DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof. Reference herein to any social initiative (including but not limited to Diversity, Equity, and Inclusion (DEI); Community Benefits Plans (CBP); Justice 40; etc.) is made by the Author independent of any current requirement by the United States Government and does not constitute or imply endorsement, recommendation, or support by the United States Government or any agency thereof.

ComStock Measure Documentation: Heat Pump Rooftop Units with Standard Performance

Janghyun Kim, Chris CaraDonna, and Andrew Parker

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated under Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5500-89042
June 2025

ComStock Measure Documentation: Heat Pump Rooftop Units with Standard Performance

Janghyun Kim, Chris CaraDonna, and Andrew Parker

National Renewable Energy Laboratory

Suggested Citation

Janghyun, Kim, Chris CaraDonna, and Andrew Parker. 2025. *ComStock Measure Documentation: Heat Pump Rooftop Units with Standard Performance*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-89042. https://www.nrel.gov/docs/fy25osti/89042.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated under Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5500-89042
June 2025

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored by the National Renewable Energy Laboratory for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Building Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

Cover photos (clockwise from left): Josh Bauer, NREL 61725; Visualization from the NREL Insight Center; Getty-181828180; Agata Bogucka, NREL 91683; Dennis Schroeder, NREL 51331; Werner Slocum, NREL 67842.

NREL prints on paper that contains recycled content.

Acknowledgments

The authors would like to acknowledge the valuable guidance, review, and input provided by Jeff Munk, Eric Bonnema, Emily Laidlaw, Deanna Cook, Nicholas Long, and Ronald Judkoff at the National Renewable Energy Laboratory.

List of Acronyms

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

Executive Summary

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

ComStock is a highly granular, bottom-up model that uses multiple data sources, statistical sampling methods, and advanced building energy simulations to estimate the annual 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.

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

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

This report describes the modeling methodology for a single end-use savings shape measure—heat pump rooftop units (HP-RTUs) with standard efficiencies that are prevalent in the current market—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	• The measure considered in this study applied HP-RTU (with standard performance) to a reasonable commercial building stock in the United States. Today, these products are claimed as standard efficiency by the manufacturers and are most commonly installed. • The definition of "standard efficiency" can be a bit vague when considering detailed specifics other than efficiency metrics of a heat pump. Thus, we have focused on reflecting products that manufacturers claim as standard efficiency and products that are not top-of-the-line in their model lineup. • This technology converts heating with a heat pump (i.e., relatively more efficient than electric resistance heating) and reasonably covering heating demand when the outdoor air temperature is above 0°F (-17.8°C).
Performance Assumptions	• Based on information gathered from nine products from five major manufacturers, there are some common (or relatively prevalent) characteristics, and we have defined standard efficiency products as follows: direct drive outdoor unit fan, two stages of heat pump cooling, single-stage heat pump heating (i.e., all compressors running at the same time), heat pump minimum lockout temperature of 0°F (-17.8°C), backup electric resistance heating, backup heating runs at the same time as heat pump heating, heat pump heating locking out below minimum operating temperature, seasonal energy efficiency rating of 14 and heating seasonal performance factor of 8 (for units with capacity of 5 tons and below), integrated energy efficiency ratio between 10.8 and 14.1, and coefficient of performance (COP) (at 47°F) between 3.2 and 3.5 (for units with capacity of 6 tons and above). The heat pump is sized to the design cooling load with electric supplemental heating used to address any remaining loads. • There are cases where some of these products have other variations: a variable frequency drive fan, dual fuel (i.e., gas backup heating) option, three or more cooling stages, two stages of heat pump heating, no backup heating as default, etc. However, this work tried to reflect a common and prevalent option for a standard efficiency product. • This report is part of a series: This document will primarily discuss the additional changes of performance and configuration of the standard efficiency HP-RTUs, whereas a comprehensive overview of the fundamental modeling methodology and background of the HP-RTU measure, including applicability, sizing scheme, and other key assumptions, can be found in the original documentation ("Heat Pump RTU," released in March 2023).
Applicability	• The HP-RTU measure is applicable to ComStock models with either gas furnace RTUs ("PSZ-AC with gas coil") or electric resistance RTUs ("PSZ-AC with electric coil"). • Buildings that do not contain gas-fired or electric resistance RTUs are not applicable. This is also not applicable to kitchen spaces. • This accounts for about 34% of the ComStock floor area.
Release	2024 Release 2: 2024/comstock_amy2018_release_2/

National annual results for site energy, greenhouse gas emissions, and energy bills are summarized in Table ES-2, Table ES-3, and Table ES-4, respectively. Note: The impact on electricity usage when replacing applicable HVAC systems with standard-performance HP-

RTUs depends on several factors: improved cooling efficiency with HP-RTUs, improved fan efficiency with HP-RTUs, improved heating efficiency with HP-RTUs when switching from electric resistance heating to heat pump heating, and additional electricity usage when replacing gas heating with HP-RTUs. Additionally, buildings in hotter climates with electric resistance heating will see electricity usage savings at the end from HP-RTU upgrades, while buildings in colder climates with gas heating will experience higher electricity usage as heating demand is now met by electricity through heat pump heating.

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

Fuel Type	Absolute Savings (TBtu)	Baseline Total (All Buildings, TBtu)	Percent Savings (All Buildings)	Baseline Total (Applicable Buildings Only, TBtu)	Percent Savings (Applicable Buildings Only)
Natural Gas	277.3	1467.5	18.9	543.1	51.1
Electricity	-9.6	3052.0	-0.3	1084.2	-0.9

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

Fuel Type	Absolute Savings (MMT CO_2e)	Baseline Total (All Buildings, MMT CO_2e)	Percent Savings (All Buildings)	Baseline Total (Applicable Buildings Only, MMT CO_2e)	Percent Savings (Applicable Buildings Only)
Natural Gas	18.5	98.0	18.9	36.3	51.1
Electricity	-3.0	231.4	-1.3	80.9	-3.7
Fuel Oil	0.6	5.5	11.3	0.7	86.1
Propane	1.2	2.7	43.4	1.6	71.5
Total	17.3	337.7	5.1	119.6	14.5

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.

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

Fuel Type	Absolute Savings (Billion USD, 2022)	Baseline Total (All Buildings, Billion USD, 2022)	Percent Savings (All Buildings)	Baseline Total (Applicable Buildings Only, Billion USD, 2022)	Percent Savings (Applicable Buildings Only)
Natural Gas	3.0	16.7	17.9	6.2	48.6
Electricity	-0.1	103.8	-0.1	38.0	-0.3
Fuel Oil	0.2	2.1	11.3	0.3	86.1
Propane	0.4	1.0	44.1	0.6	71.2
Total	3.6	123.6	2.9	45.0	7.9

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

Compared to the ComStock baseline scenario and advanced performance HP-RTU scenario (which we performed previously), the standard performance HP-RTU performs in the middle between the two scenarios, as expected, in terms of site energy savings. The difference from the advanced HP-RTU mostly comes from the part-load performance difference (shown in Figure 8); the advanced unit leverages variable-speed operation, while the standard performance unit leverages two-stage operation for cooling and single-stage operation for heating (representing the operation of standard efficiency off-the-shelf products today). In order to assess the impact of this upgrade more comprehensively, other factors such as (1) return on investment and (2) sensitivity analysis of certain configurations (e.g., different sizing, minimum compressor lockout temperature) of the HP-RTU system should also be considered.

Table of Contents

List of Figures

List of Tables

1 Technology Summary

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

Heat pumps offer an energy-efficient electric option for commercial building space heating, as they deliver space heating two to four times more efficiently than electric resistance options. 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. Most manufacturers offer heat pump rooftop units (HP-RTUs) with compressors capable of providing 105 kilowatts (kW) or less of cooling capacity (30 tons). There is a remarkable opportunity for the growth and widespread adoption of this technology, and expansion of the field will have an extensive impact on building fuel switching efforts.

In some climatic regions, HP-RTUs require the use of supplemental (or backup) heating systems, as a heat pump's heating capacity (using a compressor) diminishes as outdoor temperatures drop. Below a certain threshold, compressor-based heat pump heating is not available and supplemental heating (typically with electric resistance heating) should be used. Supplemental heating types vary, but electric resistance is a common choice for many applications. However, gas supplemental heating is also an option that may alleviate some concerns about increased winter peak demand and/or electrical panel upgrades. Gas supplemental heating may be attractive for buildings that already have natural gas lines to existing RTUs that can be repurposed for this application. Buildings that already use electric resistance heating may not be as concerned about peak demand increases or electrical panel upgrades when transitioning to HP-RTUs with electric backup, because the new units would likely be an electricity consumption improvement to their current equipment.

The analysis included in this documentation is a fourth analysis after three past and related analyses (upgrade titles including "Heat Pump RTUs"); the focus of this analysis is on reflecting standard efficiency HP-RTUs. The definition of "standard efficiency" can be a bit vague when considering detailed specifics other than efficiency metrics of a heat pump. Thus, we have focused on reflecting typical products that manufacturers claim as standard efficiency and products that are not top-of-the-line in their model lineup. Based on information gathered from nine products from five major manufacturers, there are some common (or relatively prevalent) characteristics and we have defined standard efficiency product as follows: direct drive outdoor unit fan, two stages of heat pump cooling, single-stage heat pump heating (i.e., all compressors running at the same time), heat pump minimum lockout temperature of 0°F (-17.8°C), backup electric resistance heating, backup heating runs at the same time as heat pump heating, heat pump heating locking out below minimum operating temperature, seasonal energy efficiency rating of 14 and heating seasonal performance factor of 8 (for units with capacity of 5 tons and below), and integrated energy efficiency ratio between 10.8 and 14.1 and coefficient of performance (COP) (at 47°F) between 3.2 and 3.5 (for units with capacity of 6 tons and above).

This document will primarily discuss new changes of performance and configuration of the standard efficiency HP-RTUs, whereas a comprehensive overview of the fundamental modeling methodology and background, including applicability, sizing scheme, and other key assumptions, can be found in the original documentation, “Heat Pump RTUs.”

2 ComStock Baseline Approach

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

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

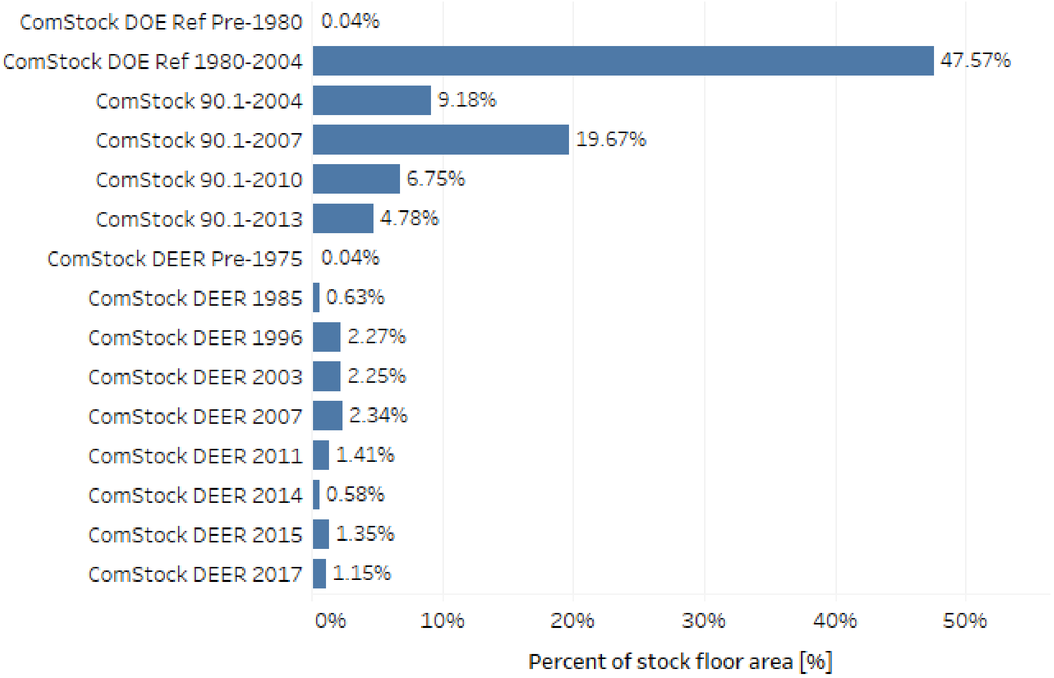


Figure 1. ComStock baseline in-force energy code followed as a percentage of applicable floor area

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

3 Modeling Approach

3.1 Applicability

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

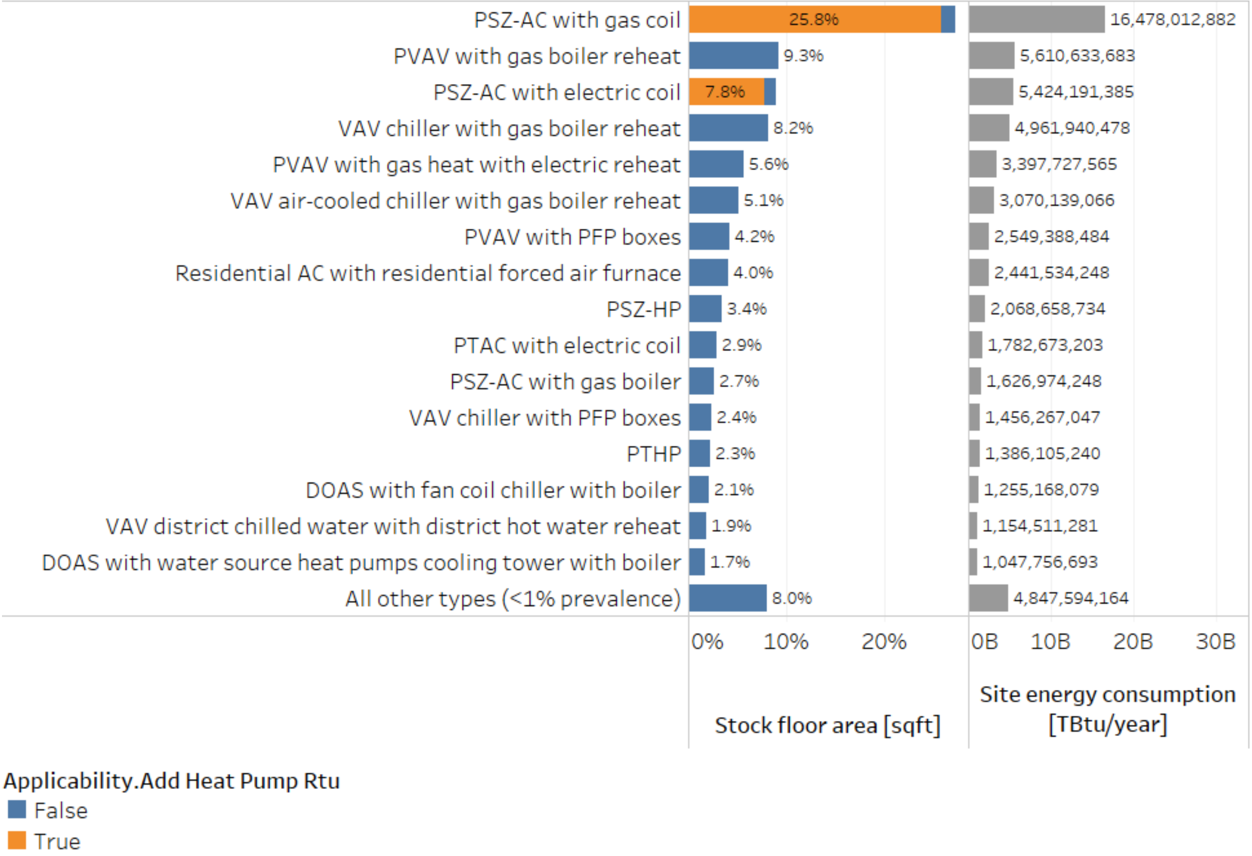


Figure 2. ComStock HVAC system type prevalence by stock floor area

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

3.2 Technology Specifics

This report is another iteration of the previous Heat Pump RTU measure. The only difference is the performance and configuration of the heat pump (e.g., performance maps in EnergyPlus, control logic, system configurations such as minimum operating temperature). The original measure, which we refer to as the "advanced performance" option, uses top-of-the-line variable-speed compressors and fans. This study leverages performance and configurations of standard efficiency heat pumps currently available in the market. This document discusses core modeling assumptions and details specific to modeling a “standard performance unit.” For a more comprehensive overview of the HP-RTU modeling, such as data sources, controls, etc., please refer to the documentation of the Heat Pump RTU measure (“Heat Pump RTUs,” released in March 2023).

