly discusses key results. Results can be accessed on the ComStock™ data lake at “end-use-load-profiles-for-us-building-stock” or via the Data Viewer at comstock.nrel.gov.

Measure Summary

Measure Title	Heat Pump Rooftop Unit With Energy Recovery
Measure Definition	This measure replaces gas-fired and electric resistance rooftop units (RTUs) with high-efficiency, variable-speed heat pump rooftop units (HP-RTUs) that include exhaust air energy (humid climates) or heat recovery (all other climates). The HP-RTUs are assumed to be top-of-the-line with variable-speed compressors and fans allowing for efficient part-load operation. Heat pumps are sized to the design cooling load and use a compressor lockout temperature of 0°F. Supplemental heating coils are used to address any additional load. Supplemental heating is electric resistance.
Applicability	The measure is applicable to buildings that contain gas-fired or electric resistance RTUs (~33% of stock floor area). Energy recovery is included with all new HP-RTUs, except for those in food service building types where the existing unit does not include energy recovery.
Not Applicable	The measure is not applicable to RTUs serving kitchen spaces. Additionally, energy recovery in not added to RTUs in food service buildings that do not already contain it.
Release	2024 Release 1: 2024/comstock_amy2018_release_1/

1 Technology Summary

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

Heat pumps offer a high-performance electric option for commercial building space heating. Their use of electricity for heating enables pathways toward decarbonization, as they 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].

Air-to-air energy/heat recovery systems exchange heat and/or moisture between conditioned exhaust air and incoming outdoor ventilation air for air handling units (AHUs) with outdoor air [1]. They are intended to precondition outdoor ventilation air using exhaust air before heating/cooling coils are used, which can reduce ventilation loads by up to 80% [1]. Energy recovery systems provide sensible and latent energy exchange, generally through motor-controlled enthalpy wheels or counterflow fixed plate membrane heat exchangers. Heat recovery systems, on the other hand, provide sensible heat exchange through aluminum fixed plate heat exchangers or heat pipes [2]. For heat pump applications, the reduced ventilation loads may help minimize the need for relatively less-efficient supplemental electric resistance heating.

Commercial HP-RTUs can include options for factory-installed heat or energy recovery systems. These are generally integrated directly into the RTU, rather than separate external systems tied into the ventilation network. The Daikin Rebel, for example, offers two factory-installed energy recovery options: either an energy recovery wheel or an enthalpy fixed plate counterflow membrane energy recovery core system. Published data sheets show 70%–75% sensible and latent effectiveness, economizer bypass controls, exhaust air temperature defrost, and outlet temperature control [2]. Alternatively, the Ventacity energy recovery ventilator system has published detailed performance data that is useful for energy modeling heat/energy recovery systems [3].

Heat/energy recovery systems add static pressure to the air delivery system to overcome the additional pressure drop of the heat exchanger. Furthermore, energy recovery systems that use motor-operated enthalpy wheels require electricity to spin the wheel. A study of energy recovery systems in Minnesota showed they use between 0.11 and 0.36 W/cfm (cubic feet per minute) to push air through the system and operate any wheel motors [4]. Plate heat exchangers generally have lower pressure drops compared to enthalpy wheel systems and have no moving parts that require power [4]. ASHRAE-90.1 2019 allows fan power pressure drop adjustments to the allowable fan power calculation to account for the added pressure. The Advanced Energy Design Guide (AEDG) for small to medium office buildings recommends that the additional pressure drop not exceed 0.85 in. w.c. (inches of water column) and 0.65 in. w.c. for the supply fan and exhaust fan, respectively [5]. A Pacific Northwest National Laboratory (PNNL) report specifies an additional 0.65 in. w.c. on both the supply and exhaust fans plus an additional 0.2 in. w.c. on the exhaust (which ultimately aligns with the AEDG values) [6]. The Northwest Energy Efficiency Alliance's very high efficiency dedicated outdoor air system (DOAS) specifies 1.3 cfm/watt at 0.5 in. w.c. [7]. The ASHRAE Handbook for HVAC Systems and Equipment shows typical membrane heat exchangers yielding pressure drops between 0.1 in. w.c. and 1.1 in. w.c., increasing linearly with airflow rate [8]. Lastly, the Ventacity DOAS-heat/energy recovery ventilator systems show between 0 in. w.c. and 2 in. w.c. of added static pressure, depending on the operating conditions, which falls within range of the PNNL and AEDG values [9]. Plate heat exchangers often include a bypass to circumvent the static pressure drop when the HRV is not needed. However, some energy recovery ventilator enthalpy wheel systems do not include bypass systems and retain the static pressure drop during operation, whereas energy recovery ventilators that use a membrane plate heat exchanger, such as the Ventacity system, do include a bypass [10][9].

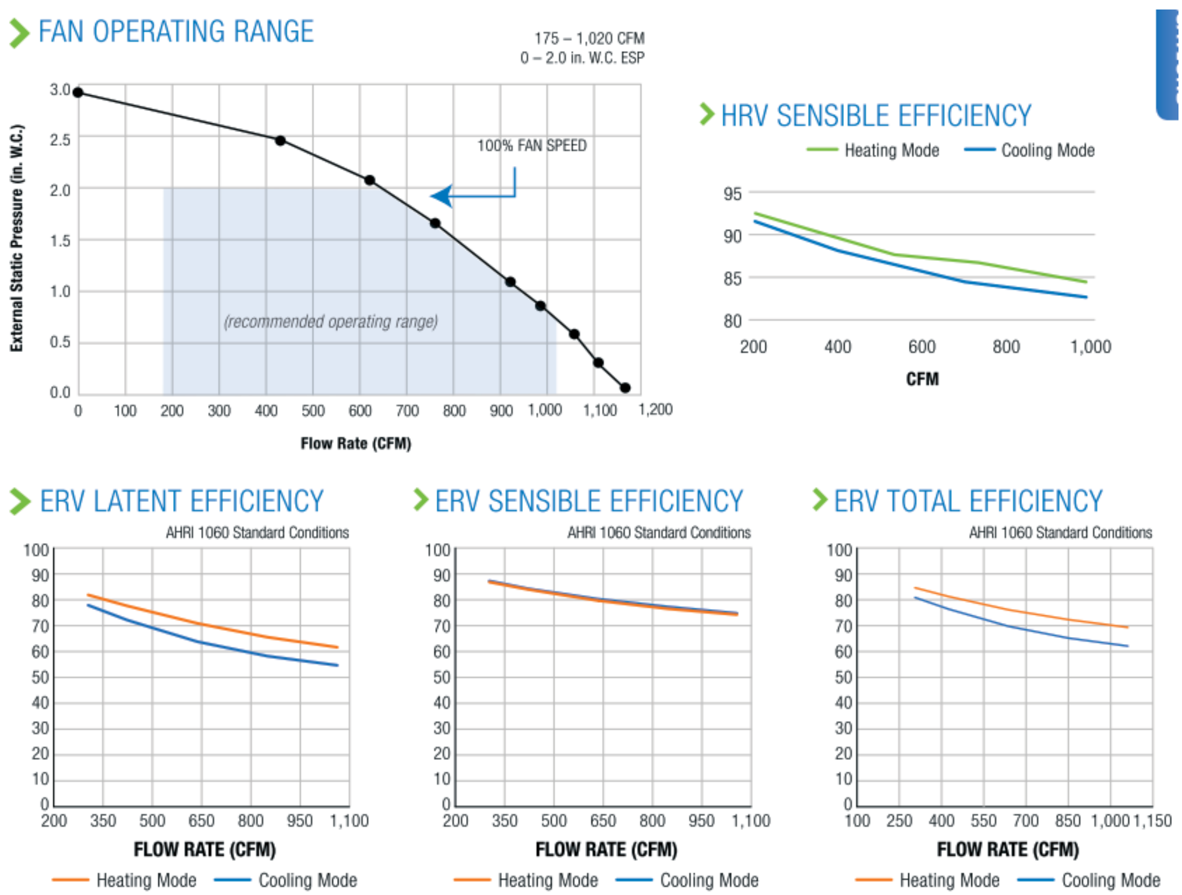

Figure 1. Product data from Ventacity heat/energy recovery system

Image from [3]

Some building types, such as food service buildings, may be less suitable for adding energy/heat recovery retrofits because most of the building exhaust tends to occur through bathroom and kitchen exhaust hoods. A PNNL technical document for reducing energy usage in quick-service restaurants recommends using a runaround energy recovery coil to utilize the large amount of heat available in kitchen exhaust air [11]. However, the study does not discuss the practicality of such a measure given the quality of kitchen exhaust. The ASHRAE HVAC Handbook describes kitchen cooking hoods as being a source of odors, causing potential plugging and corrosion of heat exchangers [12]. The prevalence of fouling of heat exchanger surfaces from smoke and grease in kitchens requires regular maintenance [12]. The ASHRAE HVAC Handbook therefore advises energy/heat recovery only in light-duty cooking applications with minimal grease production [12]. However, an assessment from Frontier Energy and Fischer-Nickel suggests that energy recovery can be applied to kitchens, although this setup may require additional measures for maintaining grease filters and addressing heat exchanger fouling [13].

Heat/energy recovery systems require a means for defrosting under certain climate conditions to avoid ice buildup [7]. Ice formation occurs on the exhaust side of the heat exchanger during cold winter months when the exhaust air temperature is below the dewpoint temperature of the ambient air. A common type of defrost for energy/heat recovery systems uses an electric heating element to preheat the outdoor air entering the heat exchanger [14]. This ensures the exhaust air is warm enough that it does not form ice. Another method is to use a supply air bypass to allow warmer exhaust air temperatures for defrost. This method does not directly consume additional energy like with the heating coil option, but it does temporarily reduce the effectiveness of the heat exchanger during periods of defrost.

2 ComStock Baseline Approach

There are a few features of the ComStock baseline that are especially impactful to this study. First is the prevalence of HVAC system types in the ComStock baseline that are applicable to the HP-RTU with energy recovery retrofit. This determines which and how many models the retrofit scenario is applied to, which impacts the magnitude of stock impact. The HVAC system type distributions used in ComStock are derived from CBECS 2012 microdata [1], and vary by census region and building type [15]. System type applicability is discussed further in Section 3.1.

