# ComStock Measure Scenario Documentation: High-Efficiency Rooftop Unit

*Janghyun Kim and Chris CaraDonna*



ComStock

# Acknowledgments

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# List of Acronyms

| | |
|---|---|
| AHRI | Air-Conditioning, Heating, and Refrigeration Institute |
| ASHRAE | American Society of Heating, Refrigerating and Air-Conditioning Engineers |
| CBECS | Commercial Buildings Energy Consumption Survey |
| COP | coefficient of performance |
| DX | direct expansion |
| EER | energy efficiency ratio |
| EIA | U.S. Energy Information Administration |
| EIR | energy input ratio |
| HVAC | heating, ventilating, and air conditioning |
| IEER | integrated energy efficiency ratio |
| kBtu | thousand British thermal units |
| PSZ-AC | packaged single-zone air conditioner |
| RTU | rooftop unit |
| SHR | sensible heat ratio |
| TBtu | trillion British thermal units |
| URDB | Utility Rate Database |

# Executive Summary

Building on the 3-year End-Use Load Profiles project to calibrate and validate the U.S. Department of Energy's ResStock™ and ComStock™ models, this work produces national datasets that enable cities, states, utilities, and other stakeholders to answer a broad range of questions regarding their commercial building stock.

ComStock is a highly granular, bottom-up model that uses various data sources, statistical sampling methods, and advanced building energy simulations to estimate the annual sub-hourly 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 of the baseline model is discussed in the ComStock Reference Documentation.

The goal of this work is to develop energy efficiency and demand flexibility measures that cover market-ready technologies and study their mass-adoption impact on the baseline building stock. "Measures" refers to various "what-if" scenarios that can be applied to buildings. The results for the baseline and measure scenario simulations are published in public datasets that provide insights into building stock characteristics, operational behaviors, utility bill impacts, and annual and sub-hourly energy usage by fuel type and end use.

This report describes the modeling methodology for a single ComStock measure scenario—High-Efficiency Rooftop Unit (RTU)—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 or building type).

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

**Table ES-1. Summary of Key Modeling Specifications**

| | |
|---|---|
| Technology Description | • This study considers the mass-adoption scenario of replacing existing RTUs with high-efficiency RTUs for the U.S. commercial building stock.<br>• "High-efficiency" refers to top-of-the-line products currently available in the United States (as of July 2025).<br>• The high-efficiency RTUs considered in this study provide cooling via direct expansion units and heating with either a gas furnace or electric resistance, depending on the building's existing heating source. |
| Performance Assumptions | • The high-efficiency RTUs considered in this study have rated cooling capacities (at 95°F) ranging from 65 to 705 thousand British thermal units per hour (kBtu/h; 5–59 tons).<br>• Their rated energy efficiency ratios (EER at 95°F) range from 10.0 to 14.6, representing products that exceed the performance requirements of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 90.1-2016 standard used in ComStock.<br>• Their rated integrated energy efficiency ratios (IEER) range from 12.2 to 25.6, representing products that exceed the performance requirements of the ASHRAE 90.1-2016 standard used in ComStock.<br>• Rated performance data (EER/IEER) were collected from the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) Certification Directory, covering 2,847 models from 35 manufacturers.<br>• Performances under various operating conditions (different outdoor/indoor temperatures and airflow rates) were extracted and averaged using detailed data from one manufacturer, enabling translation into EnergyPlus/OpenStudio formats. |
| Applicability | • The high-efficiency RTU measure is applicable to ComStock models with either gas furnace RTUs ("PSZ-AC [packaged single-zone air conditioner] with gas coil"), electric resistance RTUs ("PSZ-AC with electric coil"), gas boilers ("PSZ-AC with gas boiler"), or district heating ("PSZ-AC with district hot water").<br>• Buildings that do not contain gas-fired or electric resistance RTUs are not applicable. Also, the measure is not applicable to kitchen spaces.<br>• This accounts for about 42% of the ComStock buildings floor area. |
| Release | 2025 Release 3: 2025/comstock_amy2018_release_3/ |



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

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

"Applicable" buildings are those that receive the upgrade based on criteria defined for this study.