3.2.1 Generation of Standard Performance Data

This section describes the process of generating a new set of performance maps from available and public information that manufacturers provide. Note that manufacturer and model information are included based on what can be found from the internet. The National Renewable Energy Laboratory (NREL) does not endorse or support any particular brand, type, or model of equipment.

3.2.1.1 Gathering Public Performance Data and Selecting Relevant Data

Table 1 shows a summary of some HP-RTU products relevant to this study that can be researched online by searching for standard efficiency products claimed by manufacturers. Key highlights from the table include the following.

- We have focused on products that manufacturers claim as standard efficiency.
- These products have common/prevalent characteristics. We define a standard efficiency product as follows:
    - Direct drive supply fan
    - Two stages of heat pump cooling
    - Single-stage heat pump heating (i.e., all compressors running at the same time)
    - Heat pump minimum lockout temperature of 0°F (-17.8°C)
    - Backup electric resistance heating
    - Backup heating runs at the same time as heat pump heating
    - Heat pump heating locking out below minimum operating temperature
    - For units with capacity of 5 tons and below, seasonal energy efficiency rating of 14 and heating seasonal performance factor of 8
    - For units with capacity of 6 tons and above, integrated energy efficiency ratio between 10.8 and 14.1 and COP at 47°F (8.3°C) between 3.2 and 3.5.
- Some of these products (and their performance data) that can be scraped from the internet do not meet the latest federal minimum efficiency requirements [3]. Thus, we decided to only include products that meet the minimum requirements when generating the new performance maps.
- While the minimum lockout temperature for heat pump heating is well-described in cold-climate heat pump product manuals, these standard efficiency products rarely provide this information. We decided to set the minimum heat pump lockout temperature to 0°F (-18°C) based on default settings from a couple of products, shown in Table 1.
- No single product provides all the required performance maps for EnergyPlus implementation:

  - Other than Carrier's and Lennox's manuals, all the other product manuals only provide performance maps for fully staged performances (e.g., capacity and input power) and do not provide separate performance maps for lower stage cooling.
  - One of the Carrier products is named as a standard efficiency product. However, this product includes advanced fan technology, making the overall efficiency higher than the other products.
  - Carrier products do not provide performance maps for the input power (i.e., metric for deriving the operating COP) depending on different operating conditions.
  - Unlike other products, Lennox's performance maps provide heating performance with fixed indoor temperature (70°F [21°C]) only.
- There are cases where some of these products have a variable frequency drive fan, dual fuel (i.e., gas backup heating) option, three or more cooling stages, two stages of heat pump heating, no backup heating as default purchase setting, etc. However, we are defining the standard efficiency to reflect the most common and prevalent options.
- Smaller units (e.g., capacity less than 6 tons) tend to have a single-stage compressor. To simplify performance maps between small and large units, to apply consistent performance across units, and to reflect the relatively more common type, we chose to model two-stage heat pump cooling for all units.
- The capacity and airflow differences between low and high stage cooling are derived from the manufacturers' performance data, as shown in Table 2. Thus, after the overall (i.e., high stage) capacity and airflow are determined based on design load and sizing algorithm in EnergyPlus, the low stage rated cooling capacity and airflow are calculated and implemented by multiplying 50% and 59%, respectively, to the high stage cooling capacity and airflow. As the relevant low stage airflow information (corresponding to the high stage or rated airflow) is not available in manufacturer manuals, some assumptions were made. Because ASHRAE 90.1-2022 [4] suggests that the low speed fan be operated at no more than 66% of the full speed, we assumed 66% of the rated airflow to be the low stage airflow for calculating the corresponding capacity at low stage. While this was applied for Lennox products, 66% of the rated airflows of Carrier products were beyond the airflow range reported in performance tables. Thus, based on engineering judgement, the middle airflows from the range provided in the tables were chosen where the ratio of low stage airflow to high stage airflow varied between 50% and 60% for Carrier products [5], [6], [7], [8]. These are all depicted in Table 2.

Table 1. Summary of HP-RTUs From Major Manufacturers in the Market (as of October 2023)

Data from [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24]

Manufacturer	Series/Model name	Efficiency level defined by manufacturer	Capacity range [tons]	Efficiency range [SEER/SEER2/HSPF/HSPF2/IEER /COP@47°F]	Supply fan type by default	Number of heat pump cooling stages	Number of heat pump heating stages	Heat pump heating lockout minimum temperature [°F]	Backup heating type	Backup heating control	Performance maps published?	Performance maps fully available for EnergPlus?
York	Sunline / XN	Standard	3-5	14 / - / 8 / - / - / -	Constant volume	1	1	NA	Elec heating or no backup	Together (two stage elec heating)	Yes	No low stage cooling data
	Sunline XP	Standard	15-20	- / - / - / - / 11.8-13.2 / 3.2-3.24	Constant volume	2	1	NA	Elec heating or no backup	Together (two stage elec heating)	Yes	No low stage cooling data
	Sun Core / XX, XQ	Standard	6-10	- / - / - / - / 12.7-15.1 / 3.3-3.5	Constant volume	2	1	NA	Elec heating or no backup	Together (single stage elec heating)	Yes	No low stage cooling data
	Sun Pro / XP	Standard	6.5-12.5	- / - / - / - / 10.8-13.5 / 3.2-3.4	Constant volume	2	1	NA	Elec heating or no backup	Together (two stage elec heating)	Yes	No low stage cooling data
Trane	Precedent / WS	Standard	3-5	14.3 / 13.4 / 8-8.2 / 7.2 / NA / NA	Constant volume	1	1	NA	Duel fuel, Elec heating, or no backup	Together (two stage elec heating)	Yes	No low stage cooling data
	Precedent / WS	Standard	7.5-10	- / - / - / - / - / 14.1 / 3.4	Constant volume	2	1	NA	Duel fuel, Elec heating, or no backup	Together (two stage elec heating)	Yes	No low stage cooling data
	Precedent / WS	Standard	12.5-25	- / - / - / - / 12.5-14 / 3.2-3.3	Constant volume	3 (12.5-17.5 tons), 4 (20-25 tons)	NA	Default 0 Range -18 ~ 45	Duel fuel, Elec heating, or no backup	NA	Yes	No low stage cooling data
Lennox	Xion	Standard	2-5	14 / 13.4 / 8 / 6.7 / - / -	Constant volume	1	1	0 or 30	Elec heating	Single stage heating	Yes	Less granularity in heating performance map
	Xion	Standard	7.5-20	- / - / - / - / 13.5-14.1 / 3.3-3.4	variable frequency drive	3 (7.5-10 tons), 2 (15-20 tons)	1	0 or 30	Elec heating	Up to two stage heating	Yes	Less granularity in heating performance map
Rheem	Classic Plus	NA	7.5-10	- / - / - / - / 12.2 / 3.3	Variable frequency drive	2	NA	Default 35 Range 30 ~ 50	Elec heating or no backup	NA	Yes	No low stage cooling data
Carrier	Weather Maker / 50FCQ	Standard	3-5	14.3 / 13.4 / 8.2 / 6.7-7 / - / -	Constant volume	1	1	Default 32 Range -45 ~ 80	Elec heating or no backup	Together (two stage elec heating)	Yes	No input power data
	Weather Master / 50GCQ	High efficiency	3-5	17 / 16 / 8.7-.9 / 7.1-7.5 / - / -	Constant volume, low (75%) and high speed	2	1	Default 32 Range -45 ~ 80	Elec heating or no backup	Together (two stage elec heating)	Yes	No input power data
	Weather Maker / 50FCQ	Standard + Ecoblue (7.5-25 tons)	7.5-25	- / - / - / - / 14-15 / 3.3-3.4	low (60-66%) and high speed	2	1	Default 32 Range -45 ~ 80	Elec heating or no backup	Together (two stage elec heating)	Yes	No input power data

Table 1. Cooling Capacity Difference Between Low and High Cooling Stages

Make	Model	Capacity [ton]	Flow rate condition (rated) in high stage [cfm]	Capacity in high stage [kBtu/h]	Flow rate condition in low stage [cfm]	Capacity in low stage [kBtu/h]	% of low stage flow rate over high stage flow rate	% of low stage capacity over high stage capacity
Carrier	Weathermaker	7.5	3000	90	1500	44.4	50%	50%
Carrier	Weathermaker	8.5	3400	101	1700	53.7	50%	53%
Carrier	Weathermaker	10	4000	125	2000	61	50%	49%
Carrier	Weathermaker	12.5	5500	151	2900	74.6	53%	49%
Carrier	Weathermaker	15	6300	166	3600	110.7	57%	67%
Carrier	Weathermaker	20	8000	240	4800	139	60%	58%
Carrier	Weathermaker	25	10000	290	6000	172.6	60%	59%
Lennox	Xion	7.5	2800	92	1848	43.9	66%	48%
Lennox	Xion	8.5	3200	104	2112	41.5	66%	40%
Lennox	Xion	10	3400	120	2244	41.3	66%	34%
Lennox	Xion	15	5500	182	3630	89.4	66%	49%
Lennox	Xion	20	7000	231	4620	114.3	66%	49%

Average	**59%**	**50%**

3.2.1.2 Data Processing and Converting Available Public Data to an EnergyPlus Compatible Format

This section describes each step of data processing, showing the conversion of publicly available performance data to EnergyPlus compatible performance maps. A new set of performance maps are generated as lookup tables in OpenStudio rather than biquadratic curves to avoid any potential overfitting issues.

Table 3 includes a list of new performance maps derived and applied in this study for modeling standard performance HP-RTUs, and the table also includes which actual products (and their data) in the current market are used to derive the performance maps. Note: This is not an exhaustive list of all required performance maps for modeling HP-RTUs in EnergyPlus. Rather, it is a down-selected list that can be outsourced from the publicly available data from manufacturers. Capacity-related performance maps are all derived from 5 to 25 different Carrier and Lennox products, and performance data for energy input ratio (EIR), which is an inverse of COP, are derived from 2 to 18 York and Lennox products. While the power data from Carrier included the exact total consumption of components (i.e., compressor and condenser fan) that is compatible with what EnergyPlus requires, the power data from Lennox only included compressor power. This has an implication of slight underprediction of power, which results in slight overprediction of COP (or underprediction of EIR that EnergyPlus wants) from data points from Lennox. The new EIR curves that include Lennox data, shown in Table 3, are affected by this limitation. To reflect rated COP changes depending on the size of the unit, regression fittings are performed on Carrier and Lennox products. More detailed findings are included in the following paragraphs.

Table 3. List of New Performance Maps for Standard Performance Modeling

Performance map count	Independent variable 1	Independent variable 2	Dependent variable	Derived from	Count of products used for derivation
1	Indoor air wet-bulb temperature	Outdoor air temperature	Capacity modifier for cooling in high stage	Average performance of Carrier WeatherMaker/WeatherMaster (3-25 tons), Lennox Xion (2-20 tons)	25
2	Indoor air wet-bulb temperature	Outdoor air temperature	Capacity modifier for cooling in low stage	Average performance of Carrier WeatherMaker/WeatherMaster (3-25 tons), Lennox Xion (15-20 tons)	13
3	Indoor air dry-bulb temperature	Outdoor air temperature	Capacity modifier for heating	Average performance of Carrier WeatherMaker/WeatherMaster (3-25 tons)	15
4	Indoor air wet-bulb temperature	Outdoor air temperature	EIR for cooling in high stage	Average performance of York Sun Core, Sun Pro, Sunline (3-20 tons), Lennox Xion (2-20 tons)	18
5	Indoor air wet-bulb temperature	Outdoor air temperature	EIR for cooling in low stage	Lennox Xion (15-20 tons)	2
6	Indoor air dry-bulb temperature	Outdoor air temperature	EIR for heating	Average performance of York Sun Core, Sun Pro, Sunline (3-20 tons)	8
7	Flow fraction	-	Capacity modifier for cooling in high stage	Average performance of Carrier WeatherMaker (7.5-25 tons), Lennox Xion (2-20 tons)	16
8	Flow fraction	-	Capacity modifier for cooling in low stage	Average performance of Carrier WeatherMaker (12.5-25 tons), Lennox Xion (15 tons)	5
9	Flow fraction	-	Capacity modifier for heating	Average performance of Carrier WeatherMaker (7.5-25 tons), Lennox Xion (2-20 tons)	17
10	Flow fraction	-	EIR for cooling in high stage	Average performance of York Sun Core, Sun Pro, Sunline (3-20 tons), Lennox Xion (2-20 tons)	18
11	Flow fraction	-	EIR for cooling in low stage	Lennox Xion (15-20 tons)	2
12	Flow fraction	-	EIR for heating	Average performance of York Sun Core, Sun Pro, Sunline (3-20 tons), Lennox Xion (2-20 tons)	18
13	Rated capacity	-	Rated COP for heating	Average performance of Carrier WeatherMaker/WeatherMaster (3-25 tons), Lennox Xion (2-20 tons)	24
14	Rated capacity	-	Rated COP for cooling	Average performance of Carrier WeatherMaker/WeatherMaster (3-25 tons), Lennox Xion (2-20 tons)	24

Figure 3 and Figure 4 show the averaged or fitted results of cooling performance maps, which are also listed in Table 3. For capacity or EIR performances as a function of temperatures, performance maps are formatted as a lookup table in EnergyPlus, where two inputs (e.g., indoor wet-bulb air temperature and outdoor dry-bulb temperature for cooling) are used to derive (or interpolate) the output (i.e., normalized capacity or EIR modifier). The capacity modifier and EIR are calculated with this lookup table in each simulation time step depending on the operating conditions represented with the two inputs. Once the capacity modifier and EIR are found from the lookup table, they are multiplied to the rated capacity to reflect the performance of off-rated condition. These lookup tables are derived by normalizing and averaging the table of manufacturer spec sheets. For example, as shown in Table 3, the capacity modifier lookup table for high stage cooling is derived from 25 different products covering 2- to 25-ton units. As can be expected, cooling performances degrade (i.e., capacity decreases or EIR increases) with hotter outdoor temperatures.