The state of the existing RTUs in ComStock is another impactful feature that will determine the performance of the HVAC systems being replaced, which will drive the relative savings of implementing the HP-RTU with energy recovery upgrade scenario. 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. This is described in detail in the *ComStock Documentation* report by the National Renewable Energy Laboratory (NREL) [15]. 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 impacts the results in this analysis because energy savings are calculated by comparing the energy performance of the ComStock baseline models to an updated version of the ComStock baseline that uses the proposed HP-RTUs.

The outdoor airflow rate of an RTU can impact energy usage considerably since outdoor ventilation air needs to be properly conditioned before being discharged into the building. Outdoor air rates also influence the impact of heat/energy recovery systems since the goal is to reduce ventilation loads. Buildings with higher outdoor airflow rates have higher potential for energy savings through heat/energy recovery systems. Distributions of building average annual outdoor air fraction and design outdoor airflow rates from ComStock are shown in Figure 2, by building type. Design outdoor airflow rates in ComStock align to the governing energy code standard for each model [15]. Outdoor air fractions are a function of the outdoor airflow rate and supply airflow rate. Large variations are shown by building type due to differences among these factors.

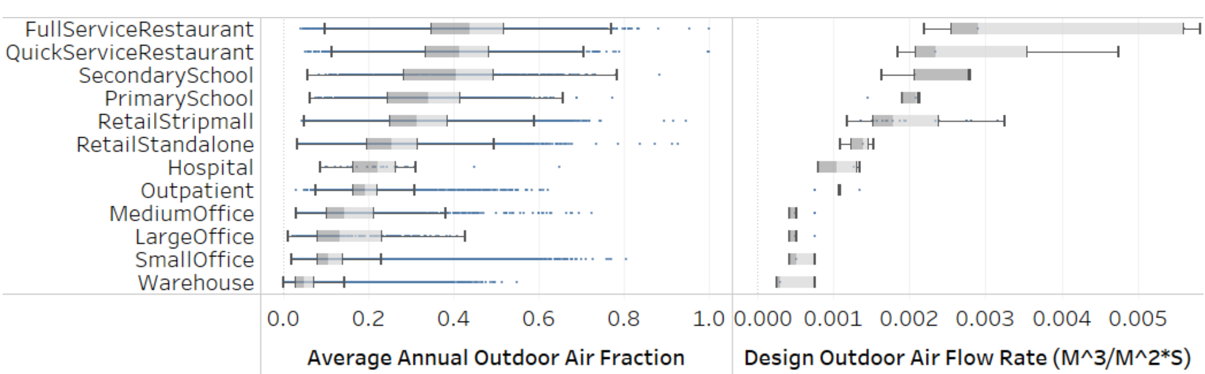

Figure 2. Average annual outdoor air fraction (left) and design outdoor airflow rate (right) by ComStock building type for buildings served by RTUs

Note that annual outdoor air fractions will be impacted by economizer operation, where applicable.

The governing energy code for the ComStock baseline is shown as a percentage of applicable floor area in Figure 3. 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 whether the feature is required. Similarly, heating, cooling, and fan efficiencies are set based on the in-force code year. For models with the "PSZ-AC with electric coil" HVAC system type, the ComStock baseline will use electric resistance coils with a 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%.

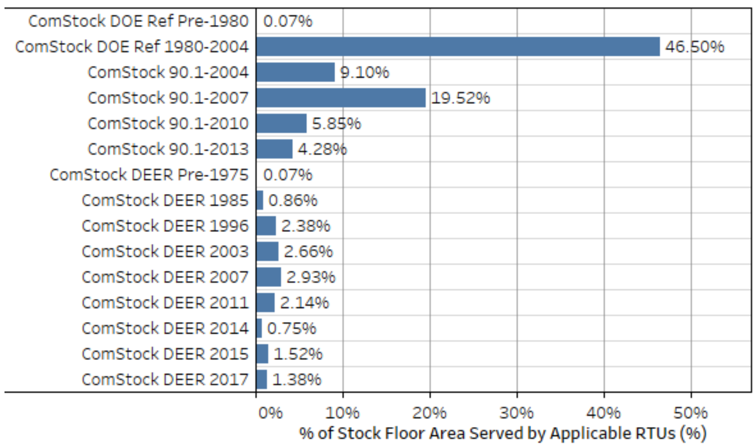

Figure 3. ComStock baseline in-force energy code followed as a percentage of applicable floor area. Applicable floor area includes ComStock buildings with "PSZ-AC with gas coil" and "PSZ-AC with electric coil" HVAC system types.

DEER stands for Database for Energy Efficiency Resources which represents building characteristics for California models following Title 24.

The ComStock baseline includes energy recovery in RTUs only when required by the governing energy code standard, which will impact the stock savings impact of including energy recovery with the new HP-RTUs. Replacing an existing RTU that already includes energy recovery may not show as high of relative energy savings versus replacing an existing RTU that does not have energy recovery. More information about the ComStock baseline heat/energy recovery systems can be found in the *ComStock Documentation* [15].

Lastly, the benefits of heat/energy recovery systems depend on routing exhaust air through the heat exchanger. As discussed, some amount of the exhaust air in buildings may not be routed back to the central exhaust or heat exchanger, either due to duct leakage or separate exhaust fans. ComStock includes exhaust fans in some space types, summarized in Table 1. Note that some prominent building types, such as small/medium/large office, warehouse, and retail, do not currently include any zone exhaust, so all exhaust air is assumed to return to the AHUs and become available for heat/energy recovery benefits, when applicable. Furthermore, ComStock models do not currently include duct leakage. These factors may overestimate the amount of exhaust air available for heat/energy recovery in ComStock models.

Table 1. Building and Space Types in ComStock Modeled With Zone Exhaust Fans

Building Type	Space Type
Full-Service Restaurant	Kitchen
Hospital	Kitchen
Large Hotel	Kitchen
Outpatient	Anesthesia
Outpatient	MRI
Outpatient	MRI Control
Outpatient	Soil Work
Outpatient	Toilet
Primary School	Restroom
Primary School	Kitchen
Primary School	Kitchen
Quick-Service Restaurant	Kitchen
Secondary School	Restroom
Secondary School	Kitchen
Small Hotel	Public Restroom
No Zone Exhaust Fans	
Retail	None
Retail Strip Mall	None (except those with kitchens)
Small Office	None
Medium Office	None
Large Office	None
Warehouse	None

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 33.3% of the ComStock floor area (Figure 4). ComStock HVAC distributions are informed by the 2012 CBECS. The methodology for interpreting CBECS data to create HVAC probability distributions for ComStock is discussed in the *ComStock Documentation* [15]. The measure is not applicable to space types that directly serve kitchens, spaces that are unconditioned, or RTUs with outdoor air ratios above 65% (due to an EnergyPlus® bug with cycling operation).

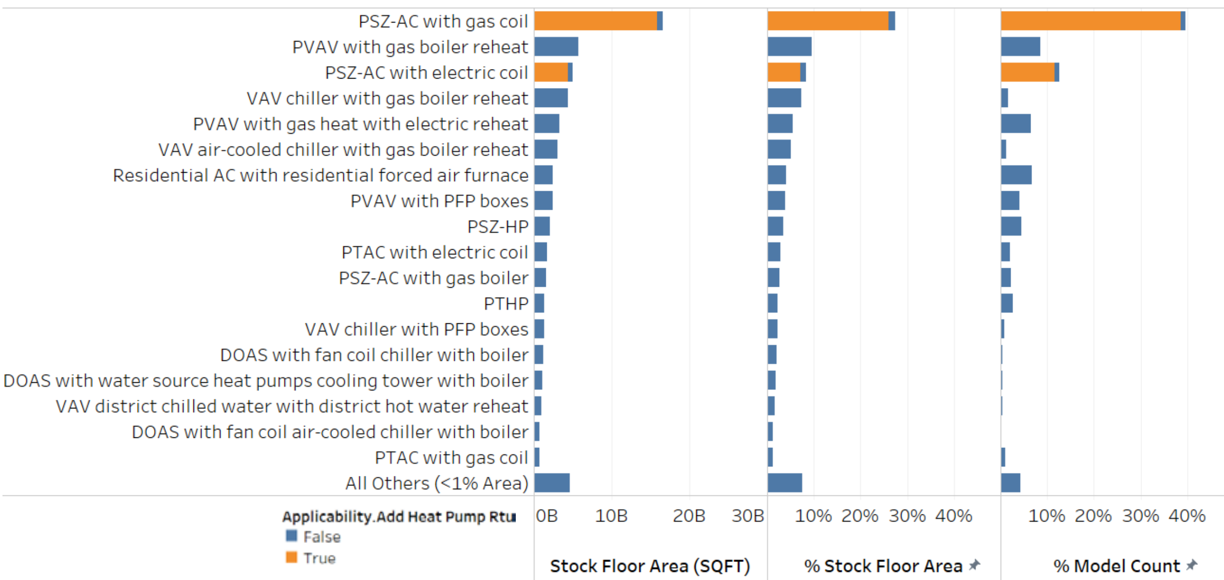

Figure 4. ComStock HVAC system type prevalence by stock floor area. Orange represents the portion of the stock applicable to the HP-RTU measure, while blue shows non-applicable portions of the stock.

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

For this study, heat/energy recovery is included in all the new HP-RTUs except for those serving food service building types. Although there is evidence to suggest that exhaust air recovery can be applied to kitchen exhaust hoods, there are additional considerations that need to be factored in to meaningfully model the application, and these are beyond the scope of this study. The only exception to this would be existing RTUs that already included energy recovery in the baseline; in these instances, a new energy recovery system is added.

Table 2 compares the stock floor area served by RTUs with heat or energy recovery for the ComStock baseline and the HP-RTU with heat/energy recovery scenarios. The baseline only includes heat/energy recovery where required by the local governing energy code at the time of last HVAC replacement. The HP-RTU scenario adds heat/energy recovery when the applicability criteria of both the HP-RTU system and the heat/energy recovery system discussed in this section are met.

Note that in most cases, there is a large increase in heat/energy recovery as a result of combining heat/energy recovery with the HP-RTU scenario. Food service building types do not show additional heat/energy recovery since they deemed not applicable for this study. Also note that we do not see 100% floor area covered by a recovery system for any building type. This is because some of the floor area is served by systems not applicable to the HP-RTU measure, and therefore they do not receive heat/energy recovery. For example, warehouses have substantial area served by unit heaters. Other cases include the prevalence of food service in some models, or outdoor air ratios that are too high.