| Fuel Type | Percent Savings (All Buildings) | Percent Savings (Applicable Buildings Only) | Absolute Savings (trillion British thermal units [TBtu]) |
|---|---|---|---|
| Natural gas | -0.93% | -1.9% | -13.4 |
| Electricity | 9.3% | 19.3% | 309 |
| Fuel oil | -1.3% | -2.6% | -0.71 |
| Propane | -0.61% | -0.81% | -0.26 |
| **Total** | **6.1%** | **12.4%** | **294** |

**Table ES-3. Summary of Key Results for Annual Utility Bill Savings**

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. "Applicable" buildings are those that receive the upgrade based on criteria defined for this study.

| End Use/Fuel Type | Percent Savings (All Buildings) | Percent Savings (Applicable Buildings Only) | Absolute Savings (million USD, 2022) |
|---|---|---|---|
| Natural gas | -0.68% | -1.4% | -0.11 |
| Electricity | 9.2% | 19.1% | 10.2 |
| Fuel oil | -1.3% | -2.6% | -0.024 |
| Propane | -0.25% | -0.33% | -0.0031 |
| **Total** | **7.8%** | **16%** | **10.1** |

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# 1 Introduction

Rooftop units (RTUs) are the predominant heating, ventilating, and air-conditioning (HVAC) technology for small to medium commercial buildings in the United States, serving over 50% of commercial floor area [1]. However, many installed RTUs are aging and operate well below current best-available efficiencies, resulting in opportunities for energy savings and peak demand reduction through retrofit or replacement [2].

This study models the impacts of replacing existing RTUs with top-of-the-line, high-efficiency RTUs currently available on the U.S. market, including units that comply with or exceed the most recent building energy standards [3] and incorporate advanced features such as variable-speed compressors. The primary motivation for this measure is to quantify how modern RTUs can cost-effectively reduce HVAC energy use, lower operating costs for building owners, and contribute to grid peak load management goals.

Key parameters impacting the performance of RTU retrofits (i.e., full replacement retrofit or, in other words, replacing existing RTUs with new RTUs) include capacity and efficiency at rated conditions, off-rated performance, and control strategies such as demand-controlled ventilation or advanced economizers [4], [5]. Assumptions for these parameters are informed by Air-Conditioning, Heating, and Refrigeration Institute (AHRI)-certified performance ratings, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 90.1 standards, and performance data from manufacturer specifications. For readers interested in analyses focused on upgrading RTU control strategies, refer to the report by Allen and CaraDonna [6].

Several laboratory and field demonstrations have validated the energy and demand benefits of advanced RTU retrofits. In 2017, The U.S. Department of Energy’s Advanced Rooftop Unit Campaign showcased the broad and impactful role of RTUs in commercial buildings—which cover 60% of floor area and consume a fifth of total buildings energy use—demonstrating that comprehensive upgrades and replacements across 77,000 units by 300 partners have achieved over $166 million in energy savings, with participating organizations realizing up to 50% reductions in cooling and ventilation energy use [7], [8]. Field studies by Pacific Northwest National Laboratory have confirmed that adding advanced controls, such as variable-speed operation and demand-controlled ventilation, can improve performance under real-world conditions [5].

However, barriers and risks to successful RTU retrofits still remain. Known concerns include improper installation, lack of commissioning, inadequate maintenance, and underutilization of advanced control features, which can erode expected savings [5], [9]. Financial hurdles, split incentives between building owners and tenants, and unrealistic expectations for short-term payback can also hinder widespread adoption. Furthermore, performance—and therefore outcomes—can vary with climate, occupancy patterns, and building system interactions, making robust modeling essential for evaluating real savings potential.

This analysis aims to address these uncertainties by simulating representative high-efficiency RTU retrofit scenarios leveraging ComStock and using current market-leading technologies to inform stakeholders of achievable benefits and potential limitations.

# 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 Reference Documentation report [10]. HVAC equipment performance is assumed to meet the energy code requirements in force at the time and place of installation. For this reason, most existing RTUs are modeled as constant-air-volume units with single-speed compressors and either gas or electric resistance backup heat, with no degradation in performance modeled over time.