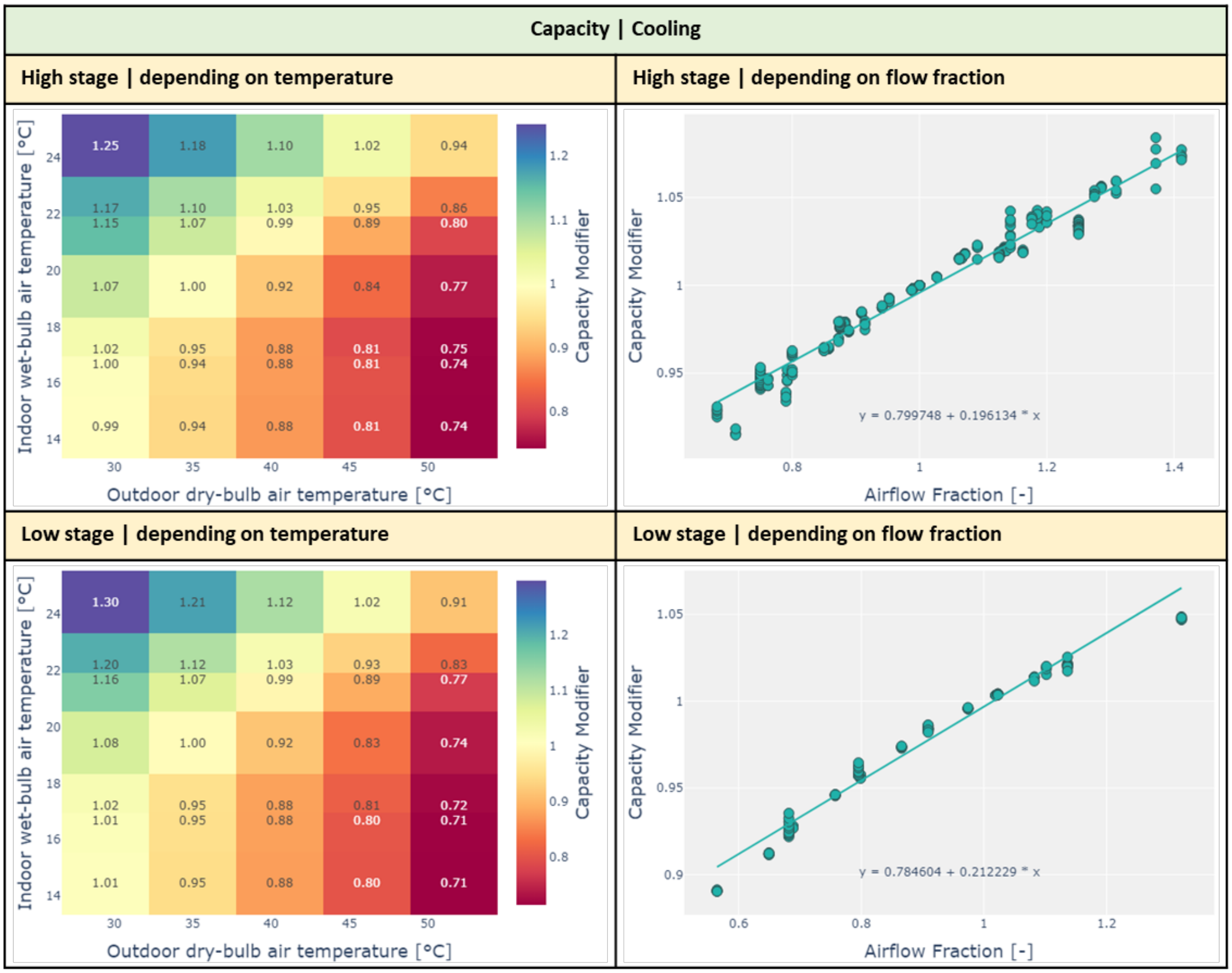
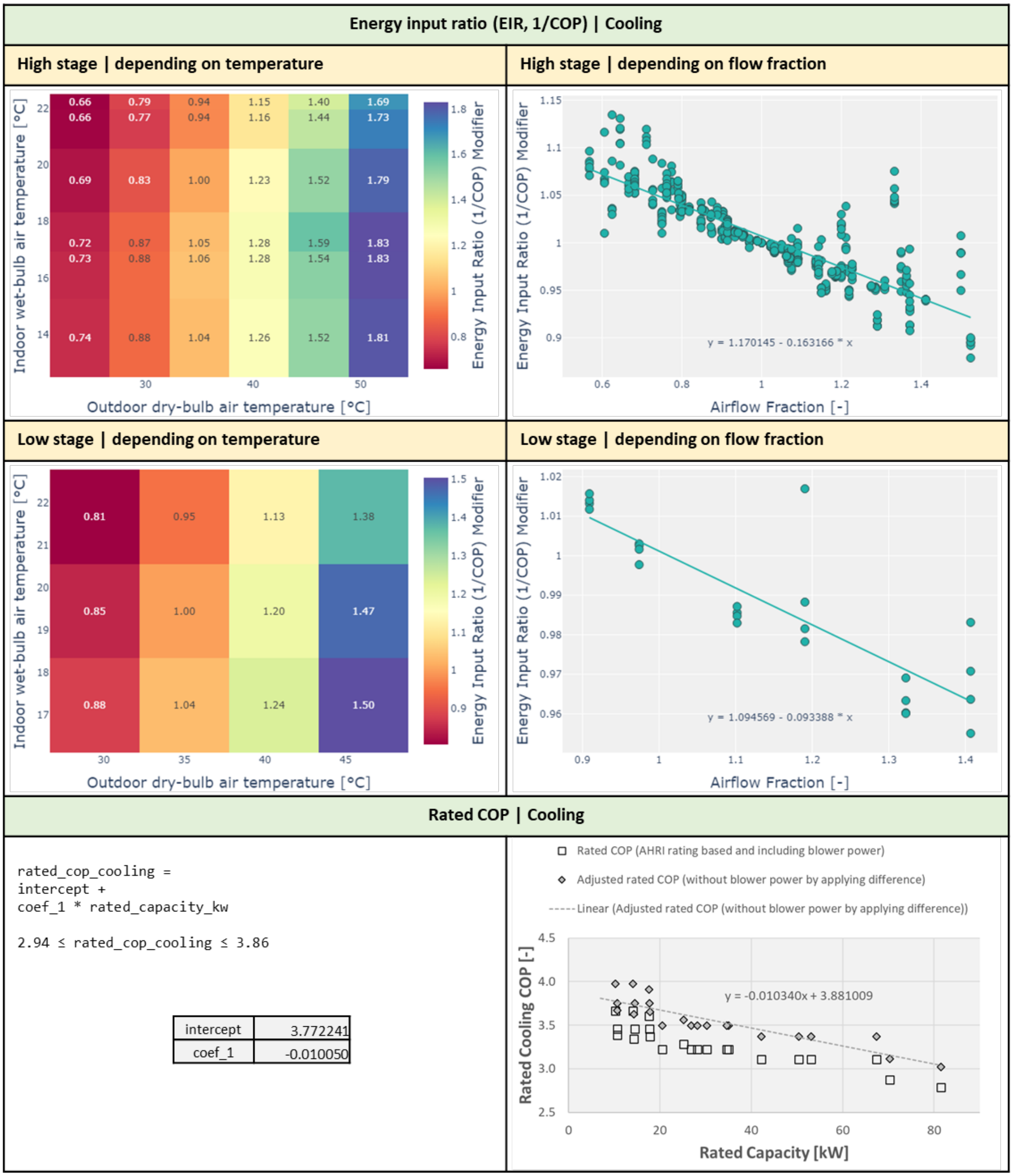


Figure 3. Averaging/fitting results of new performance maps: cooling capacity



```
rated_cop_cooling =
intercept +
coef_1 * rated_capacity_kw

2.94 ≤ rated_cop_cooling ≤ 3.86
```

intercept	3.772241
coef_1	-0.010050

Figure 4. Averaging/fitting results of new performance maps: cooling efficiency

Capacity and EIR performances as a function of airflow fraction are derived by fitting a regression model based on data available in the manufacturer spec sheets. Relevant data in Table 1 are used to gather sample points and to derive a linear regression model as shown in Figure 3 and Figure 4. The regression fitting results (based on the EnergyPlus' formulation requirement) also show how capacity or EIR under off-rated conditions can vary between different products within the same manufacturer.

Figure 4 also includes the fitting result of the rated cooling COP as a function of rated capacity (in kW). While the bottom left pane includes the equation and coefficients of the regression model, the figure in the bottom right shows the fitting results. During measure application, the final rated cooling COP applied to the model is 1) first calculated with the rated cooling capacity by using the equation shown in the figure (and where the value is capped with minimum [2.98] and maximum [3.92] values based on data available from the manufacturer spec sheets) and then 2) the output value from the equation is adjusted again with the EIR modifier curve (function of flow fraction shown in top right pane of Figure 4) based on a reference cfm/ton (i.e., rated airflow divided by rated capacity) threshold. The second adjustment is to properly reflect the differences of cfm/ton between initial modeling inputs (determined by EnergyPlus sizing algorithm) versus actual products. The rated COPs in manufacturer spec sheets are based on specific rated conditions, especially a specific rated airflow, and the rated airflow that EnergyPlus determines via the sizing logic will not align perfectly with the cfm/ton value of actual products. Thus, the second adjustment is necessary to properly shift the reference point performance of actual products' rated COP to EnergyPlus-compatible rated COP. The reference cfm/ton values are determined, separately for heating and cooling, by averaging the values of all products that were used to derive rated COP regression equations.

Additionally, the "rated" COPs (for both heating and cooling) used as inputs to EnergyPlus are based on rated conditions and only account for compressor power and outdoor fan power. The rated conditions of cooling are indoor wet-bulb temperature of 67°F/19.4°C and outdoor dry-bulb temperature of 95°F/35°C. The rated conditions of heating are indoor dry-bulb temperature of 70°F/21.1°C and outdoor dry-bulb temperature of 47°F/8.3°C. Rated COP values are first extracted from the manufacturers' performance sheets corresponding to these rated conditions and based on AHRI rating. However, because rated COPs based on AHRI rating include blower power and heat gain in the COP calculation, we have increased those COP values from spec sheets by 5% and 8.5% for heating and cooling, respectively, to reflect the calculation regarding the blower power and fan heat gain. The two values were derived from Lennox's spec sheets, which include blower performance tables for units in different sizes. Fan input power is calculated from the brake horsepower values shown in the table and the fan heat gain is calculated with rated airflow and the external static pressure defined by the rated operating conditions. The rated COP figure in Figure 4 is also including the 5% shift.

Figure 5 and Figure 6 show the averaged or fitted results of heating performance maps, which are also listed in Table 3. As mentioned previously, heating is modeled with a single-stage operation (i.e., all compressors running if there are multiple compressors), thus not requiring lower stage performance maps. While performance degradations (i.e., capacity decrease and EIR increase) are shown as expected in the lower outdoor air temperature region in the figure, the actual heating lockout temperature is set to 0°F (-18°C) in the simulations. The rated heating COP fitting results are also included in Figure 6 with minimum (3.46) and maximum (3.99) bounds.

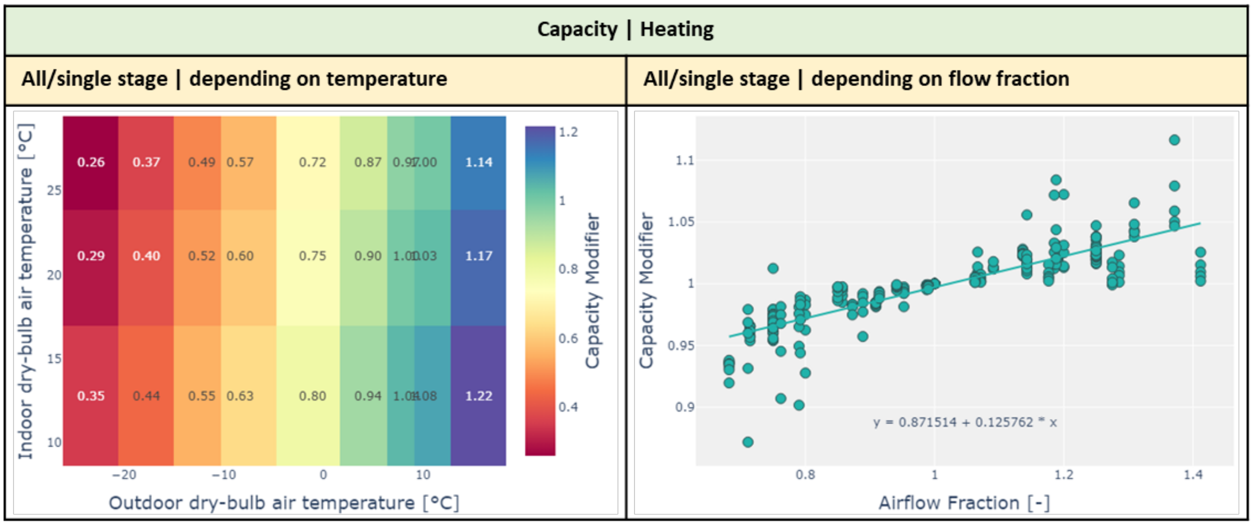
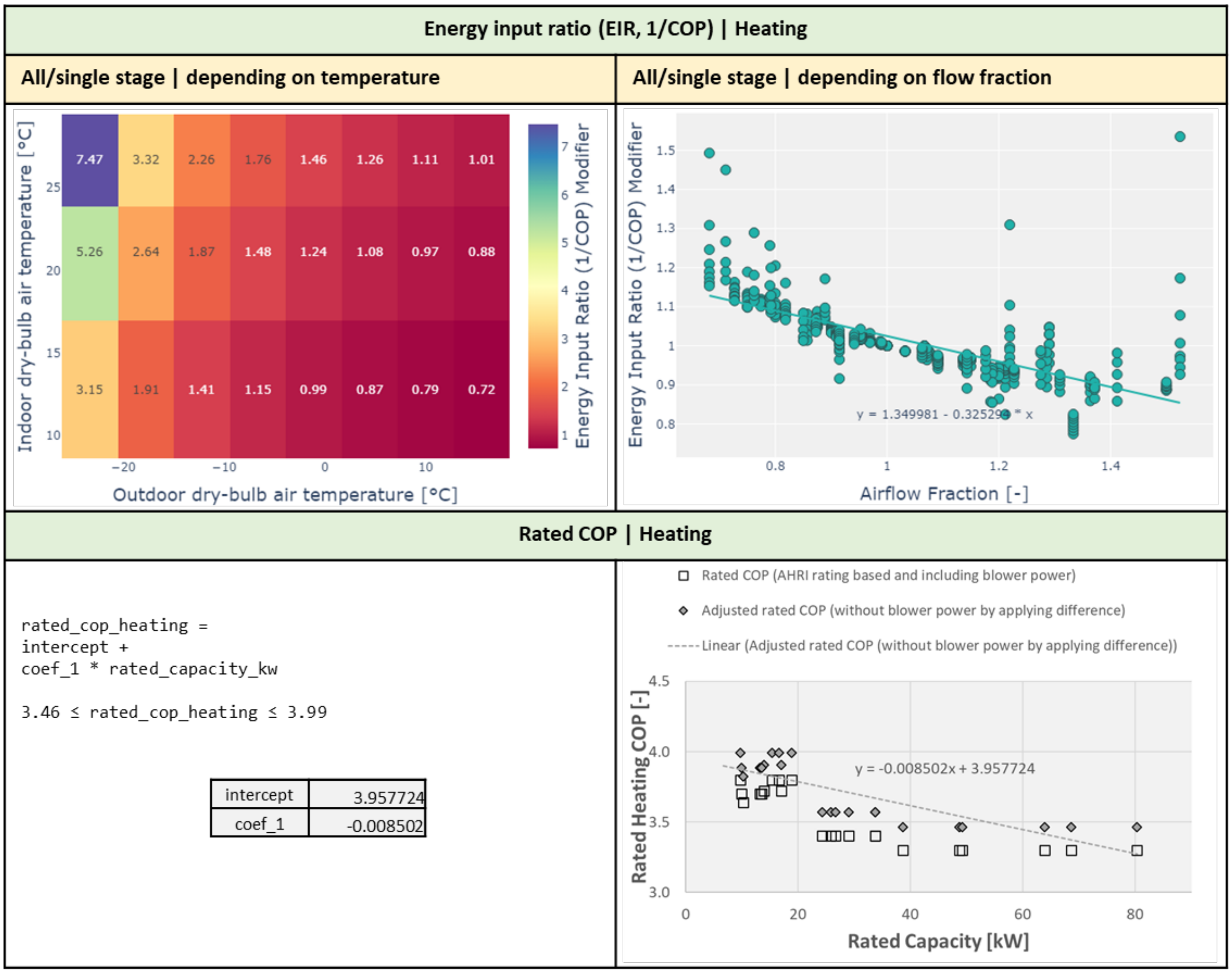


Figure 5. Averaging/fitting results of new performance maps: heating capacity



```
rated_cop_heating =
intercept +
coef_1 * rated_capacity_kw

3.46 ≤ rated_cop_heating ≤ 3.99
```

intercept	3.957724
coef_1	-0.008502

Figure 6. Averaging/fitting results of new performance maps: heating efficiency

3.2.2 *Other Key Considerations From Previous Work*

Besides the new performance data applied in this study, most of the other modeling assumptions are the same as in the previous study of the Heat Pump RTU measure, released in March 2023. Some of the key assumptions include:

- This measure replaces RTUs with either gas-fired or electric resistance heating with HP-RTUs.
- All energy efficiency features in the existing RTUs (energy recovery, demand control ventilation, etc.) as well as operating schedule are transferred to the new HP-RTU system for consistency.
- The heat pump system is sized to the design cooling load (based on sizing conditions defined in the weather file), with supplemental heating used to address any heating loads not met by the heat pump.