Table 2. Fraction of Stock Floor Area Served by Heat or Energy Recovery Systems for the ComStock Baseline and the HP-RTU with Heat/Energy Recovery Scenarios

Table only includes buildings served by RTUs.

Building Type	Baseline	HP-RTU With Heat/Energy Recovery
FullServiceRestaurant	4%	4%
Hospital	0%	93%
LargeOffice	5%	74%
MediumOffice	0%	75%
Outpatient	0%	71%
PrimarySchool	4%	68%
QuickServiceRestaurant	1%	1%
RetailStandalone	2%	97%
RetailStripmall	2%	80%
SecondarySchool	8%	57%
SmallOffice	0%	94%
Warehouse	0%	28%

3.2 Technology Specifics

3.2.1 Heat Pump Rooftop Unit Performance

This report is a slight modification to the HP-RTU with electric backup heat measure from Commercial End-Use Savings Shapes 2023 Release 1. The only difference is that this study includes exhaust air energy recovery in the new HP-RTUs. Therefore, this document will only minimally discuss core modeling assumptions and details. For a more comprehensive overview of the HP-RTU modeling, such as performance curves, data sources, controls, etc., please refer to the documentation for the original measure.

Key assumptions include:

- The new HP-RTUs are modeled with variable-speed compressors and fans. Performance curves are used to determine how efficiency and capacity vary with indoor and outdoor temperature and part-load ratio, including cycling losses. At full compressor speed, the performance curves yield 56% COP and 46% capacity retention at 0°F.

- The heat pump system is sized to the design cooling load, with electric resistance supplemental heating used to address any additional loads. The supplemental heating coil is assumed to have a COP of 1. The supplemental heating coil can operate simultaneously with the heat pump heating to minimize usage of the relatively less efficient supplemental coil as described in [2]. Note that heat pump sizing is not influenced by the prevalence of heat/energy recovery for this study, although this could be considered in future work.

- The minimum operating temperature for the heat pumps is modeled at 0°F, which is the default setting for some manufacturers [2]. The compressor will lock out below this temperature, and only supplemental heat will be available.

3.2.2 Energy Recovery Type

The measure applies heat recovery to the new HP-RTUs in drier climate zones (ASHRAE climate zones 3B, 3C, 4B, 4C, 5B, 5C, and 6B) where addressing latent energy loads is of lesser concern. The heat recovery is modeled as aluminum counterflow plate heat exchangers and includes a bypass for temperature control and economizer lockout where applicable. Note that this measure does not modify the prevalence or operation of economizers in the existing AHUs; these properties are retained from the baseline ComStock model.

The measure applies energy recovery to the HP-RTUs in humid climate zones where addressing latent loads with energy recovery would be beneficial. The energy recovery systems are modeled as membrane counterflow heat exchangers and include a bypass for temperature control and economizer lockout where applicable.

3.2.3 Energy Recovery Effectiveness

Both the energy recovery and heat recovery systems are modeled using the effectiveness performance of the Ventacity systems shown in Table 3 [9]. These values dictate how much energy is transferred between the supply and exhaust airstreams and will vary based on specific products and configurations. Note that the Ventacity system is an energy recovery ventilator, which would not be installed inside a packaged RTU. These performance values are used since Ventacity publishes detailed performance data that can be leveraged for energy modeling. In practice, it is likely more common to choose an RTU with heat/energy recovery already integrated into the system, like the options available for the Daikin Rebel, rather than a separate system.

EnergyPlus allows latent and sensible effectiveness assignments at 100% and 75% airflow, respectively, for both heating and cooling, which can be determined from Ventacity performance curves. Because the heat recovery system is only suitable for sensible energy recovery, the latent effectiveness is modeled as 0% for all cases. The modeled inputs for effectiveness are shown in Table 3. Note that performance values can change based on product selection, configuration, and operation.

Table 3. Modeled Effectiveness Inputs for Energy and Heat Recovery Based on Ventacity Systems Shown in Figure 1

	Energy Recovery		Heat Recovery	
	Heating	Cooling	Heating	Cooling
Sensible 100% Airflow	75%	75%	84%	83%
Sensible 75% Airflow	78%	78%	86%	84%
Latent 100% Airflow	61%	55%	0%	0%
Latent 75% Airflow	68%	60%	0%	0%

As mentioned, ComStock does account for zone exhaust fans in some building types, but not in offices, retail buildings, or warehouses, which are prominent in the stock. Furthermore, ComStock does not currently account for duct leakage. A PNNL study using the DOE prototype models assumes that 90% of exhaust air is available for energy recovery to account for both zone exhaust and duct losses [6]. To account for this, the energy/heat recovery measure assumes that 90% of return air is available for recovery through a derating of the recovery effectiveness.

3.2.4 Energy Recovery Added Fan Static Pressure

Adding heat exchangers to the airstream for heat/energy recovery creates additional pressure drops that the supply and exhaust fans need to overcome. The pressure drops are modeled as an additional 0.85 in. w.c. and 0.65 in. w.c. for the supply fan and exhaust fan, respectively. These values align with both the AEDG and PNNL values [5], [6].

The static pressure values for the fan objects in EnergyPlus are not informed by the bypass status of the heat exchanger objects. This ignores the reduced static pressure that occurs when bypassing the heat exchanger. To account for this, the additional fan power is added directly to the heat exchanger objects in the form of motor energy for the enthalpy wheel. This is preferred because the power for the wheel object does modulate based on heat exchanger bypass status, so the additional static pressure due to the heat exchanger will be removed when the system is bypassing the heat exchanger. Note that additional fan power will therefore be reflected in the "Energy Recovery" end use rather than the "Fans" end use as a result of this workaround.

3.2.5 Energy Recovery Controls

The energy recovery system is modeled with a bypass for economizer lockout operation. The system also includes wheel speed modulation for increased discharge temperature control.

Defrost operation is modeled by controlling the exhaust temperature of air leaving the energy recovery system. This ensures the exhaust air from the outlet of the heat exchanger is above the temperature that permits frost formation. For this modeling, the default EnergyPlus value of 35°F was chosen as the minimum exhaust temperature. When the temperature is at or below this point, the system redirects some of the incoming air around the recovery system (bypass). This reduces heat transfer between air streams which maintains the exhaust air temperature above the minimum setpoint.

3.3 Greenhouse Gas Emissions

Three electricity grid scenarios are presented to compare the emissions of the ComStock baseline and the window replacement scenario. 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 data set, and the last uses the eGrid data set [16], [17]. All three scenarios vary the emissions factors geospatially to reflect the variation in grid resources used to produce electricity across the United States. The Cambium data sets also vary emissions factors seasonally and by time of day. This study does not imply a preference for any particular grid emissions scenario, but other analysis suggests that the choice of grid emissions scenario can impact results [18]. Emissions due to on-site combustion of fossil fuels use the emissions factors shown in Table 4, which are from Table 7.1.2(1) of draft American National Standards Institute/Residential Energy Services Network/International Code Council 301 [19]. To compare total emissions due to both on-site fossil fuel consumption and grid electricity generation, the emissions from a single electricity grid scenario should be combined with all three on-site fossil fuel emissions.

Table 4. On-Site Fossil Fuel Emissions Factors

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

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

3.4 Limitations and Concerns

Limited comprehensive heat pump performance maps exist, which are required for detailed energy modeling. Consequently, understanding of heat pump performance and operation in this work is also limited. Heat pump modeling is sensitive to performance assumptions due to the strong relationship between efficiency and capacity with outdoor air temperature. This impacts both annual energy consumption and peak demand. This work attempts to use the most informative data available and makes documented assumptions about heat pump operation and performance. These will notably impact results. Please consider these assumptions.

Stock savings are sensitive to ComStock baseline assumptions. Compared to CBECS 2012, which is another prominent data source for commercial building stock energy usage, ComStock currently shows lower gas heating consumption and higher electric heating consumption [20]. This can affect the net impact of converting both gas furnace and electric resistance RTUs to HP-RTUs.

There is a known EnergyPlus bug regarding cycling operation for multispeed coil objects. This can cause the modeled HP-RTU systems to cycle at higher part-load fractions than the baseline single-speed RTU systems. Many units are only minimally impacted by this since the HP-RTU systems are variable speed and can turn down to lower part-load fractions. There is another known bug in the measure that caused a few models to show greater than 100% cooling savings. This is because the performance curves used in the measure do not currently have realistic limit boundaries. There were some odd conditions that caused the performance curve to produce a negative COP in the EnergyPlus simulation for these few models, causing the negative cooling consumption and therefore greater than 100% cooling savings. However, the limited prevalence is not expected to have a notable impact on results.

Another prominent limitation of this study is a lack of data on the prevalence of once-through air delivery systems that do not exhaust air at the AHU, but rather through a dedicated exhaust fan. This complicates adding a heat/energy recovery system because the exhaust air and outdoor ventilation air need to pass through the same heat exchanger to achieve energy recovery benefits. If air is exhausted across multiple separate locations, additional work may be required to route the airstreams to the same location. Otherwise, the portion of exhaust air not passing through the heat/energy recovery system will not be utilized for energy recovery, which can limit the effectiveness of the system.

ComStock does account for zone exhaust fans in some building types, but not in offices, retail buildings, or warehouses, which are prominent building types. Furthermore, ComStock does not currently account for duct leakage. A PNNL study using the DOE prototype models assumes that 90% of exhaust air is available for energy recovery to account for both zone exhaust and duct losses [6]. To account for this, the energy/heat recovery measure assumes that 90% of return air is available for recovery. However, it is unclear how realistic this assumption is, and how it might vary between buildings, which can impact the savings of this measure. Overestimating the return air fraction would increase the savings suggested by this measure.