3.3 Greenhouse Gas Emissions

Three electricity grid scenarios are presented to compare the emissions of the ComStock baseline and the HP-RTU standard performance scenario. More are available in the full public dataset. The choice of grid scenario will impact the grid emissions factors used in the simulation, which determines the corresponding emissions produced per kilowatt-hour. Two scenarios—Long-Run Marginal Emissions Rate (LRMER) High Renewable Energy (RE) Cost 15-Year and LRMER Low RE Cost 15-Year—use the Cambium dataset, and the last uses the eGrid dataset [25], [26]. 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 [27]. 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 [28]. 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 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 [29]. Summary statistics from this implementation are shown in Table 5. Note that ComStock does not currently estimate utility bills for district heating and cooling.

Table 5. Summary Statistics of Utility Bill Implementation in ComStock by Fuel Type

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

Natural gas bills are estimated using 2022 EIA averages by state. 2022 U.S. EIA Natural Gas Prices - Commercial Price and U.S. EIA Heat Content of Natural Gas Delivered to Consumers are used to create an energy price in dollars per kBtu [30].

Propane and fuel oil bills are estimated using 2022 EIA averages by state. Residential No. 2 Distillate Prices by Sales Type, U.S. EIA residential Weekly Heating Oil and Propane Prices (October – March), and EIA-assumed heat content for these fuels are used to create an energy price in dollars per kBtu [31]. Residential prices are used because commercial prices are only available at the national resolution. Additionally, most commercial buildings using these fuels are assumed to be smaller buildings where a residential rate is likely realistic. For states where state-level pricing was available, these prices are used directly. For other states, Petroleum Administration for Defense District (PADD) average pricing is used. For states where PADD-level pricing is not available, national average pricing is used.

The primary resource for ComStock electric utility rates is the Utility Rate Database (URDB), which includes rate structures for about 85% of the buildings and 85% of the floor area in ComStock [32]. 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 [33]. While this method does not reflect the detailed rate structures and demand charges, it is a fallback for the 15% of buildings in ComStock with no utility assigned.

3.5 Limitations and Concerns

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

- Stock savings are sensitive to ComStock baseline assumptions. 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 [1]. This can affect the net impact of converting both gas furnace and electric resistance RTUs to HP-RTUs.
- In order to place a safety measure whenever heat pump heating 1) cannot meet the load or 2) cannot operate because the outdoor air temperature is extremely cold, a backup heating is implemented in HP-RTU models. While the simple concept is to operate backup heating during the two conditions mentioned above, in reality there can be different control logics. One example based on an informal conversation we had with one of the manufacturer representatives was that the compressor operating stage can be reduced (for multi-speed systems) when the backup electric resistance heating coil gets energized. This is mostly to stay within the safe amperage in a given electric panel size by avoiding concurrent operations of all compressors (or full stages) and the backup electric resistance coil. While this specific control logic has an implication of reducing the positive impact of HP-RTU implementation because the ratio of backup heating over heat pump heating increases, our modeling in this analysis does not capture this specific control logic. The HP-RTU measure's backup heating operates concurrently with all available heat pump heating stages in our model. However, we will explore the implementation of this control logic in a future analysis.
- Similar to the context of backup heating mentioned above, EnergyPlus does not currently have a mechanism to bring on backup heating to temper the air during defrost cycles, which is typically done in reality. This is less of an issue when the heat pump cannot meet the entire heating load, and load that is not met by the heat pump is covered by backup heating. However, at mild temperatures when the heat pump is defrosting and cycling in the time step in the simulation, EnergyPlus will not include supplemental heat to temper the air during the defrost cycle. This is also one of the future areas to be improved in EnergyPlus.
- While the power data from Carrier included the exact total consumption of components (i.e., compressor and condenser fan) that is compatible with what EnergyPlus requires, the power data from Lennox only included compressor power. This has an implication of slight underprediction of power, which results in slight overprediction of COP (or underprediction of EIR that EnergyPlus wants) from data points from Lennox. The new EIR curves that include Lennox data shown in Table 3 are affected by this limitation.

4 Output Variables

includes a list of output variables that are calculated in ComStock. These variables are important in terms of understanding the differences between buildings with and without the "HP-RTU with standard performance" measure applied. These output variables can also be used 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 6. Output Variables Calculated From the Measure Application

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

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.
out.params.unitary_sys_cycling_ratio_cooling	Annual average cycling ratio for cooling operation
out.params.unitary_sys_cycling_ratio_heating	Annual average cycling ratio for heating operation

5 Results

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

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

5.1 Single Building Measure Tests

In this section, the standard performance implementation described in this document is compared against the original “advanced performance” HP-RTU measure (“Heat Pump RTUs,” released in March 2023) using a sample model represented with typical meteorological year 3 weather for New York City (ASHRAE climate zone 4A).

To be clear, the original “advanced performance” measure investigated a *high-performance* variable-speed HP-RTU, whereas this study investigates a *standard performance* HP-RTU with two cooling speeds and one heating speed. Figure 7 shows the operating difference between the original HP-RTU (advanced performance) and the standard performance HP-RTU. Annual simulations are performed for both scenarios, and normalized airflow rates and operating stages are marked against the heating (negative value) and cooling (positive) loads in each simulation time step. As shown in Figure 7, the original advanced performance HP-RTU operates between four different stages for both heating and cooling. This is how we represent full variable speed operation in the simulation program (EnergyPlus). On the other hand, the standard performance HP-RTU operates between two stages for cooling and with single heat pump stage for heating (i.e., always using both compressors simultaneously). Because of this difference in compressor operation, the standard performance HP-RTU cycles more, which may show lower efficiencies under part-load operation compared to the advanced performance HP-RTU.

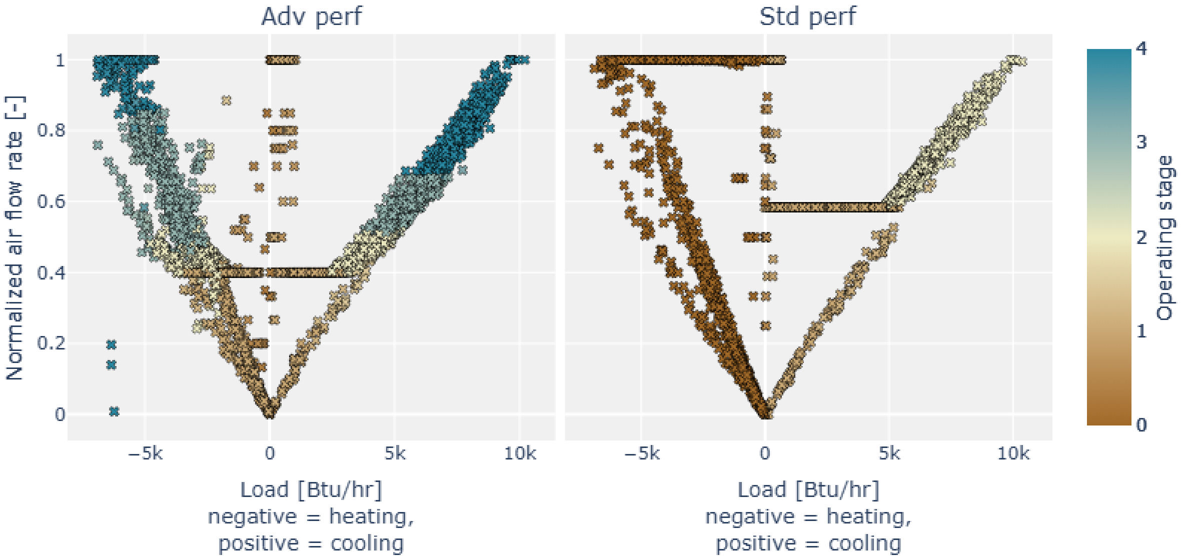


Figure 7. Single building results: operating stage comparison

Figure 8 shows the operating COPs (accounting for compressor and outdoor fan power for cooling and also including defrosting power, crankcase power, and supplemental heating for heating) against the outdoor air temperature across the annual simulation for the two scenarios. As expected, operating COPs are generally lower in standard performance HP-RTU compared to the advanced performance HP-RTU. This difference is less prevalent for heating at colder temperatures when both systems are operating under full-load conditions, and more prevalent when operating at more mild outdoor temperatures. The difference in COPs under part-load conditions (i.e., heating and cooling in mild weather conditions) is because the standard performance HP-RTU only operates between two stages during cooling operation and a single stage (both compressors running simultaneously) during heating operation. Note that both systems incur efficiency losses due to short cycling (low part-load ratios), but this is less prevalent in the advanced performance RTU that uses variable speed compressors.

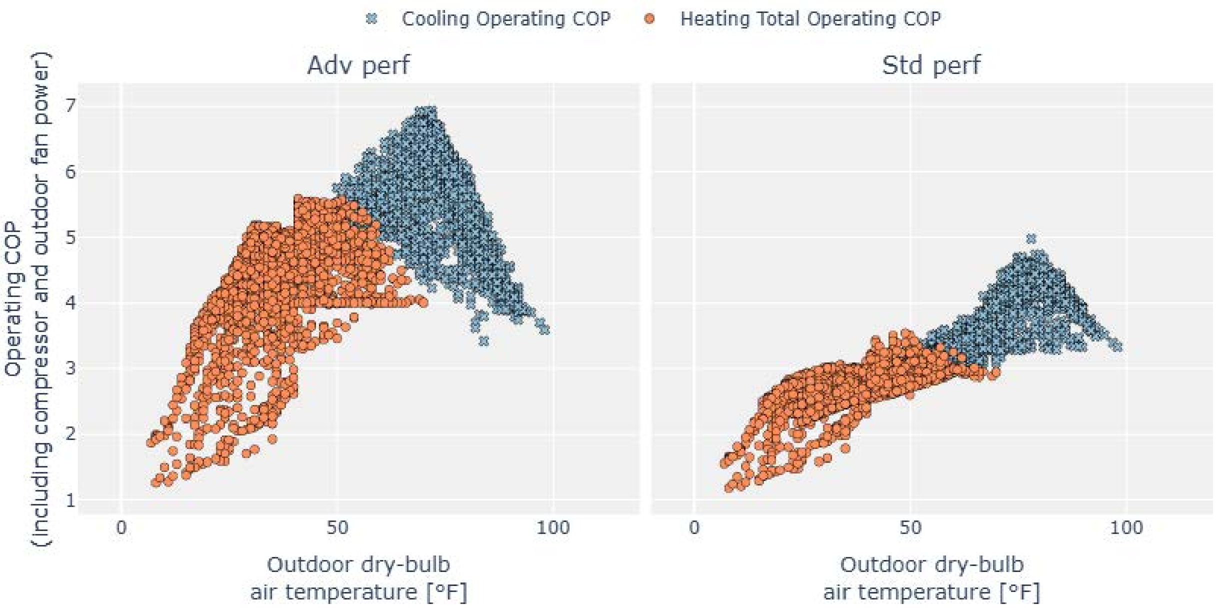


Figure 8. Single building results: operating COP comparison

Figure 9 is another example that highlights the part-load performance differences between the advanced and standard performance scenarios on the heating operation side. The figure is a heat map (x-axis is day in a year and y-axis is hour in a day) showing heating operating COP (only including compressor and outdoor fan power), where the color shows how much improvement to COP the advanced performance unit has compared to the standard performance unit. The smallest improvements (i.e., red areas) come from full-load conditions where the heat pump runs on full capacity at the beginning of a cold day (e.g., 6 a.m.). Other than those hours, the better part-load performance of the advanced unit takes over and the operating heating COP can improve by 2.5.

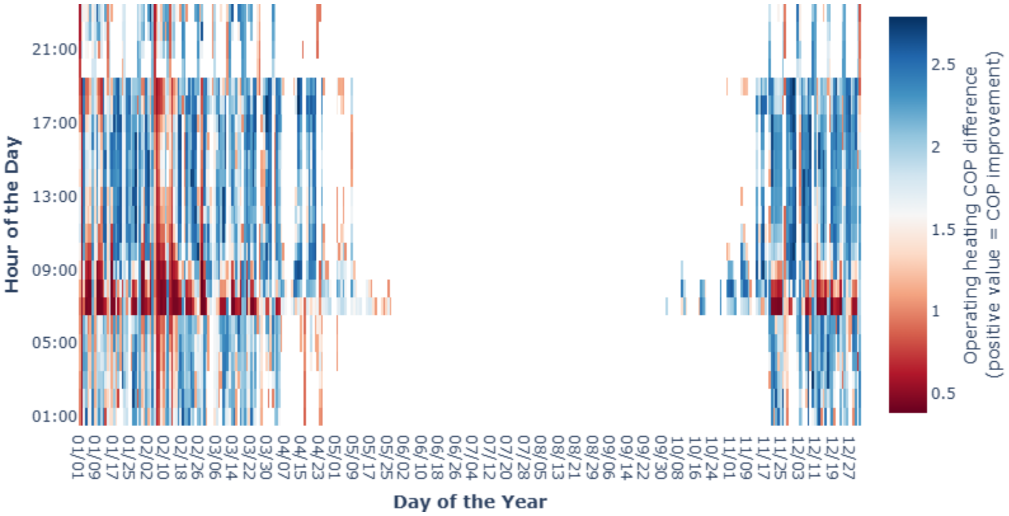
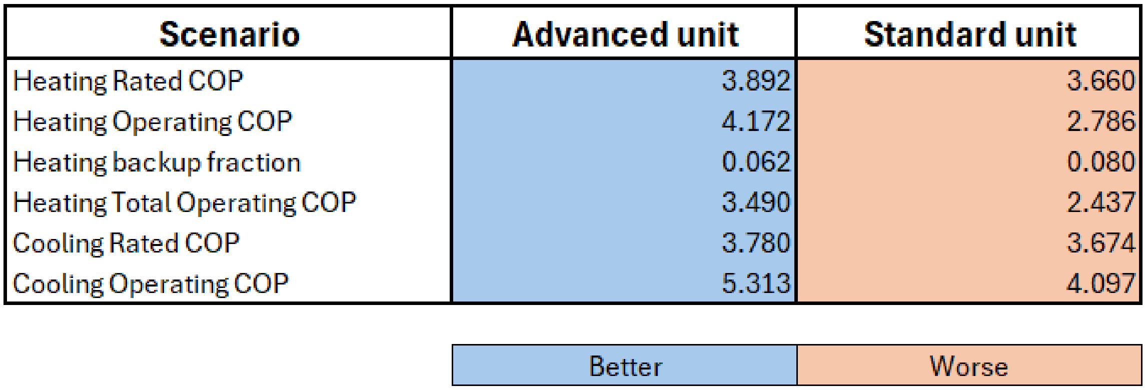


Figure 9. Single building results: heating operating difference between two performance scenarios

Table 7 summarizes the annual simulation results of the two scenarios showing the differences in performance metrics. Because of consistent inefficiency of the standard performance HP-RTU compared to the advanced performance HP-RTU, the advanced performance unit outperforms the standard performance unit in all categories: rated COP, operating COP, and portion of backup heating load against the entire heating load. Multiple HP-RTUs are installed in this example building model, and additional calculations are performed to extract representative performance metrics (e.g., COP). For instance, the rated heating (or cooling) COP shown in Table 7 is the weighted average of the rated COPs of the nine HP-RTUs, with weights based on their annual heating (or cooling) loads. To calculate the operating heating COP in Table 7, the annual heat pump heating load and annual electricity consumption (only including compressor and outdoor unit fan power) of each HP-RTU are used to determine the annual average operating COP for each unit. These individual COPs are then used to calculate the weighted (also by annual heating load) average operating heating COP across all HP-RTUs. The heating backup fraction is determined by dividing the annual backup heating load by the total annual heating load for all HP-RTUs. While the operating COP accounts only for the heat pump heating load, compressor power, and outdoor unit fan power, the "total" operating heating COP also includes backup heating load/electricity, crankcase heater electricity, and defrosting electricity. The same metrics released in our data are calculated using these methods.

As mentioned, the “rated” COPs (for both heating and cooling) shown in Table 7 and other parts of this report are based on rated conditions and only account for compressor power and outdoor fan power. Rated COP values are extracted from the manufacturers’ performance sheets and correspond to standard rated conditions, which are typically available in performance tables (e.g., variations of capacity and power with indoor and outdoor temperatures). However, rated COPs reported in this study can be different from the rated COP reported with AHRI performance rating (i.e., more common rated COP definition in general), as the AHRI COP calculation will include not only outdoor fan power but also supply air blower power.

Table 7. Single Building Results: Annual End-Use Consumptions



Scenario	Advanced unit	Standard unit
Heating Rated COP	3.892	3.660
Heating Operating COP	4.172	2.786
Heating backup fraction	0.062	0.080
Heating Total Operating COP	3.490	2.437
Cooling Rated COP	3.780	3.674
Cooling Operating COP	5.313	4.097

Better	Worse

Other factors should also be considered (such as utility cost impacts on peak demand charges, greenhouse gas emissions and its time dependence, and return on investment) in order to comprehensively assess the impact of a standard efficiency HP-RTU versus a high-efficiency HP-RTU.

5.2 Stock Energy Impacts

Figure 10 and Figure 11 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. As expected, the standard performance HP-RTU demonstrates lower performance than the advanced performance HP-RTU.

The HP-RTU standard performance measure shows 6% total annual site energy savings (289 trillion British thermal units [TBtu]) for the U.S. commercial building stock modeled in ComStock (compared to the "Baseline," representing the existing building stock). To put this number in context, Figure 10 shows the entire commercial building stock, even including buildings that did not receive the upgrade (i.e., only 34% of the entire stock floor area received the upgrade due to our applicability definition). The savings of the HP-RTU standard performance against the baseline scenario are primarily attributed to:

- 28.4% stock heating natural gas savings (277.3 TBtu)
- 12.0% stock fan electricity savings (67.0 TBtu)
- 3.4% stock cooling electricity savings (23.9 TBtu)
- 24.8% stock heating other fuel savings (21.7 TBtu)
- -57.2% stock heating electricity savings (-100.5 TBtu).

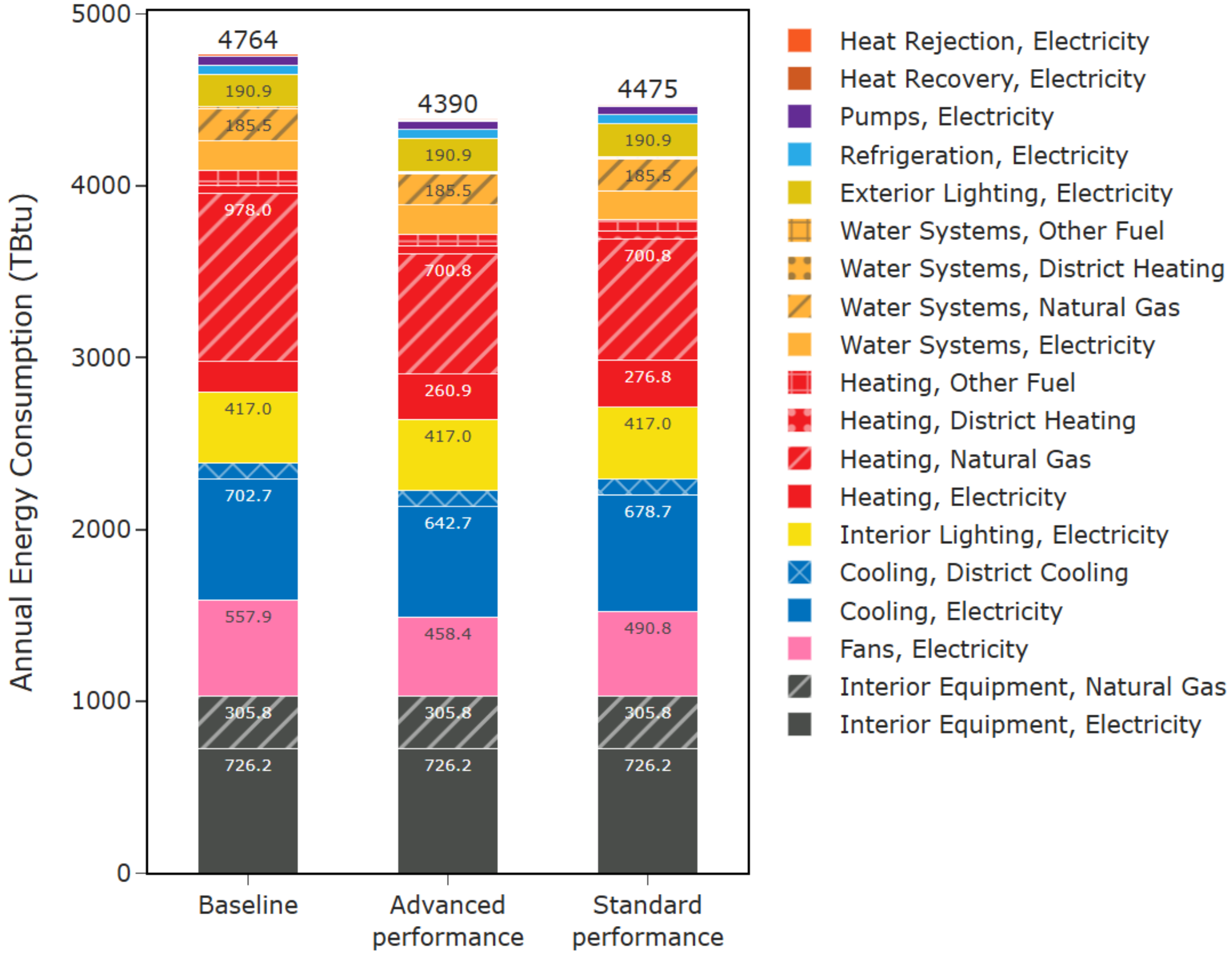


Figure 10. Comparison of annual site energy consumption between the ComStock baseline and the HP-RTU measure scenarios for the entire building stock, including buildings not applicable to the upgrade

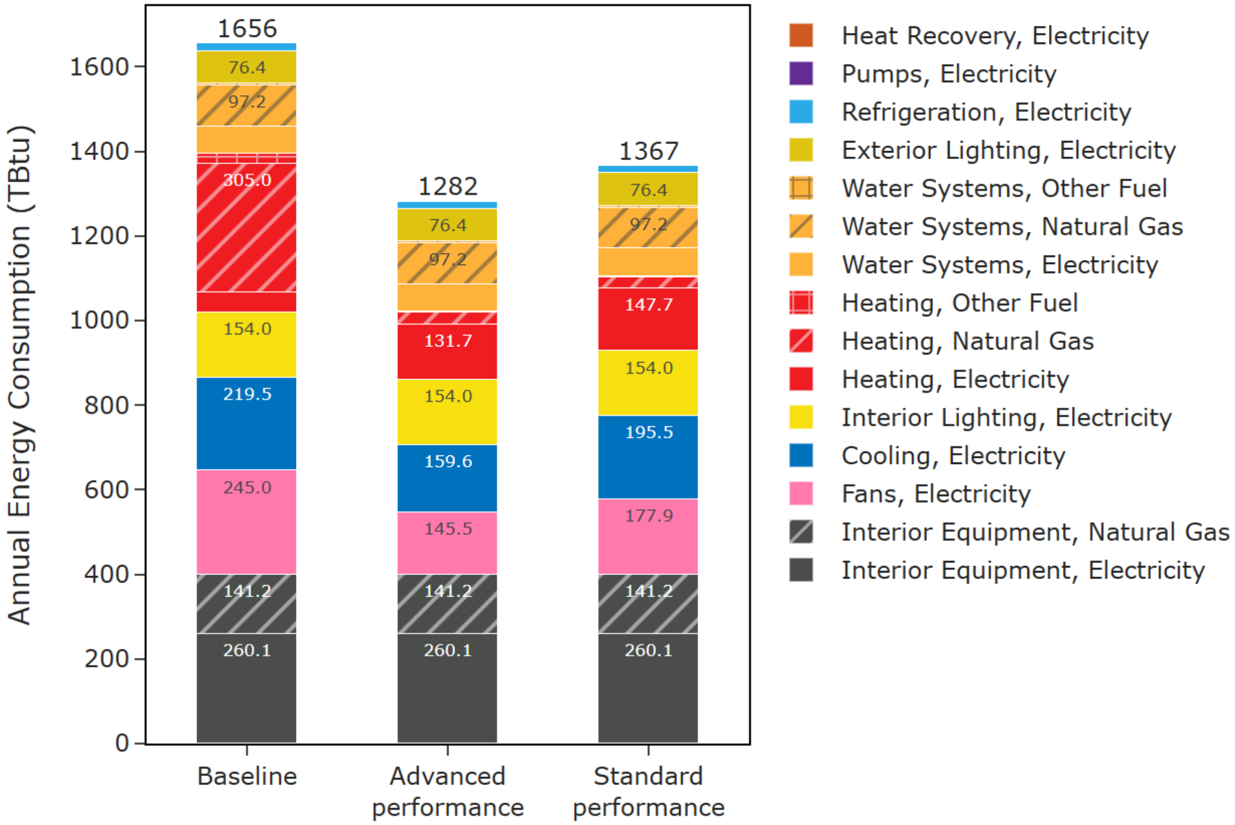


Figure 11. Comparison of annual site energy consumption between the ComStock baseline and the HP-RTU measure scenarios, only for buildings applicable to the upgrade

Figure 10 and Figure 11 also show the advanced performance HP-RTU from the previous analysis as a comparison. The standard performance HP-RTU consumes 2% (83 TBtu) more site energy compared to the advanced performance HP-RTU. The standard performance HP-RTU still shows site energy savings potential compared to the ComStock baseline. In other words, these simulation results show that converting gas-fired heating systems to electric heat pumps results in a 76% penalty in site electric heating end use, but savings of 38% natural gas heating end use. Leveraging more efficient heating (with the heat pump compared to electric resistance heating) and even achieving reasonable heating performance in colder regions are the key factors for this savings potential. These results assume electric resistance supplemental heat when outdoor air temperatures drop to levels where the heat pump capacity is insufficient to meet the building load or when operating below the compressor lockout temperature. More detailed findings are presented in Sections 5.4 and 5.7.

5.3 Stock Greenhouse Gas Emissions Impacts

Figure 12 shows ComStock simulation results for greenhouse gas emissions avoided across all electricity grid scenarios and on-site combustion fuel types. Three electricity grid scenarios are presented in this report, but other scenarios are available in the ComStock public dataset. Overall, the HP-RTU with standard performance measure demonstrates between 16 and 17 million metric tons (MMT) of greenhouse gas emissions avoided (for all fuel types) annually for the three electricity scenarios presented, compared to the ComStock Baseline. The 16 MMT number corresponds to a 7% reduction for the LRMER Low RE Cost 15 scenario, while the 17 MMT number corresponds to a 4% reduction for the eGRID 2021 scenario. These results are mostly attributed to 1) reduced electricity consumption from cooling and fans (which is due to replacing older, less efficient RTUs with newer RTUs), 2) increased electricity usage from fuel switching gas heating systems, 3) replacing electric resistance heating with heat pump heating, and 4) reduced natural gas usage with fuel switching gas heating systems. The 18% emissions avoided from on-site combustion are attributable to fuel switching some of these combustion-based heating systems.

Compared to the advanced performance option, the standard performance scenario shows slightly lower electricity emissions avoided, as it is less efficient. Gas emissions avoided are consistent between the two scenarios because this avoidance reflects removal of applicable gas RTUs and is therefore agnostic of the equipment replacing them.

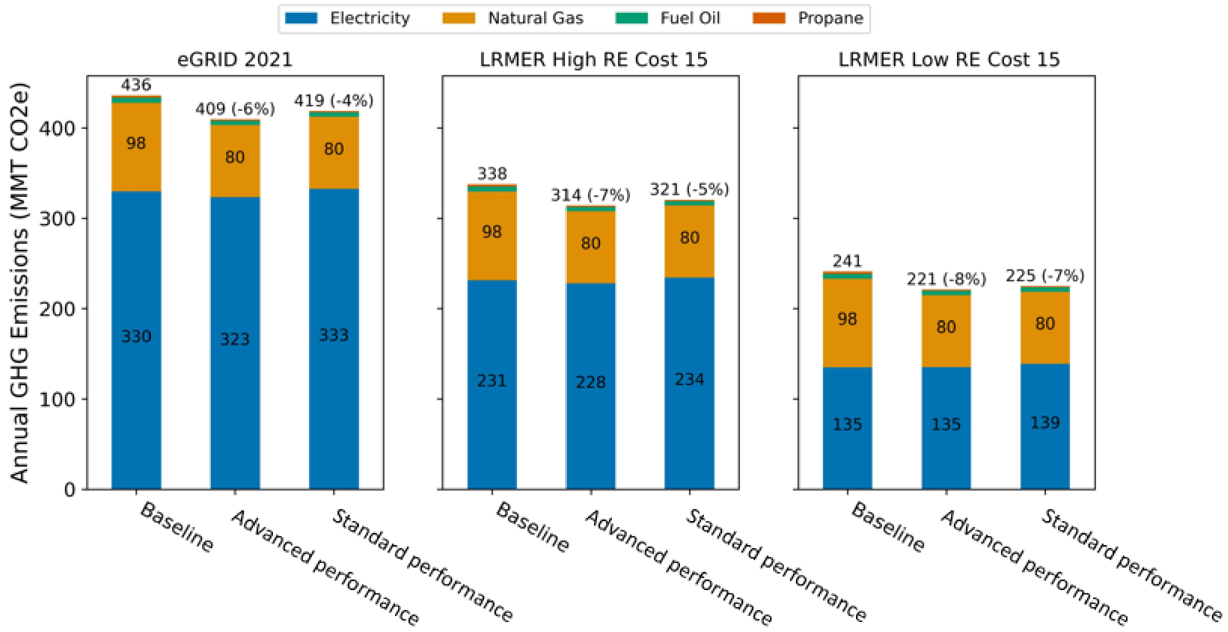


Figure 12. Greenhouse gas emissions comparison of the ComStock baseline and the HP-RTU scenario

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.

5.4 Stock Utility Bill Impacts

This section includes a comparison of national-level annual utility bills that buildings are subject to across different energy sources (i.e., electricity, natural gas, propane, fuel oil). Because we apply many electricity utility rate structures that are available for a building located in a certain geographical location, our data includes many annual utility bills per a building model. The comparison in this section highlights three statistics (i.e., maximum, mean, and minimum) across all electric utility bill costs.

Figure 13 shows the comparison between three scenarios (i.e., ComStock baseline, advanced performance HP-RTU, and standard performance HP-RTU) and including three different electricity utility bill statistics. For more detailed information regarding the utility rates implementation, refer to the ComStock Reference Documentation [29].

Figure 10 showed aggregated "site" energy consumption, which is not reflecting the "primary" energy perspectives. The cost of electricity and natural gas not only reflects the difference between energy costs, but also the primary energy conversion factor differences. Thus, the annual aggregated cost comparisons shown in Figure 13 can also somewhat indicate the primary energy consumption comparisons between different scenarios.