Lastly, the prevalence of heat/energy recovery in ComStock baseline AHUs is based on code requirements for the HVAC code year of each model. However, no data sources were found to validate the fraction of floor area of the building stock against what ComStock assumes using the code-baseline methodology. Heat/energy recovery prevalence impacts the measure savings, because heat/energy recovery prevalence in existing AHUs is inversely proportional to the number of applicable AHUs for the measure and therefore the stock-level savings achieved from the measure. Moreover, heat and energy recovery code requirements frequently depend on the size of the system. ComStock relies on assumptions about zoning to determine system size, but inaccuracies in these assumptions can result in inaccuracies in estimating the potential applicability of adding heat/energy recovery to systems that do not already include it.

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 measure scenario applied. These output variables can also be used for understanding 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 5. Output Variables Calculated From the Measure Application

Variable Name	Description
stat.area_fraction_with_heat_recovery	Fraction of model floor area served by an AHU with heat/energy recovery
stat.num_air_loops_heat_recovery	Number of airloops with heat/energy recovery in model (unweighted)

5 Results

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

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

5.1 Single Building Measure Tests

In this section, we describe the operation behavior of a small office building in Yellowstone Lake, WY, 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. The HP-RTU measure is applied, which replaces the gas-fired RTUs with HP-RTUs as described in this report. The HP-RTUs are applied both with and without energy recovery for comparison.

Figure 5 illustrates RTU air temperatures for the HP-RTU with energy recovery scenario during a cold week in February. Outdoor air (blue) ranges from -25°F to 5°F. This is the temperature of outdoor ventilation air that enters the heat recovery section of the RTU. The air temperature after the energy recovery section (orange) increases roughly 25°F, varying based on temperature and flow conditions. The increased air temperature of the ventilation air during cold heating conditions reduces the heating load on the heat pump and electric resistance supplemental heating coils. Ultimately, the combined impact of the heating coils must ensure the supply air temperature (green) following the impact of mixing with return air and fan heat. Heat recovery reduces the electricity required to meet this target. Alternatively, the HP-RTU scenario without the energy recovery applied requires the heat pump and supplemental heat to cover a larger lift.

The outcome for this sample period is illustrated in Figure 6, where the HP-RTU scenario with no heat recovery (blue) shows higher site electricity consumption compared to the HP-RTU scenario with heat recovery applied (orange). These savings (in orange) are from the energy recovery reducing loads on the heating and cooling coils. Because this plot shows total building electricity, other end uses that are not impacted by the HVAC scenarios are included (e.g., lighting, plug loads), thereby showing a smaller impact than if only HVAC electricity were shown.

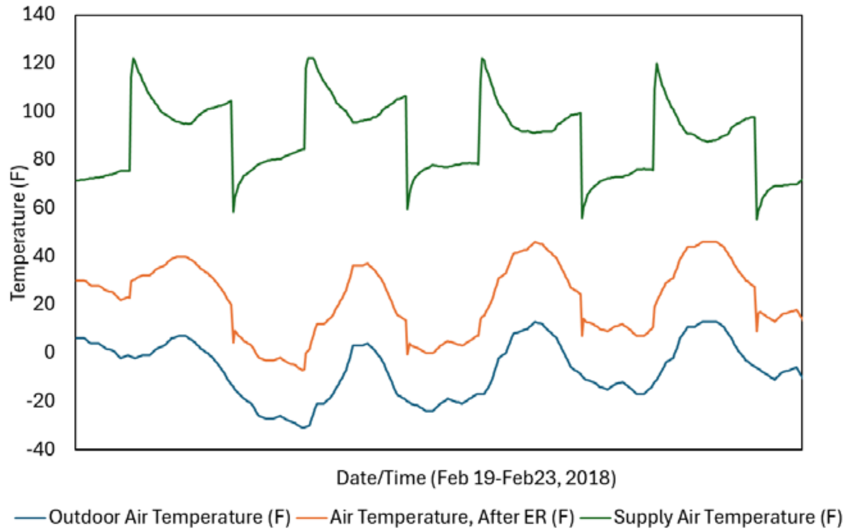

Figure 5. Air temperatures for a HP-RTU with heat recovery applied

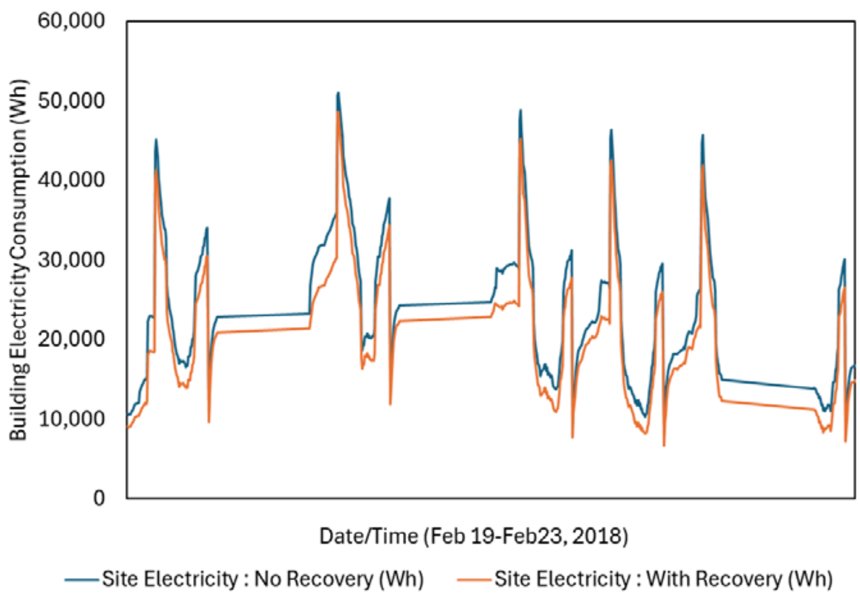

Figure 6. Total building electricity usage for HP-RTU scenario (blue) and HP-RTU with energy recovery scenario (orange)

The HP-RTU with no energy recovery scenario ("HP-RTU, No ER") shows 42% site energy savings versus the baseline scenario that uses natural gas RTUs (Table 6). These savings are attributable to the combination of 100% natural gas savings, since this scenario electrifies natural gas heating, and 42% increase in electricity usage from transitioning to electric heating. When adding energy recovery ("HP-RTU, with ER"), we see a 7% reduction in electricity usage compared to the HP-RTU scenario without energy recovery. These savings are primarily due to reduced heating loads when using energy recovery. This model example is from a very cold climate (ASHRAE climate zone 7), so the impact may be higher than many other cases.

Table 6*.* Annual Site Energy Comparison for Single Model Example Between the Baseline, HP-RTU With No ER (Energy Recovery), and HP-RTU With ER Scenarios

Note that these results include the prevalence of electric resistance supplemental heating when the HP system is unable to meet the full heating load.

	Natural Gas (KBtu)	Electricity (KBtu)	Total Site Energy (KBtu)
Baseline	855,869	526,304	1,382,173
HP-RTU, No ER	0	807,095	807,095
HP-RTU, with ER	0	733,023	733,023

5.2 Stock Energy Impacts

The HP-RTU with heat/energy recovery measure ("HP-RTU + ER") is applicable to buildings comprising 33% of the stock floor area and demonstrates 9% total site energy savings (382 trillion British thermal units [TBtu]) for the U.S. commercial building stock ("Baseline") modeled in ComStock (Figure 7a). The savings are primarily attributed to:

- **28%** stock **heating gas** savings (235 TBtu)
- **-22%** stock **heating electricity** savings (-39 TBtu)
- **13%** stock **cooling electricity** savings (85 TBtu)
- **15%** stock **fan + heat recovery electricity** savings (81 TBtu)
    - Fan static pressure increases due to heat/energy recovery are categorized under the "heat recovery" end use.

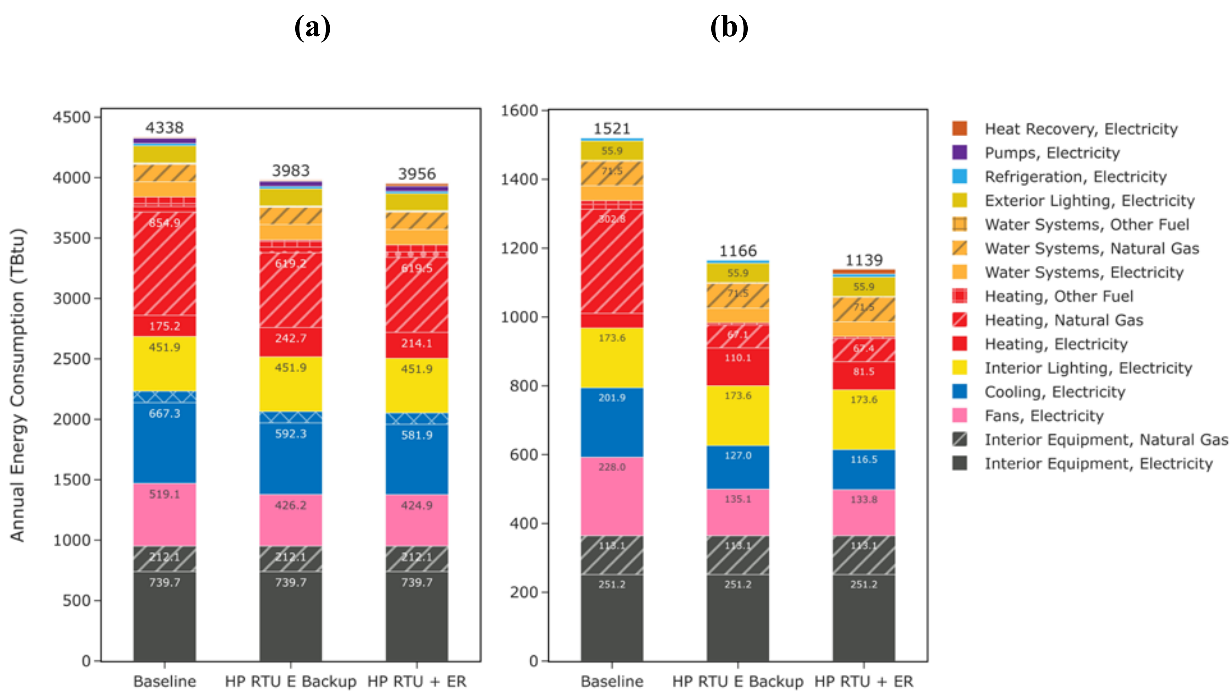

Figure 7. Annual site energy consumption by end use and fuel type for (a) the total commercial building stock, including buildings not applicable to the upgrades measure(s), and (b) the applicable commercial building stock where the upgrade measures are applied.

"HP-RTU E Backup" is the standalone variable-speed heat pump rooftop unit measure with electric backup heat, while "HP-RTU + ER" is the same measure plus heat or energy recovery applied.

Adding energy recovery reduces site heating electricity by 12% (29 TBtu) compared to the standalone variable-speed HP-RTU scenario ("HP-RTU E Backup") for the total commercial building stock (Figure 7a), or 26% for the stock segment applicable to the upgrades (Figure 7b). This is due to the energy recovery system pre-heating outdoor ventilation using building exhaust air, thereby reducing the heating load. Note that the gas heating totals do not change between the HP-RTU and HP-RTU + ER scenarios, since this remaining consumption represents heating in buildings not applicable to either upgrade scenario.

Similarly, the heat/energy recovery scenario reduces site cooling electricity by 2% (10 TBtu) compared to the standalone variable-speed HP-RTU scenario for the total commercial building stock (Figure 7a), or 8% (10 TBtu) for the stock segment applicable to the upgrades (Figure 7b). The added cooling savings are due to pre-cooling the outdoor ventilation air using building exhaust air.

The HP-RTU with heat/energy recovery scenario adds 3% (12 TBtu) combined fan and heat recovery electricity energy for the stock compared to the HP-RTU scenario alone (Figure 7a). This energy penalty is attributed to the additional fan energy required when adding heat/energy recovery, as these systems increase the static pressure the fans must overcome. Note that the fan power associated with heat/energy recovery is categorized under the "heat recovery" end use due to the energy modeling workflow, which is why these two end uses are being evaluated together. Despite showing a small decrease in the fans end use alone when moving to the heat/energy recovery scenario, the combined impact when considering heat recovery impact does show increased fan energy for the heat/energy recovery scenario, as expected.

Both the HP-RTU and the HP-RTU + heat/energy recovery scenarios show notable decrease in fan energy consumption versus the existing building stock ("Baseline"). There are two primary factors driving this result. First, both upgrade scenarios are replacing existing RTUs, which may be over a decade old and therefore use older and less-efficient fan systems, whereas the upgrade scenarios both leverage new and higher-efficiency supply fans. Second, both upgrade scenarios use single-zone variable-speed supply fans. This allows the system to decrease the supply air volume during periods of reduced zone loads, therefore saving fan energy. Note that the supply fan savings could be similarly realized in new non-heat pump variable-speed RTUs, although this study is specific to heat pump RTUs.

The increase in the electric heating end use for the HP-RTU scenarios is due to electrifying existing RTUs that use natural gas heat. More systems using electric heat is expected to increase aggregate electric heating usage across the stock, noting that the HP-RTU with heat/energy recovery scenario shows less electric heating compared to the HP-RTU scenario alone. However, this transition also causes a notable decrease in natural gas heating. These factors should be considered together. This study also includes replacing existing RTUs that use electric resistance heating. In these cases, electric heating energy is expected to decrease since heat pump heating is generally more efficient than electric resistance heating. However, since there are far fewer electric resistance RTUs than gas RTUs in the stock (Figure 4), the aggregate stock impacts still show a net increase in electric heating due to this transition.

The decrease in electric cooling energy for both HP-RTU scenarios versus the existing building stock is primarily attributed to replacing older, less-efficient RTUs with new, more-efficient RTUs. Most RTUs in the ComStock baseline scenario follow an energy code year of 2004 or earlier, so higher efficiencies are expected with a new RTU. Note that energy code year often predates installation year, so energy code year should not be interpreted as the age of the existing RTUs. Additionally, both HP-RTU scenarios use variable-speed compressors which offer higher cooling efficiencies when the RTUs are operating in part-load conditions.

5.3 Stock Greenhouse Gas Emissions Impact

The HP-RTU with heat/energy recovery scenario (HP-RTU + ER) shows 7%–9% annual GHG emissions avoided (219 to 372 MMT CO_2e) against the baseline building stock depending on the grid electricity scenario (Figure 8). The natural gas emissions avoided are due to electrifying existing natural gas heated systems. The electricity emissions results are due to multiple factors. First, there are additional GHG emissions induced from adding electric heat with the transition from natural gas RTUs to electric HP-RTUs. However, there are electricity emissions avoided due to (1) replacing existing electric resistance RTUs with relatively more efficient HP-RTUs, (2) higher cooling efficiencies with the new variable-speed HP-RTUs, (3) higher fan efficiencies with newer, variable-speed fans, and (4) reduced heating/cooling loads from heat/energy recovery. Comprehensively, reduced electricity emissions are shown across all electricity grid scenarios in aggregate for the building stock, although these results may vary by region or other factors.

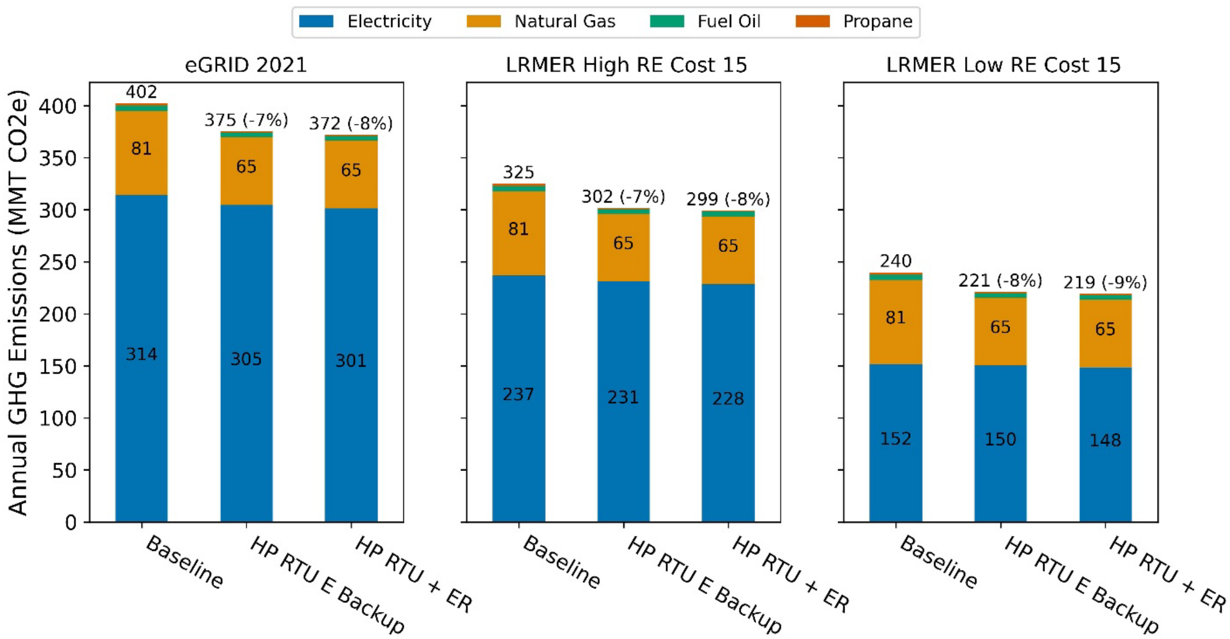

Figure 8. Greenhouse gas emissions comparison of the ComStock baseline, the standalone variable-speed HP-RTU scenario (HP-RTU E Backup), and the HP-RTU scenario with heat/energy recovery (HP-RTU + ER)

Three electricity grid scenarios are presented: Cambium Long-Run Marginal Emissions Rate (LRMER) High Renewable Energy (RE) Cost 15-Year, Cambium LRMER Low RE Cost 15-Year, and eGrid. MMT stands for million metric tons.

Adding heat/energy recovery to the HP-RTU scenario shows approximately 1% increase in GHG emissions avoided from all fuels for the total building stock compared to the HP-RTU scenario alone (Figure 8). This result remains consistent between grid scenarios. The net difference shows an additional 2-4 MMT CO_2e avoided for the HP-RTU with heat/energy recovery scenario. This is due to reduced heating and cooling loads from the recovery systems.

5.4 Site Energy Savings Distributions

This section discusses site energy consumption for quality assurance/quality control purposes. Specifically, it focuses on analyzing the distribution of energy savings across different characteristics (e.g., end use, fuel type) to better understand how the measure is affecting the building stock. Note that site energy savings can be useful for these purposes, but other factors should be considered when drawing conclusions, as these do not necessarily translate proportionally to source energy savings, greenhouse gas emissions avoided, or energy cost.

Figure 9 shows the distribution of percent site energy savings by end use and fuel type for the ComStock baseline versus the upgrade scenario. Therefore, each datapoint in the distribution represents the percent energy savings between a baseline ComStock model and the corresponding upgrade model with the HP-RTU with heat/energy recovery measure applied. The biggest differences are observed for heating, fans, cooling, and heat recovery end uses.