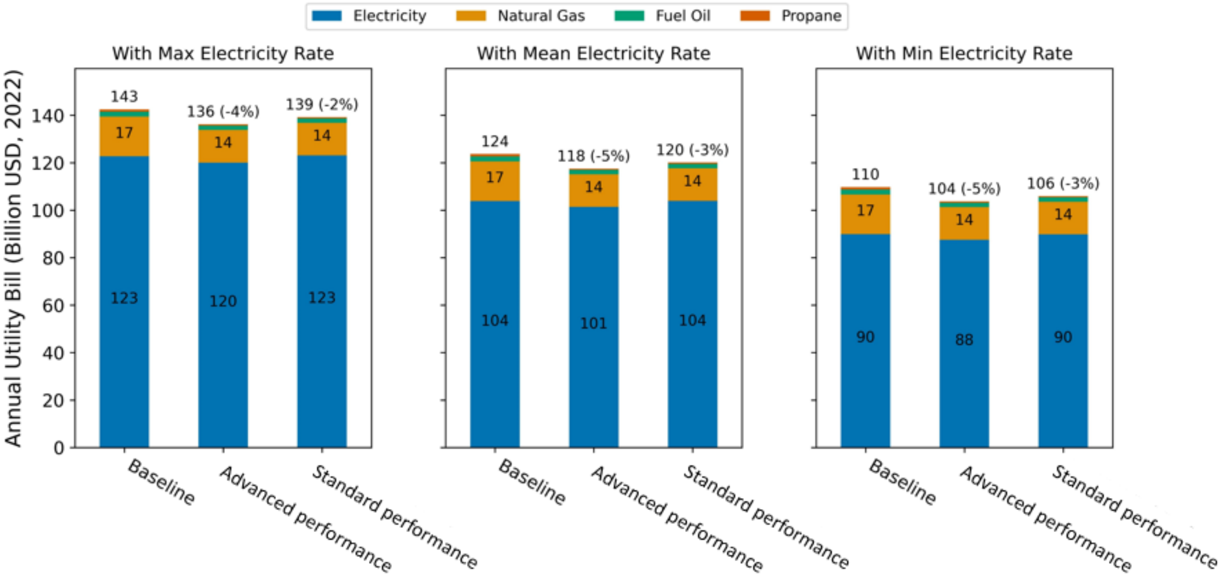


Figure 13. Utility bill comparison of the ComStock baseline and the HP-RTU scenario

The major difference between advanced and standard performance scenarios considered in this study is simply how efficient HP-RTUs are. As mentioned in Section 5.1, not only the rated COPs, but also operating COPs under part load, results in a difference between advanced and standard performance units. Thus, similar to site energy savings results, results of standard performance HP-RTU also position between baseline and advanced performance HP-RTU scenarios.

5.5 Site Energy Savings Distributions

This section discusses site energy consumption savings between the standard performance and baseline scenario 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. This is because site energy savings do not necessarily translate proportionally to source energy savings, greenhouse gas emissions avoided, or energy cost, which vary widely across the United States.

Figure 14 through Figure 16 show distributions of the applicable baseline ComStock models versus the standard performance HP-RTU upgrade scenario for percent site energy or site end use intensity (EUI) savings with different end use, fuel type, or climate zone. Percent savings provide relative impact of the measure at the individual building level, while site EUI savings provide absolute (or aggregated) scale of impact. Also, the data points that appear above some of the distributions indicate outliers in the distribution, meaning they fall outside 1.5 times the interquartile range. The value for *n* indicates the number of ComStock models that were applicable for energy savings for the fuel type category.

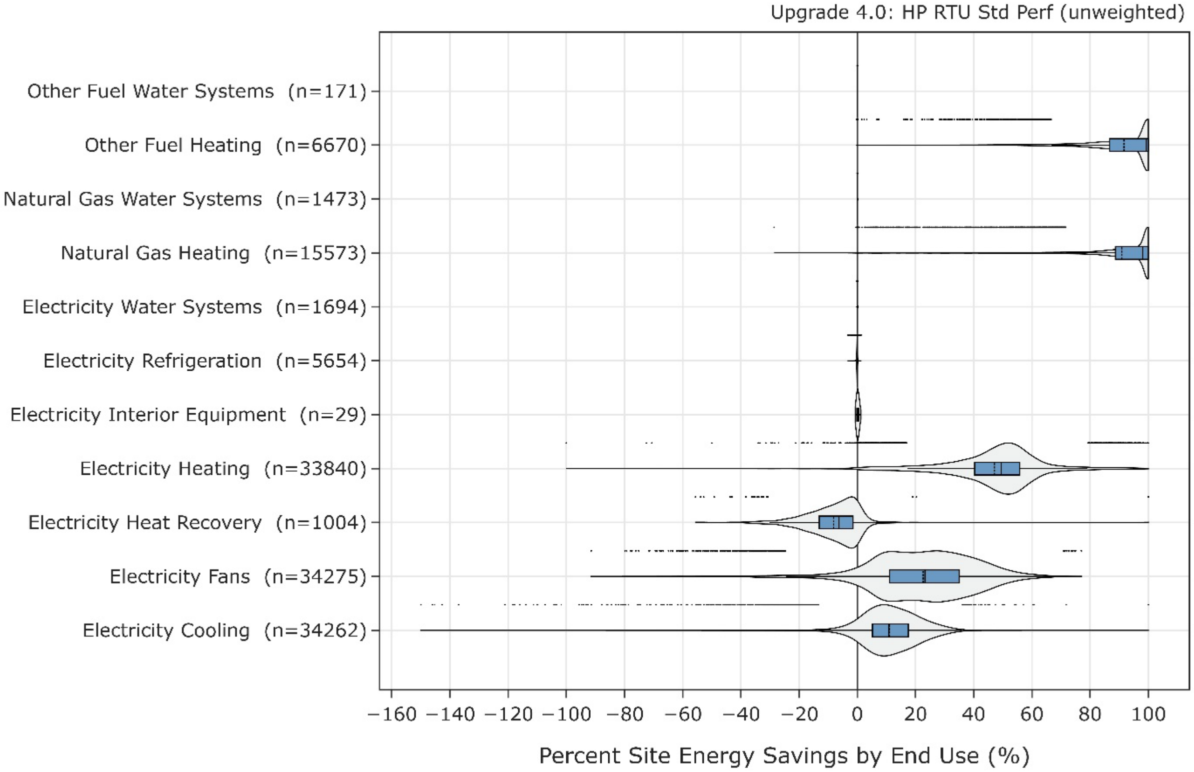


Figure 14. Percent site energy savings (compared to baseline) distribution for ComStock models with the HP-RTU measure applied by end use and fuel type

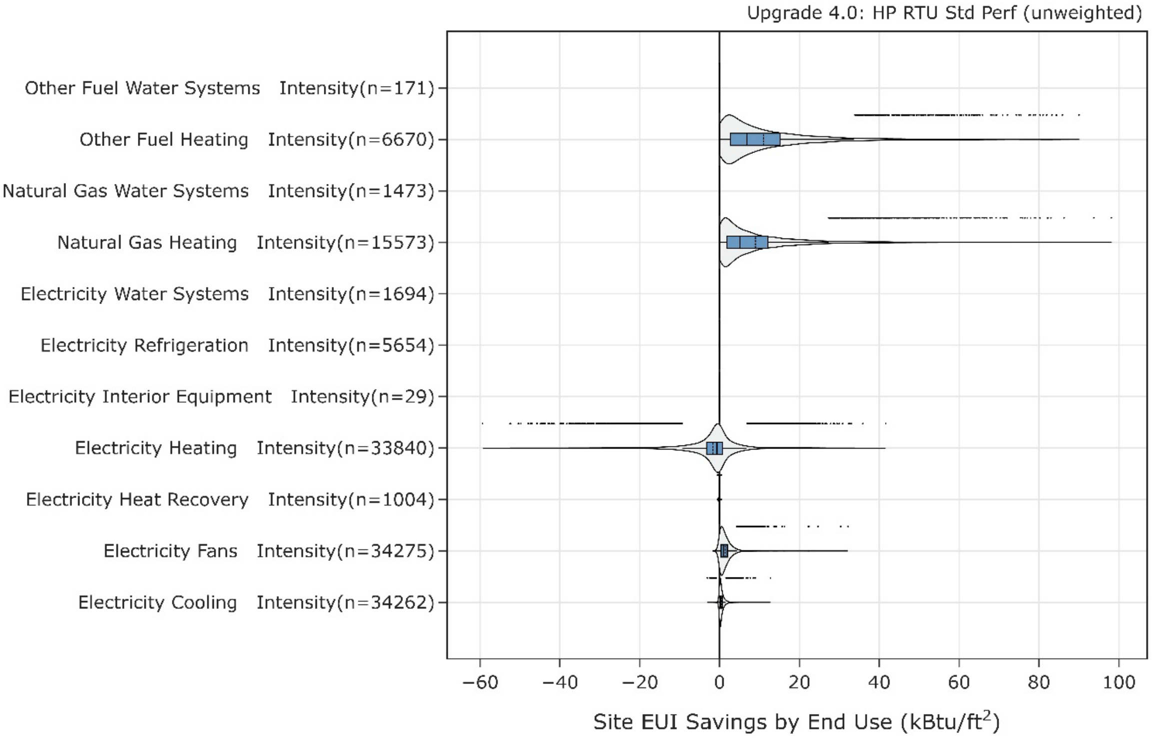


Figure 15. Site EUI savings (compared to baseline) distribution for ComStock models with the HP-RTU measure applied by end use and fuel type

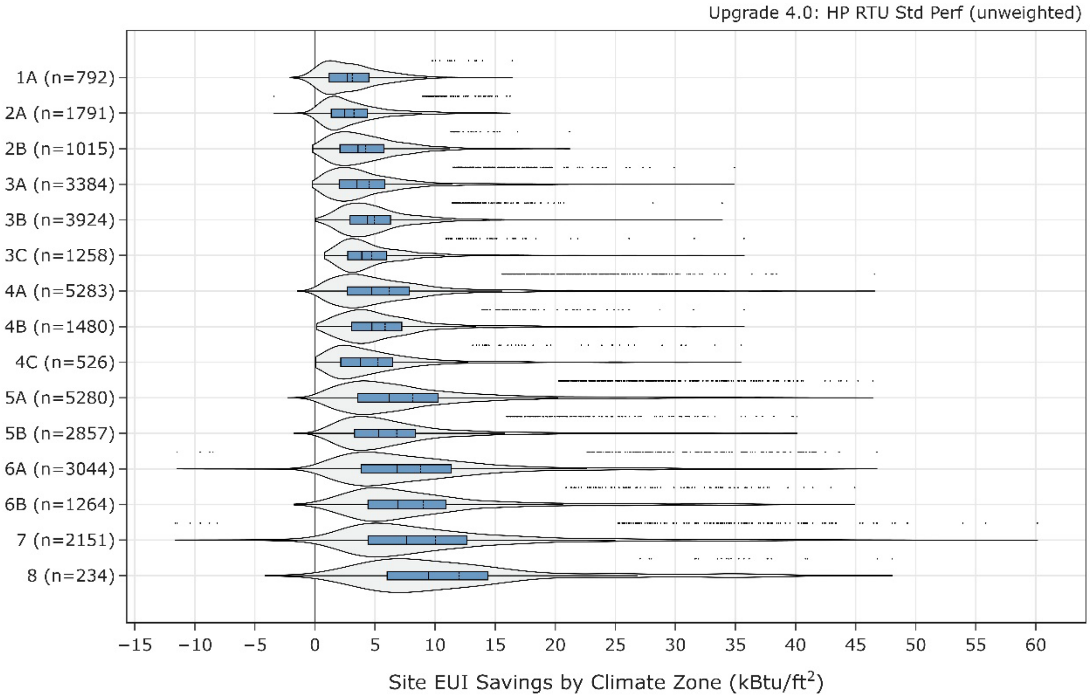


Figure 16. Site EUI savings (compared to baseline) distribution for ComStock models with the applied HP-RTU measure by climate zone

Highlights of conclusions drawn from Figure 14 through Figure 16 include:

- Fuel switching of combustion fuel-based heating:
    - Up to 100% savings on combustion fuel used for heating, as shown in Figure 14. Data points showing savings less than 100% indicate buildings with multiple heating fuels 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 15.
    - Absolute or aggregated savings penalty of electricity for heating due to fuel switching is well-depicted in Figure 15. This is especially noticeable in the colder climates.
- Conversion of electric resistance heating to HP-RTU heating:
    - Positive savings on electricity used for heating, as shown in Figure 14, leveraging more efficient heat pump compared to electric resistance heating.
    - Electric heating distribution only includes buildings in the baseline that had at least some electric heating load, and therefore does not show the electric heating increase of buildings without electric heating load with heat pumps.
- 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 14.
    - Absolute or aggregated savings scale is depicted in Figure 15.
- Increased site energy savings potential in colder climates:
    - By leveraging heat pumps that can operate down to 0°F (-17.9°C), savings potential is increased compared to hotter regions by leveraging higher efficiencies on both (heating and cooling) ends, as shown in Figure 16.
    - This is because heat pumps generally have higher heating “site” energy COPs compared to gas or electric resistance RTUs, and colder climates have higher overall heating loads. However, as mentioned, site energy savings do not necessarily translate to energy cost savings.
- Others:
    - Data points for extreme (e.g., -150% savings for electricity used for cooling) positive/negative savings, shown in Figure 14, are 1) buildings either in very hot or very cold climates, 2) where absolute heating or cooling demand is small, and 3) a small change (due to upgrade) in heating or cooling demand (e.g., MWh) resulting 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 advanced HP-RTU can be found in the previous documentation, released in March 2023).
    - It should also be noted that figures showing higher site EUI savings toward colder climates in Figure 16 may not correspond to cheaper utility bills or decreased

greenhouse gas emissions. The only reason this trend happens is because we get more heating load in colder climates, so the COP improvements make a bigger relative impact.

5.6 Other Findings

This section includes additional and more detailed findings specific to the standard performance HP-RTU measure that are not covered in the previous sections. Figure 17 shows the rated and (annual average) operating COPs from all models (represented with a box plot excluding outliers) between advanced and standard performance scenarios. Based on operating performance differences (especially part-load performances) depicted in Figure 8, the stock level operating COPs are consistently lower in standard performance HP-RTUs compared to advanced HP-RTUs (leveraging variable speed compressors), as shown in Figure 17.

Operating heating COPs, including the impact of defrost and backup electric resistance heating energy, decrease more in colder climates. However, from the minimum bound perspective, the majority of the standard performance HP-RTUs' overall heating COPs (including backup heating, crankcase heater electricity, and defrosting electricity) remain higher than 1 (i.e., better than electric resistance heating). Again, this reflects the average performance derivation described in Section 3.2.1.2 and the minimum operating (or lockout) temperature of 0°F (-17.9°C) we implemented in our models.

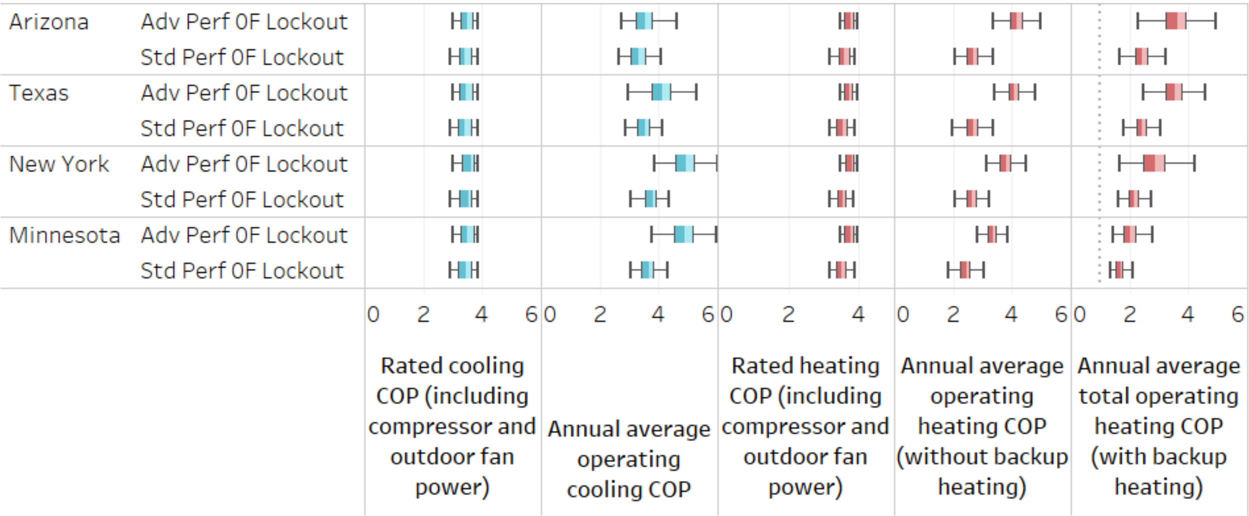


Figure 17. Distributions between advanced and standard performance HP-RTU scenarios: COP

Again, the "rated" COPs (for both heating and cooling) shown in the figures above account only for compressor power and outdoor fan power. The rated COPs reported in this study may differ from those reported under the AHRI performance rating (i.e., the more commonly used definition of rated COP). This is because the AHRI COP calculation includes not only outdoor fan power but also supply air blower power.