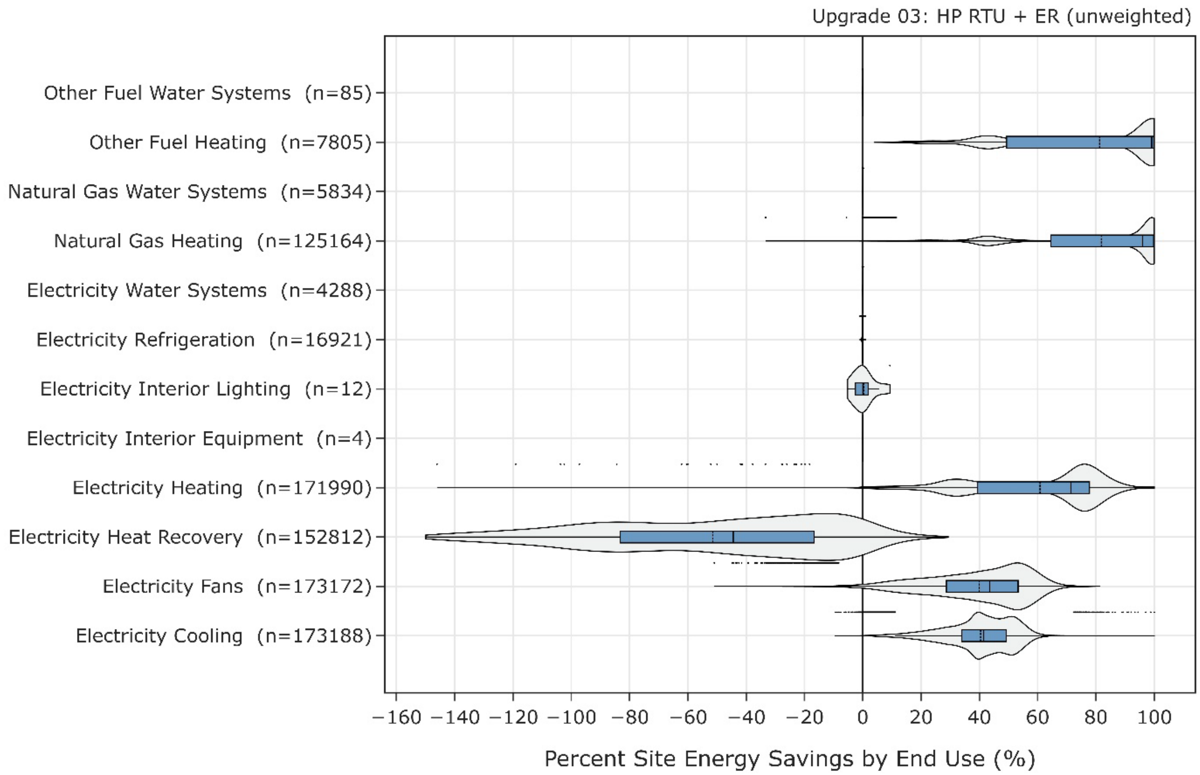

Figure 9. Percent site energy savings distribution for ComStock models with the applied HP-RTU with heat/energy recovery measure by end use and fuel type

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.

The combustion fuel space heating end uses show the highest savings, with much of the distribution clustered around 100% savings. This represents buildings where the HP-RTU upgrade scenario replaces all gas heating in the building with electric heat pump heating. Models that show less than 100% savings for the combustion fuel heating end uses either have some nonapplicable RTUs (e.g., units in kitchens, gas unit heaters). Note that these distributions only include models if they consume energy for the end use and fuel type combination in the baseline. In other words, models that use no combustion fuels in the baseline do not show up in these plots. Also, these plots only include models applicable to the HP-RTU scenario, and do not include nonapplicable models.

The electricity heating end use also shows notable savings, with the median building demonstrating site energy savings around 70%. These savings are primarily models that start with an RTU with electric resistance heating. The heat pumps in the upgrade model can show 2–4 times higher efficiency than electric resistance heating. Additionally, the heat/energy recovery further reduces the heating load and therefore the energy used for heating.

Some models show high electric heating penalties. Many of these samples are primarily gas-heated buildings with a small amount of electric heating in the baseline (for example, a zone may have an electric baseboard). Transitioning to an electric HP-RTU adds much more electric heating to the building and therefore causes a savings penalty. These models generally save energy at the site level through the elimination of on-site gas use. This distribution excludes buildings that initially had no electric heating (e.g., those that relied solely on gas RTUs). Consequently, it doesn't provide a complete overview of the potential increase in electric consumption when transitioning from gas heating to HP-RTUs.

The median fan and cooling energy savings are both roughly 40%, which aligns with the results from a lab testing and modeling study performed by PNNL on variable-speed RTUs [21]. These savings are due to the high-efficiency, variable-speed fan/compressor systems. Notably, these savings could also be achieved with a high-performance non-HP-RTU system. A small set of outliers show negative cooling savings. These are generally attributed to the beforementioned EnergyPlus night cycling issue with the multispeed coil objects used in this study. However, we expect this to have very minimal impact on the results due to the small prevalence of this issue.

The electricity heat recovery end use shows high negative savings. There are generally models that start with energy recovery on only one or a few systems. When the HP-RTU with heat/energy recovery scenario is applied, much more energy recovery is added causing an energy penalty for this end use. This penalty primarily captures additional fan static pressure required when adding heat/energy recovery to the airstream. However, the heat recovery end use makes up a very small fraction of energy consumption in buildings (Figure 7), and this penalty is generally outweighed by heating and cooling energy savings causing net energy savings.

The interior lighting end use shows 12 samples with savings/penalties because of applying this measure scenario. This is a known bug in the workflow as this measure does not impact the lighting end use. However, this bug affects very few buildings and therefore the impact is minimal.

Other end uses show minimal change such as water heating and refrigeration. The small differences that do exist are caused by slight variations in space conditions because of the measure scenario that interacts with these systems.

Figure 10 shows the distribution of site energy savings by fuel type. The median building shows approximately 25% site energy savings from the HP-RTU with the heat/energy recovery scenario applied. The savings are generally attributed to improved heating/cooling efficiencies with the new HP-RTUs, higher efficiency variable-speed fans, and reduced heating/cooling loads from heat/energy recovery.

The electricity fuel type shows site energy savings above the 25th percentile, with the median building saving around 10%, and increased electricity usage for buildings below the 25th percentile. This result is driven by many factors. Buildings that start with electric resistance RTUs are more likely to show electricity savings since they are being replaced with a relatively more efficient version of electric heating. On the other hand, buildings that start with gas-fired RTUs are electrifying the heating end use by transitioning to electric heat pumps, which increases electricity in buildings. However, the high-performance HP-RTUs modeled in this study also save electricity energy for cooling and fans, which reduces or eliminates the increased electricity for space heating. Lastly, the heat/energy recovery system increases electricity for fans since these systems add static pressure to the airstream but can reduce electricity by decreasing heating/cooling loads for ventilation.

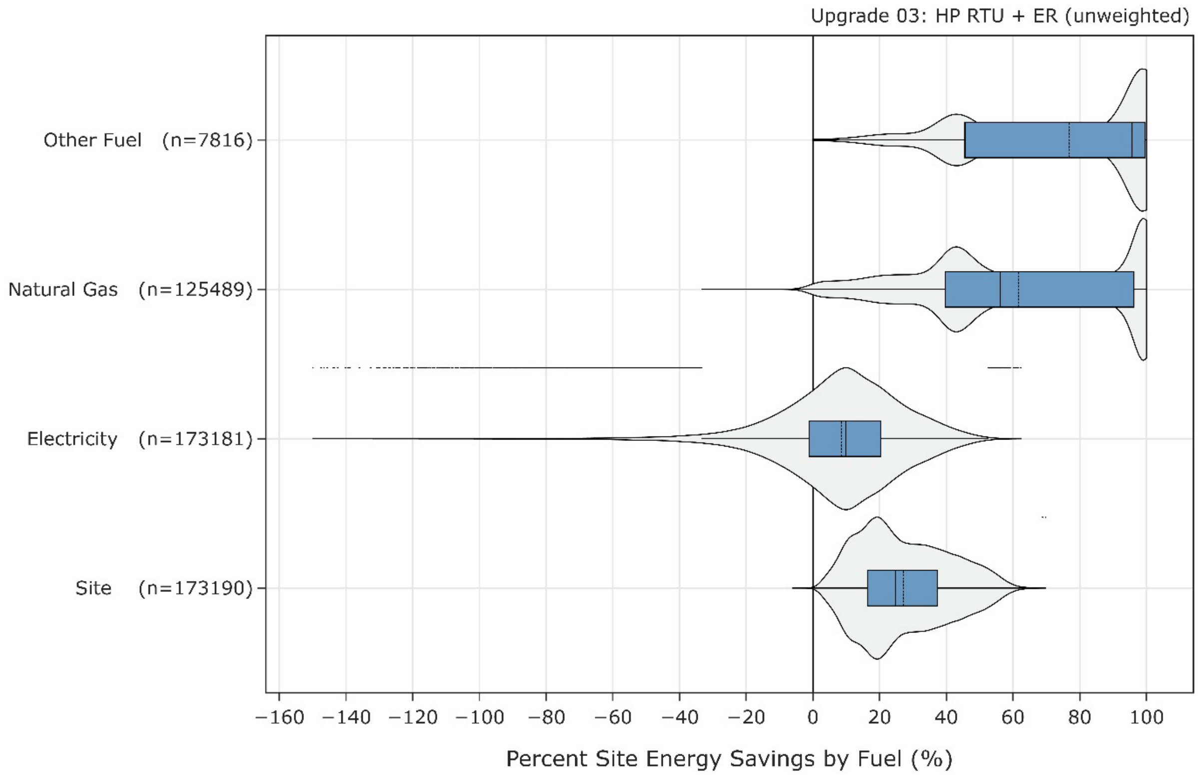

Figure 10. Percent site energy savings distribution for ComStock models with the applied HP-RTU with heat/energy recovery by fuel type

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

The "other fuel" (fuel oils, etc.) and natural gas fuel types show over 90% and 50% site energy savings, respectively. These savings are from replacing RTUs using combustion fuel for heating. Note that the natural gas and other fuel savings are not always 100%. This is from a mix of factors. First, there are other end uses in commercial buildings that use natural gas that are not impacted by this RTU replacement scenario including cooking and water heating. Additionally, this measure does not necessarily replace all existing gas heating equipment in buildings (unit heaters, RTUs serving kitchens, etc.).

Higher site energy savings are observed for buildings in colder climates (Figure 11). Warmer climates zones such as 1 through 3 show median site energy savings of 15%–25%, while colder climates (such as 5 through 9) show median site energy savings between 25% and 30%. Warmer climates have a much lower heating load, so they will see reduced benefit from site heating energy savings compared to colder climates. However, there is considerable overlap and high variability in the climate zone savings distributions, suggesting influence from several factors.

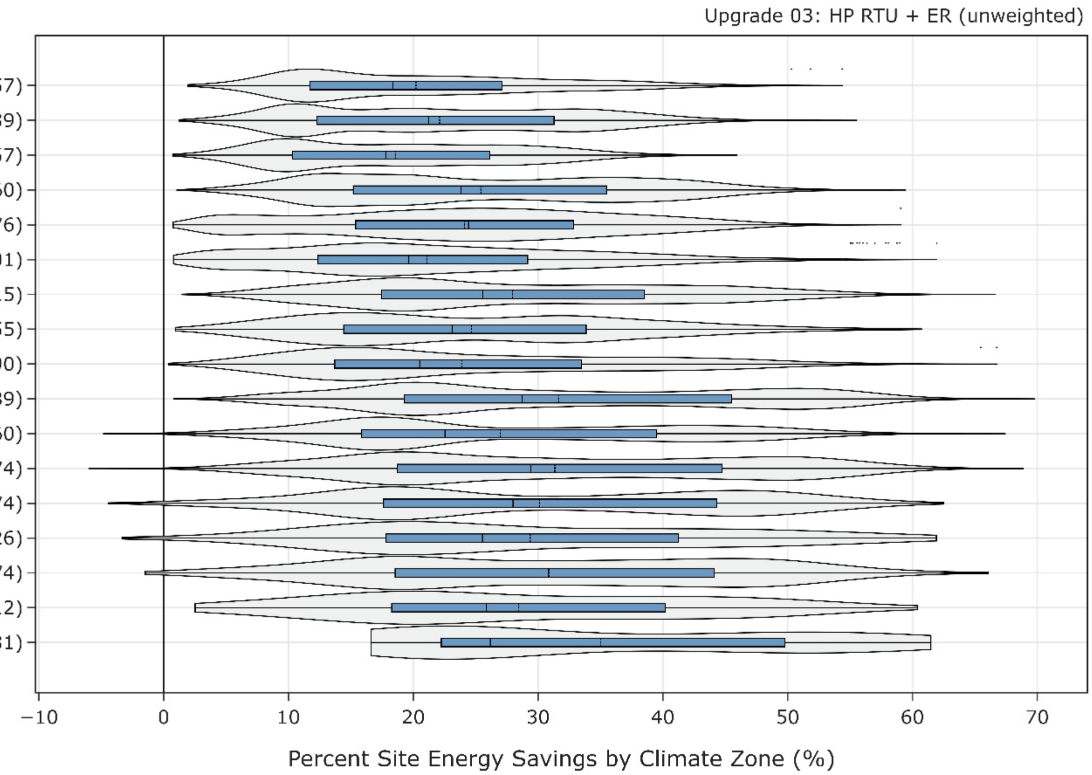

Figure 11. Percent site energy savings distribution for ComStock models with the applied HP-RTU with heat/energy recovery measure by ASHRAE climate zone

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.

5.5 Non-Coincident Peak Electricity Demand

Adding heat/energy recovery to the HP-RTU measure scenario shows an 18% reduction (3.4 W/ft² to 2.8 W/ft²) in winter peak demand intensity for the median building in Building America's "cold" climate zone (Figure 12). This is because heat/energy recovery pre-conditions outdoor ventilation air that can be very cold in the winter, lessening the heating load on the heat pump heating and/or electric resistance backup heating. This can be an attractive result since peak demand often has notable impact on building electrical capacity limits as well as some electric utility bill rate structures. These are building-level non-coincident peak demands.

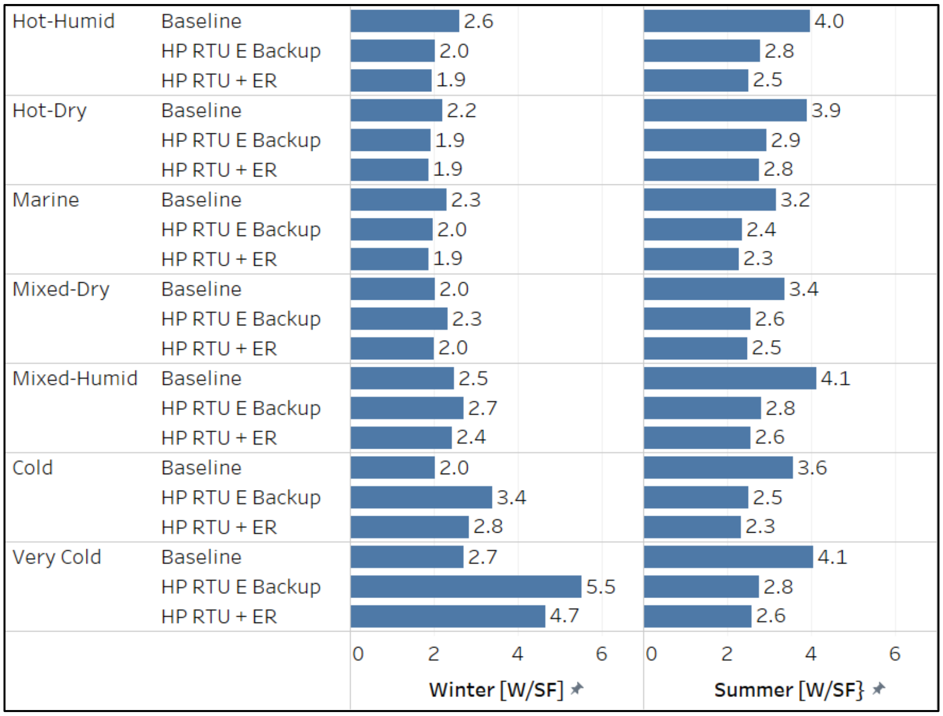

Figure 12. Comparison of the median noncoincident peak demand for applicable models between the baseline (representing the building stock of today), the HP-RTU electric backup scenario ("HP-RTU E Backup"), and the HP-RTU with heat/energy recovery scenario ("HP-RTU + ER"; also uses electric backup)

Results shown by Building America climate zone.

The disparity in winter peak intensity between the HP-RTU E Backup and HP-RTU + ER scenarios for the median building widens as climate zones become colder. This is because the addition of heat/energy recovery has greater impact on winter peak demands when there are higher heating loads. The warmer climate zones show little difference between the two scenarios, while the "very cold" climate zone demonstrates 15% reduction for the median building.

The HP-RTU E Backup and HP-RTU + ER scenarios show reductions in winter peak intensity versus the baseline for warmer climates, but higher winter peak intensities for the colder climates. Warmer climates have relatively lower heating loads, so the fan savings can often compensate for the added electric heating load. But in colder climates with higher heating loads, the added electric supplemental heating dwarfs the fan energy savings, and so we see increases in peak demand driven by the added prevalence of electric supplemental heating. However, this is a tradeoff with reductions in gas heating usage.

The HP-RTU scenarios show summer peak demand intensity reductions for the median building versus the baseline scenario across all climates. Reductions range from 25% up to 37% depending on scenario and climate. This is due primarily to fan and cooling savings with the newer, high-efficiency RTUs versus the generally older, less-efficient existing RTUs in the ComStock baseline. Adding energy/heat recovery to the HP-RTU scenario shows between 3% and 11% peak demand reductions for the median building, depending on climate zone. Again, this is due to cooling load reductions from pre-conditioning the outdoor air with the heat/energy recovery system.

5.6 Supplemental Heating Prevalence

Adding heat/energy recovery to HP-RTUs reduces the prevalence of backup heating for the median building across all Building America climate zones (Figure 13). This is due to reduced heating loads from pre-conditioning outdoor ventilation air with the heat/energy recovery system. Supplemental electric resistance heating generally has 2-4x lower efficiency than heat pump heating, so its use should be limited where possible.

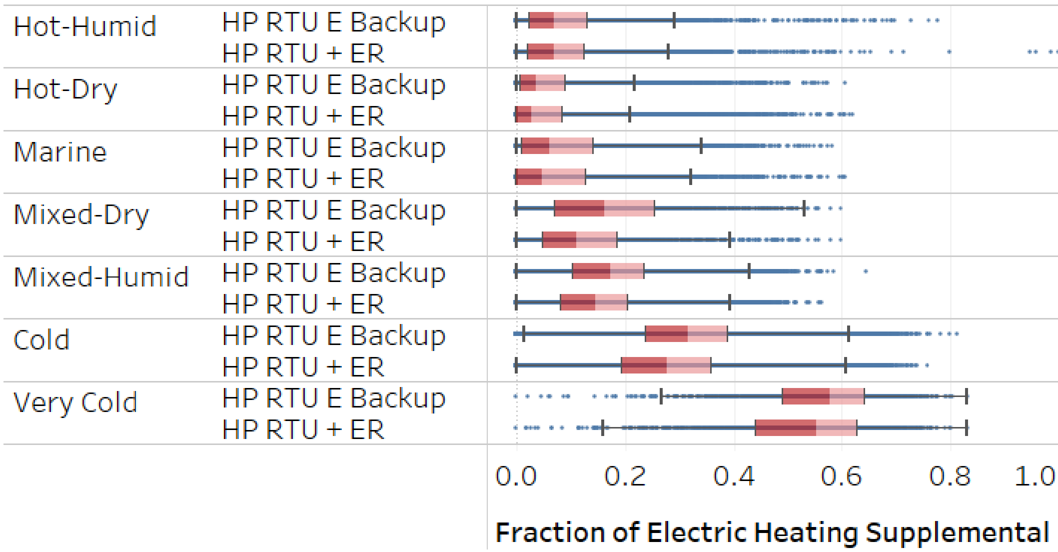

Figure 13. Stock annual average percent heating electricity input used for supplemental heating for applicable models between the baseline (representing the building stock of today), the HP-RTU electric backup scenario ("HP-RTU E Backup"), and the HP-RTU with heat/energy recovery scenario ("HP-RTU + ER"; also uses electric backup)

Supplemental electric resistance heating occurs for multiple reasons. First, RTUs in this analysis are sized to the design cooling load, which in some cases means the system design requires the use of supplemental heat to meet the design heating load at design temperatures. Additionally, heat pump heating capacity generally decreases with lower outdoor air temperatures, which can be further exacerbated by increased heat pump defrost operation during colder outdoor periods. Regardless of the reason, the supplemental electric resistance heating in this analysis is used to address any heating load not met by the heat pump. As expected, colder climate zones show higher prevalence of supplemental electric resistance heat on average due to higher heating loads, colder temperatures that derate available heat pump capacity, and insufficient heat pump capacity when sized to cooling loads, which in cold climates may be much smaller than the heating loads.