Figure 18 shows the annual average cycling ratio in cooling operation for two different performance scenarios and under four different weather conditions. Cycling ratio represents cycling losses where higher average ratio means lower cycling losses. One other metric reflecting how hot the weather is throughout the year is also included in this figure: total hours above 65°F in a year. As shown in the figure, a standard performance unit with two stage cooling undergoes more frequent short cycling (i.e., efficiency loss) compared to the advanced unit with variable speed. As the weather conditions get hotter (i.e., toward Arizona), the annual average cycling ratio in both performance scenarios increases because the unit experiences hotter outdoor conditions more frequently.

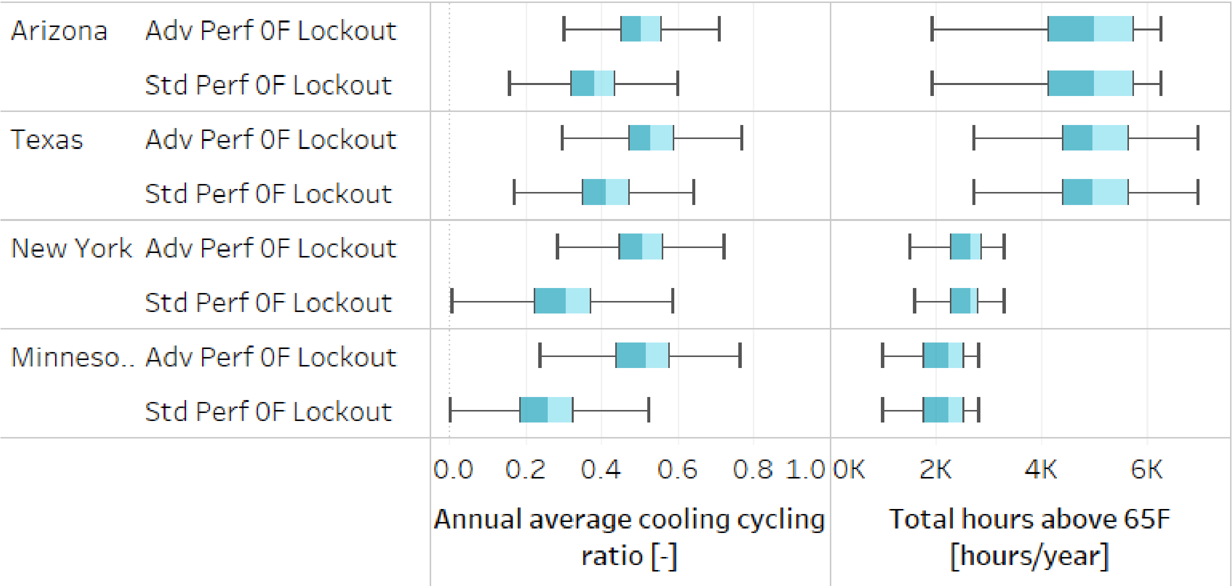


Figure 18. Distributions between advanced and standard performance HP-RTU scenarios: COP

Figure 19 and Figure 20 are highlighting the median annual operating COPs for cooling and heating, respectively, across contiguous U.S. states. The heating operating COP in Figure 20 includes backup heating, defrosting electricity, and crankcase heater electricity. Compressor and outdoor fan powers are included in both heating and cooling operating COPs, but the blower fan power is not. These COP values represent median COPs of either advanced or standard performance HP-RTUs for stock of buildings in each state and reflect the performance difference depending on weather characteristics. The biggest differences in heating operating COP occur in warmer climates where variable speed is more beneficial. The same differences are only slightly notable in the coldest climates.

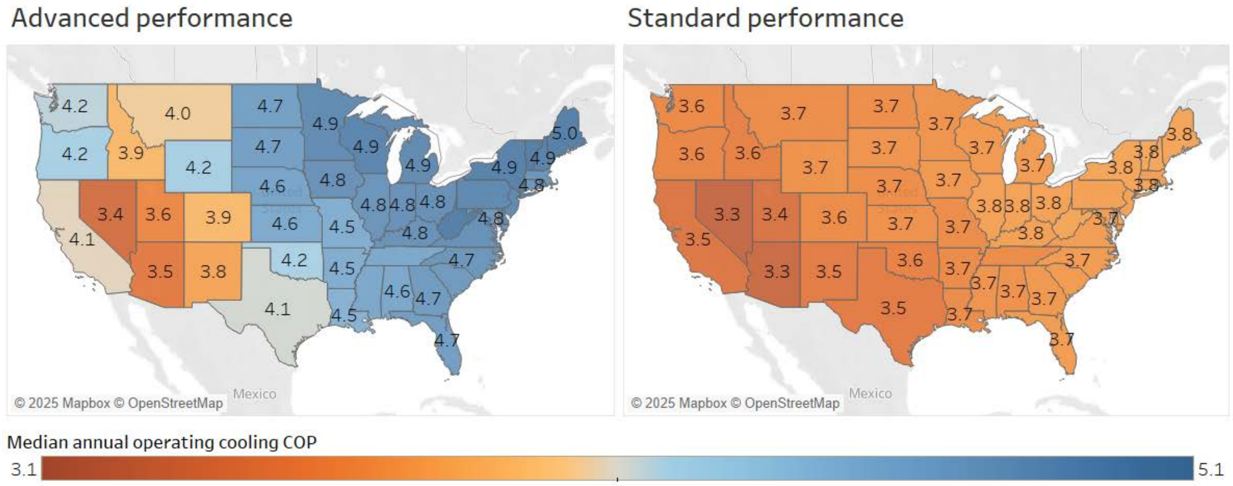


Figure 19. Annual operating median cooling COP between contiguous U.S. states

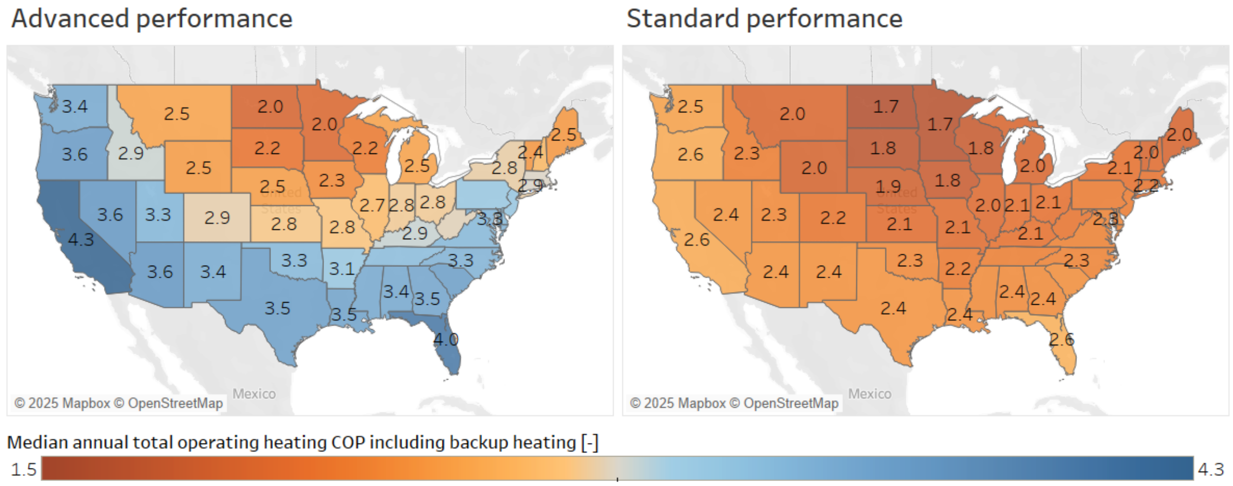


Figure 20. Annual operating median heating COP between contiguous U.S. states

Figure 21 shows the state-level peak power implications (using normalized peak metric of W/ft^2) between three different scenarios: baseline, advanced performance HP-RTU, and standard performance HP-RTU. As can be expected, an increased winter peak due to fuel switching of gas heating systems is illustrated in Figure 21. A consistent decrease in summer peak leveraging relatively higher COP (compared to older units in reality) is also shown in Figure 21.

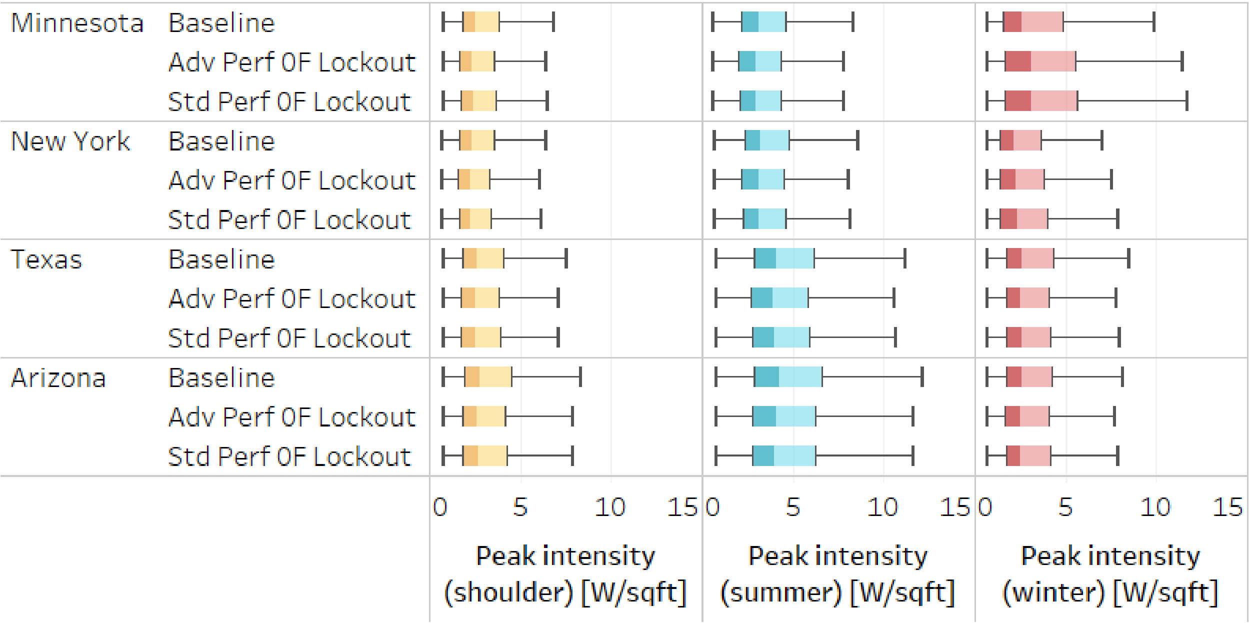


Figure 21. Distributions among all scenarios: peak power intensity

Figure 22 shows the peak power timing implications between three different scenarios: baseline, advanced performance HP-RTU, and standard performance HP-RTU. Fuel switching of gas heating system shifts the peak to an earlier time in colder regions, which is often when outdoor air temperatures are coldest and when commercial buildings are warming up in the morning from an unoccupied evening time with setback temperature set points. Peak timing differences in the shoulder and summer seasons are less noticeable compared to the winter peak timing shift. Future research regarding the results shown in Figure 22 should examine better controls of thermostats (e.g., relaxed or delayed thermostat set point change) when using heat pumps to mitigate the morning peak happening in colder climates.

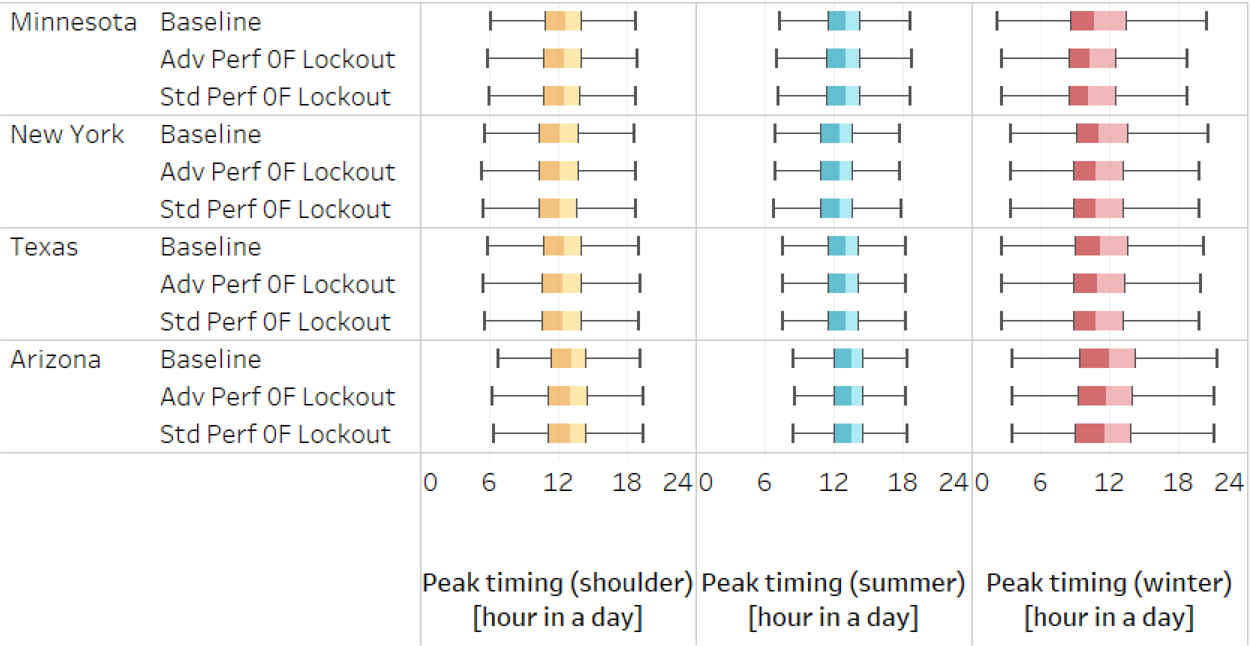


Figure 22. Distributions among all scenarios: peak power timing

References

[1] "2018 COMMERCIAL BUILDINGS ENERGY CONSUMPTION SURVEY (CBECS)." Accessed: Nov. 14, 2022. [Online]. Available: https://www.eia.gov/consumption/commercial/

[2] A. Parker *et al.*, "ComStock Reference Documentation: Version 1," Golden, CO, 2023.

[3] "Energy Conservation Program: Energy Conservation Standards for Air Cooled, Three-Phase, Small Commercial Air Conditioners and Heat Pumps With a Cooling Capacity of Less Than 65,000 Btu/h and Air-Cooled, Three-Phase, Variable Refrigerant Flow Air Conditioners and Heat Pumps With a Cooling Capacity of Less Than 65,000 Btu/h," Federal Register. Accessed: May 02, 2024. [Online]. Available: https://www.federalregister.gov/documents/2023/06/02/2023-10181/energy-conservation-program-energy-conservation-standards-for-air-cooled-three-phase-small

[4] "Standard 90.1." Accessed: May 02, 2024. [Online]. Available: https://www.ashrae.org/technical-resources/bookstore/standard-90-1

[5] "Product Data WeatherMaker® Single Package Heat Pump Rooftop 3 to 6 Nominal Tons," Carrier, 50FCQ-4-7–04PD Rev. B, 2023.