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Appendix A. Additional Figures

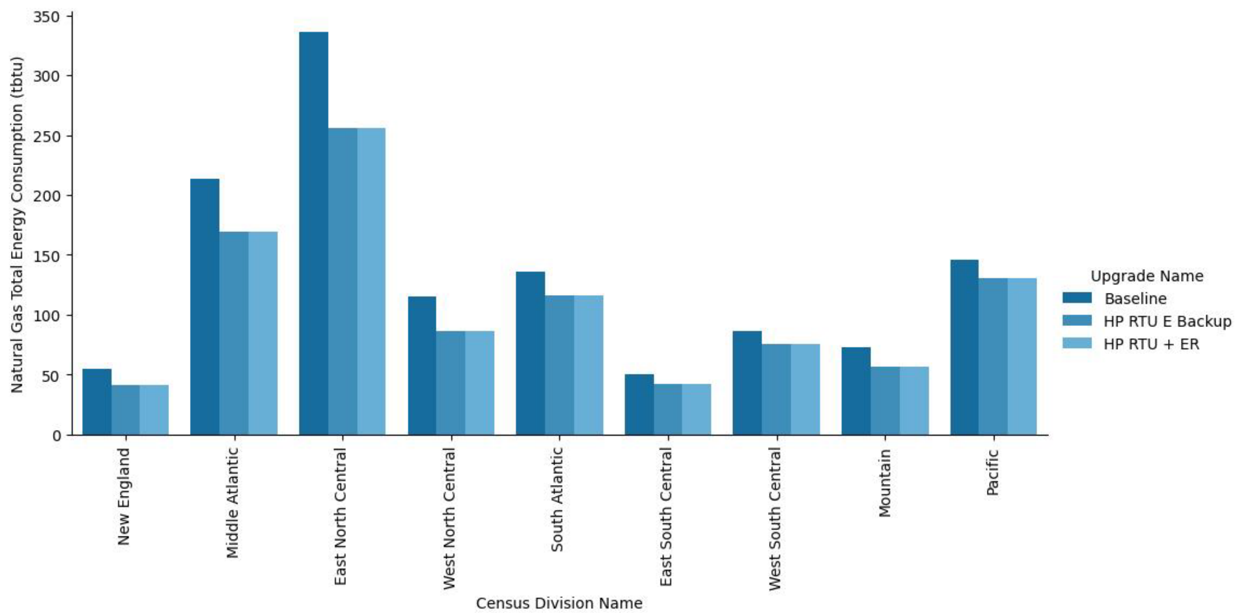

Figure A-1. Site annual natural gas consumption of the ComStock baseline and the measure scenario by census division

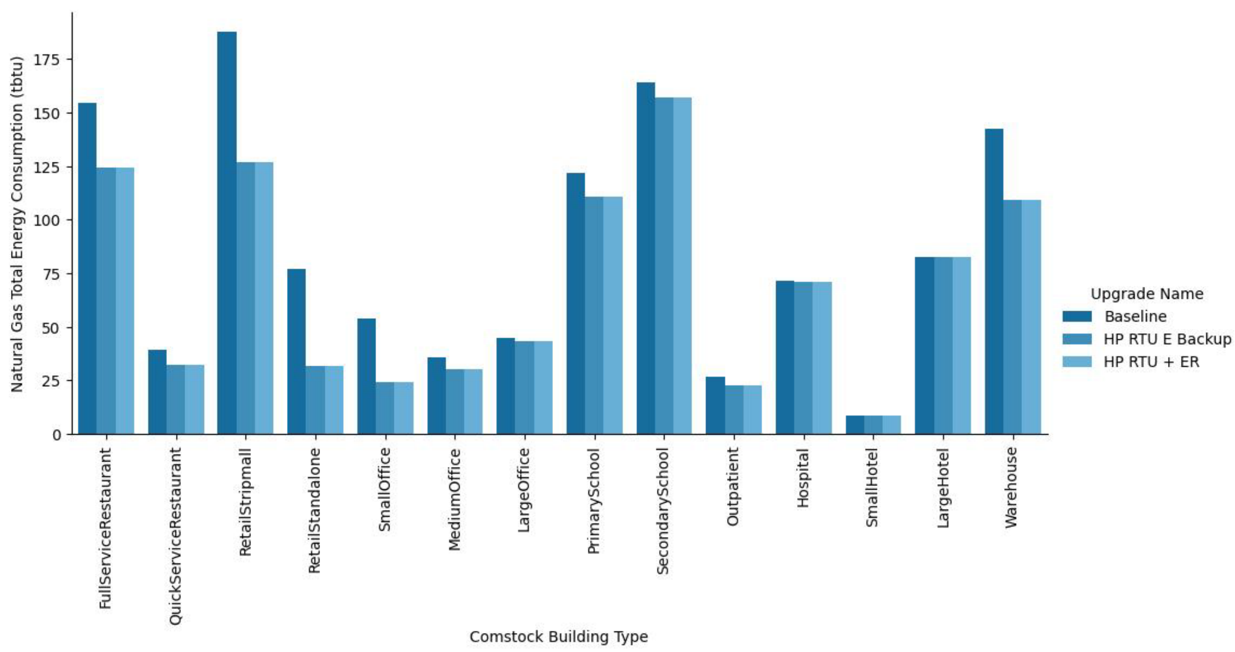

Figure A-2. Site annual natural gas consumption of the ComStock baseline and the measure scenario by building type

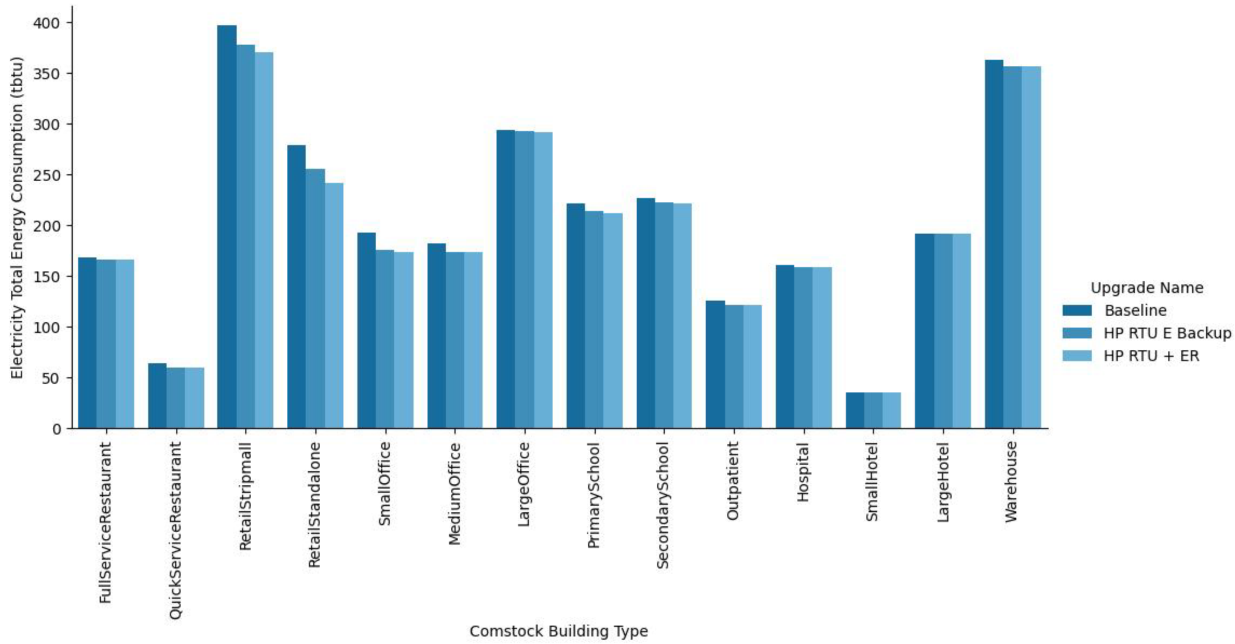

Figure A-3. Site annual electricity consumption of the ComStock baseline and the measure scenario by building type

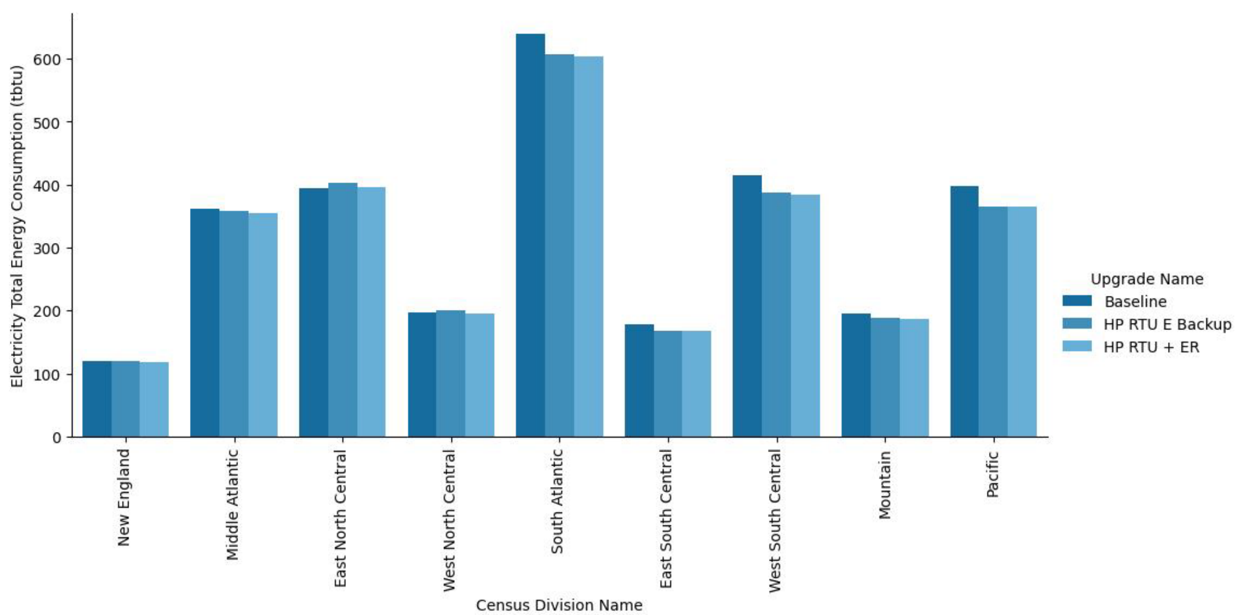

Figure A-4. Site annual electricity consumption of the ComStock baseline and the measure scenario by census division