[6] "Product Data WeatherMaker® Single Package Heat Pump Rooftop 7.5 to 12.5 Nominal Tons," Carrier, 50FCQ-8-14–01PD Rev. A, 2022.

[7] "Product Data WeatherMaker® Single Package Heat Pump Rooftop 15 to 25 Nominal Tons," Carrier, 50FCQ-17-28–01PD, 2023.

[8] "Product Data WeatherMaster® High Efficiency Single Packaged Heat Pump Rooftop 3 to 5 Nominal Tons," Carrier, 50GCQ4-6–04PD Rev. A, 2023.

[9] "Installation manual R-410A XP SERIES W/SMART EQUIPMENT™ 6-1/2 - 12-1/2 Ton 60 Hertz," York, 5377290-YIM-D-1019.

[10] "Installation manual R-410A XP SERIES W/SMART EQUIPMENT™ 15/20 Ton 60 Hertz," York, 5168273-YIM-G-0119.

[11] "Installation manual R-410A XQ SERIES 3 - 5 Ton 60 Hertz," York, 5287216-UIM-D-0819.

[12] "Installation manual R-410A XX SERIES 6 - 10 Ton 60 Hertz," York, 5261049-UIM-I–0120.

[13] "Installation, Operation, and Maintenance Packaged Rooftop Air Conditioners Precedent™ — Heat Pump 3 to 10 Tons — 60 Hz," Trane, RT-SVX23R-EN, 2022.

[14] "Installation, Operation, and Maintenance Packaged Rooftop Air Conditioners Precedent™ Heat Pump Standard Efficiency 12.5 to 25 Tons — 60 Hz," Trane, PKGP-SVX010C-EN, 2023.

[15] "Package Heat Pump RHPD Series Commercial 7.5-10 Ton Renaissance™ Line Package Heat Pump," Rheem, P11-815 REV. 2.

[16] "PACKAGED HEAT PUMP KHB Xion™ Rooftop Units Standard Efficiency - 60 Hz," Lennox, 210995, 2023.

[17] "PACKAGED HEAT PUMP KHC Xion™ Rooftop Units Standard Efficiency - 60 HZ," Lennox, 210996, 2023.

[18] "PACKAGED HEAT PUMP KHC Xion™ Rooftop Units Standard Efficiency - 60 Hz," Lennox, 210997, 2023.

[19] "Product Catalog Packaged Rooftop Air Conditioners Precedent™ — Heat Pump 3 to 10 Tons — 60 Hz," Trane, PKGP-PRC013AA-EN, 2022.

[20] “Product Catalog Packaged Rooftop Air Conditioners Precedent^{TM} Heat Pump Standard Efficiency 12.5 to 25 Tons — 60 Hz,” Trane, PKGP-PRC019D-EN, 2023.

[21] “TECHNICAL GUIDE R-410A XP SERIES 6.5 THRU 12.5 TON 60 Hertz,” York, 5167824-YTG-K-0120.

[22] “TECHNICAL GUIDE R-410A XP SERIES 15/20 TON 60 Hertz,” York, 5168280-YTG-F-0119.

[23] “TECHNICAL GUIDE R-410A ZE/XN SERIES 3 - 6 TON 60 Hertz,” York, 5190086-YTG-J-1120.

[24] “TECHNICAL GUIDE XYE/XXE/XQE SERIES 3 - 10 TON 60 HERTZ,” York, 5147362-YTG-P-0921.

[25] “Cambium | Energy Analysis | NREL.” Accessed: Sep. 02, 2022. [Online]. Available: https://www.nrel.gov/analysis/cambium.html

[26] “Emissions & Generation Resource Integrated Database (eGRID) | US EPA.” Accessed: Sep. 02, 2022. [Online]. Available: https://www.epa.gov/egrid

[27] E. Present, Pieter Gagnon, Eric J.H. Wilson, Noel Merket, Philip R. White, and Scott Horowitz, “Choosing the Best Carbon Factor for the Job: Exploring Available Carbon Emissions Factors and the Impact of Factor Selection,” 2022.

[28] G. Vijayakumar *et al.*, “ANSI/RESNET/ICC 301-2022 - Standard for the Calculation and Labeling of the Energy Performance of Dwelling and Sleeping Units using an Energy Rating Index,” Oceanside, CA, 2022.

[29] A. Parker *et al.*, “ComStock Reference Documentation: Version 1,” National Renewable Energy Laboratory, Golden, CO, NREL/TP-5500-83819. [Online]. Available: https://www.nrel.gov/docs/fy23osti/83819.pdf

[30] “Use of natural gas - U.S. Energy Information Administration (EIA).” Accessed: Jul. 02, 2024. [Online]. Available: https://www.eia.gov/energyexplained/natural-gas/use-of-natural-gas.php

[31] “No. 2 Distillate Prices - Residential.” Accessed: Jul. 02, 2024. [Online]. Available: https://www.eia.gov/dnav/pet/pet_pri_dist_a_epd2_prt_dpgal_a.htm

[32] S. Ong and R. McKeel, “National Utility Rate Database: Preprint,” National Renewable Energy Lab. (NREL), Golden, CO (United States), NREL/CP-6A20-54633, Aug. 2012. doi: 10.2172/1050105.

[33] “U.S. Energy Information Administration - EIA - Independent Statistics and Analysis.” Accessed: Jul. 02, 2024. [Online]. Available: https://www.eia.gov/totalenergy/data/browser/index.php?tbl=T07.06#/?f=A

Appendix A. Supplementary Figures

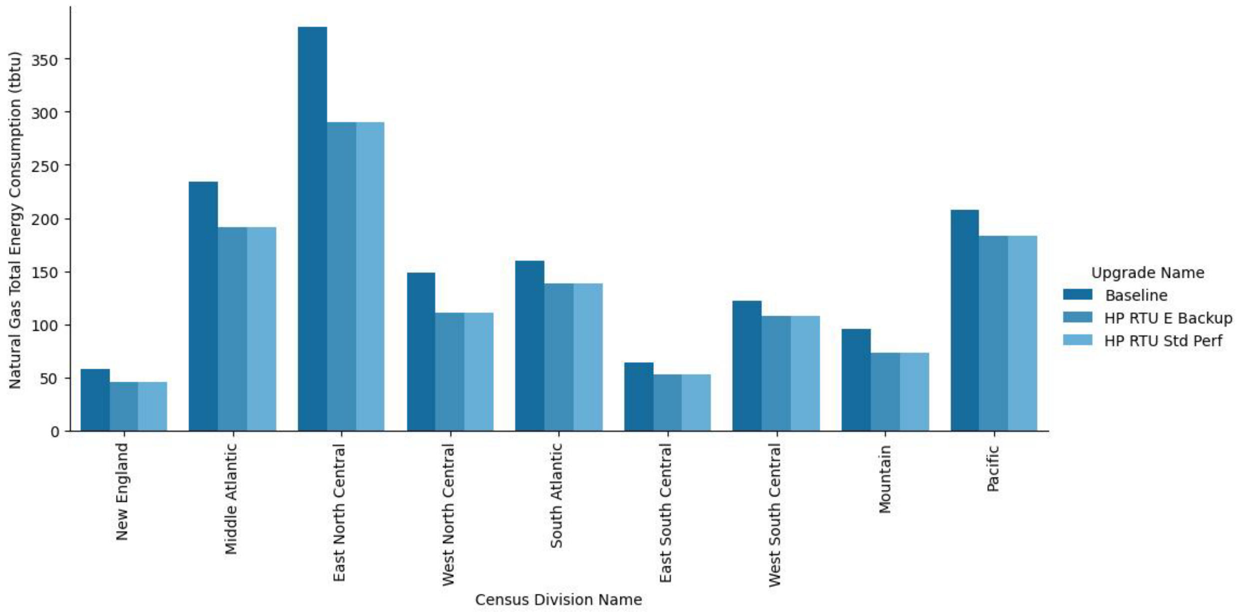


Figure A-1. Site annual natural gas consumption of the ComStock baseline and the measure scenario by census division

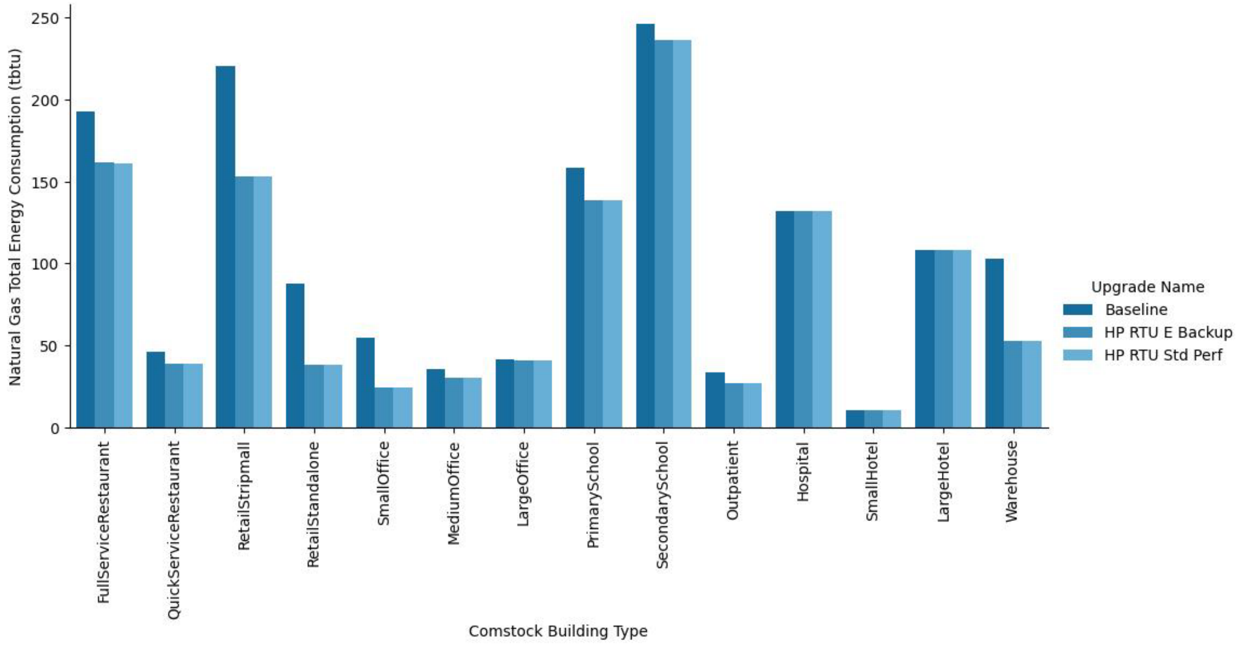


Figure A-2. Site annual natural gas consumption of the ComStock baseline and the measure scenario by building type

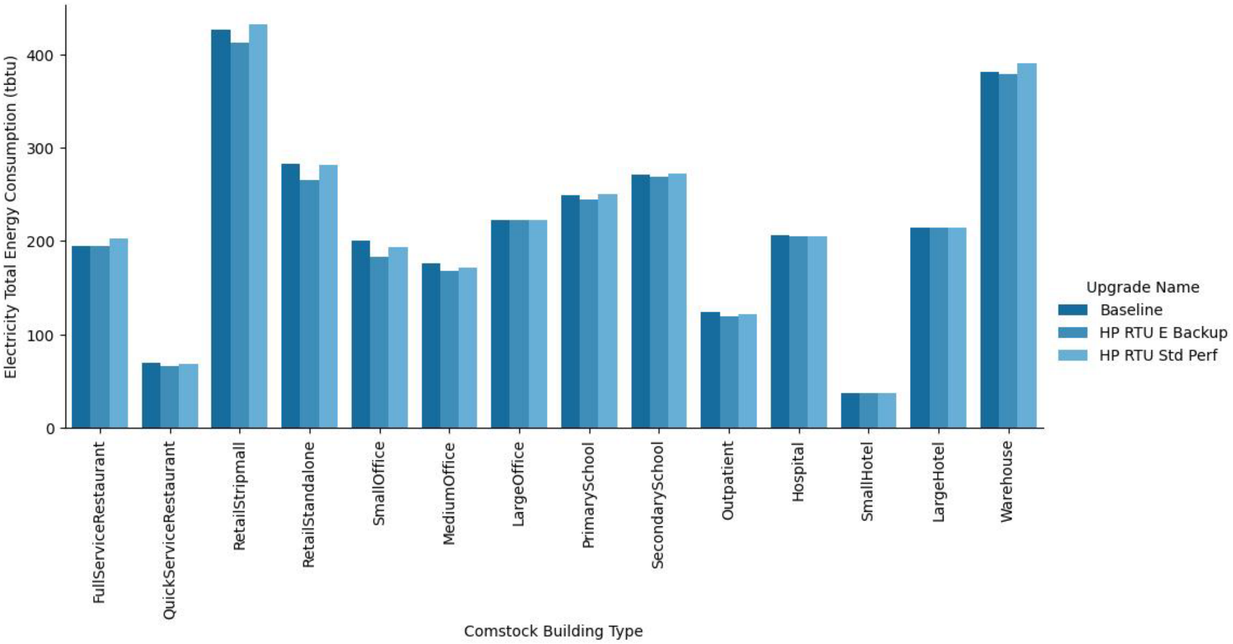


Figure A-3. Site annual electricity consumption of the ComStock baseline and the measure scenario by building type

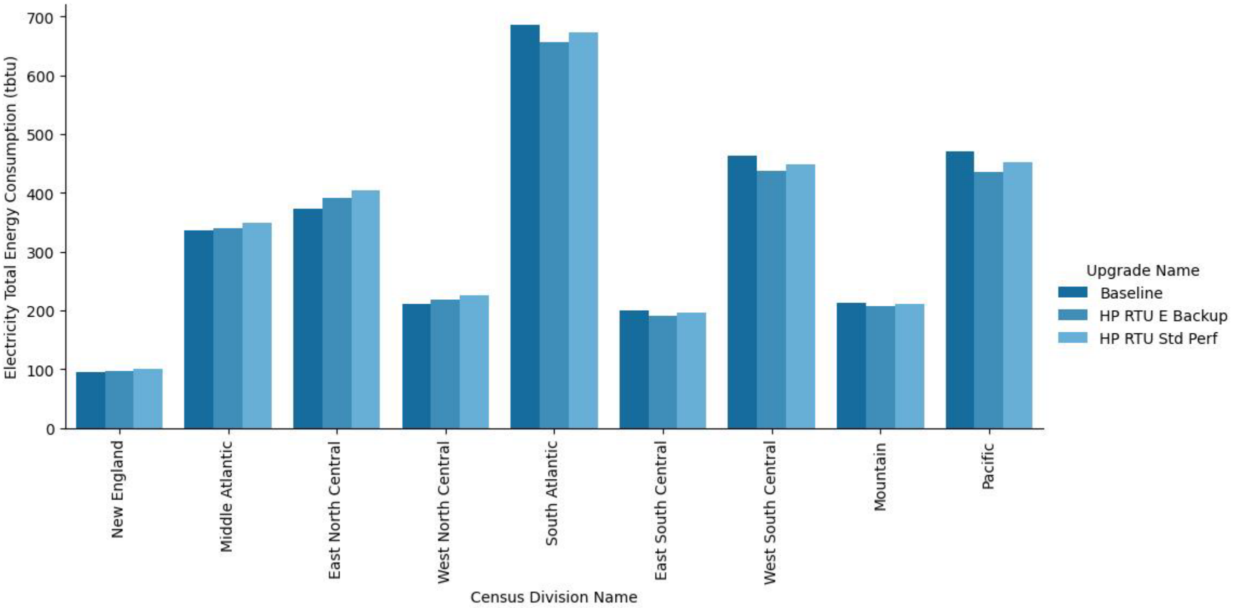


Figure A-4. Site annual electricity consumption of the ComStock baseline and the measure scenario by census division