Direct expansion (DX) cooling is the predominant cooling technology in commercial buildings and is implemented across multiple ComStock HVAC system types, including packaged single zone, packaged terminal, packaged variable air volume, and residential split systems. These systems are typically modeled with single-speed compressors and constant-speed supply fans, which limit modulation capabilities and reduce part-load efficiency. Rated performance is assigned based on equipment capacity and the applicable ASHRAE 90.1 standard or U.S. Department of Energy reference building vintage, with both full-load and part-load efficiency values sourced from code templates. To capture performance variability under non-standard conditions, ComStock applies five modifier curves that adjust energy input ratio (EIR) and cooling capacity as functions of part-load ratio, outdoor air temperature, entering coil wet-bulb temperature, and supply airflow fraction.

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%.

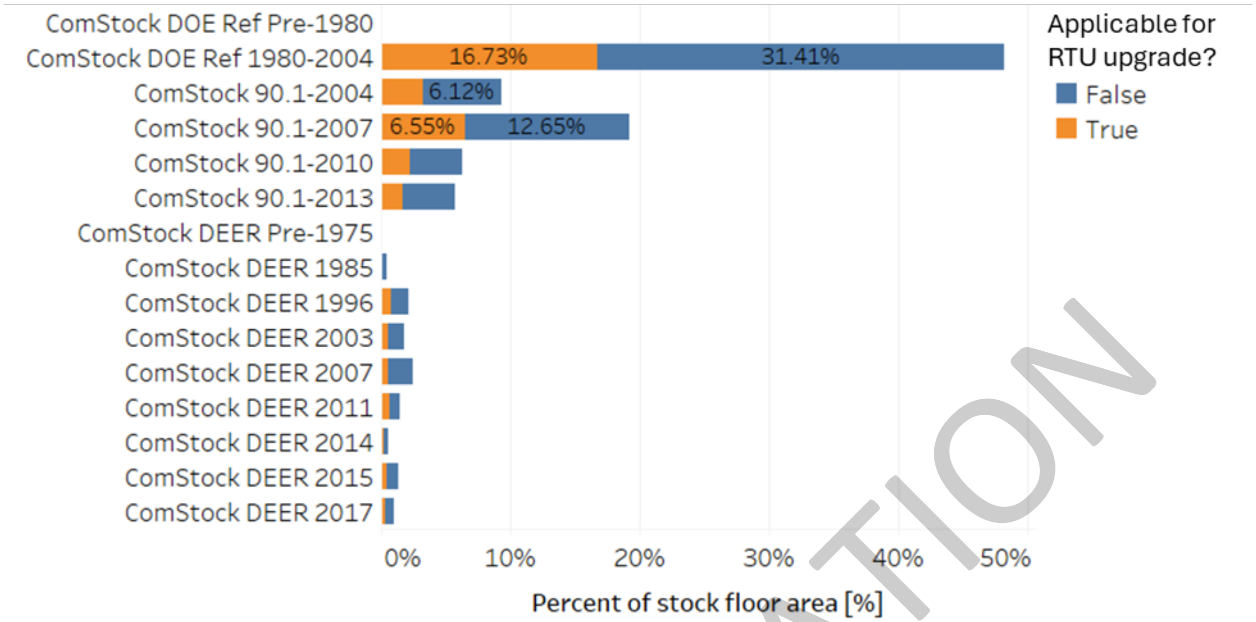



**Figure 1. ComStock baseline in-force energy code followed as a percentage of applicable floor area. Applicable floor area includes ComStock buildings with “PSZ-AC with gas coil” and “PSZ-AC with electric coil” HVAC system types.**

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 high-efficiency RTU measure is applicable to ComStock models with either gas furnace RTUs (“PSZ-AC with gas coil”), electric resistance RTUs (“PSZ-AC with electric coil”), gas boilers (“PSZ-AC with gas boiler”), or district heating (“PSZ-AC with district hot water”). This accounts for about 42% of the ComStock floor area (Figure 2). ComStock HVAC distributions are informed by the 2012 Commercial Buildings Energy Consumption Survey (CBECS). The methodology for interpreting CBECS data to create HVAC probability distributions for ComStock is discussed in the ComStock Reference Documentation [10]. 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).

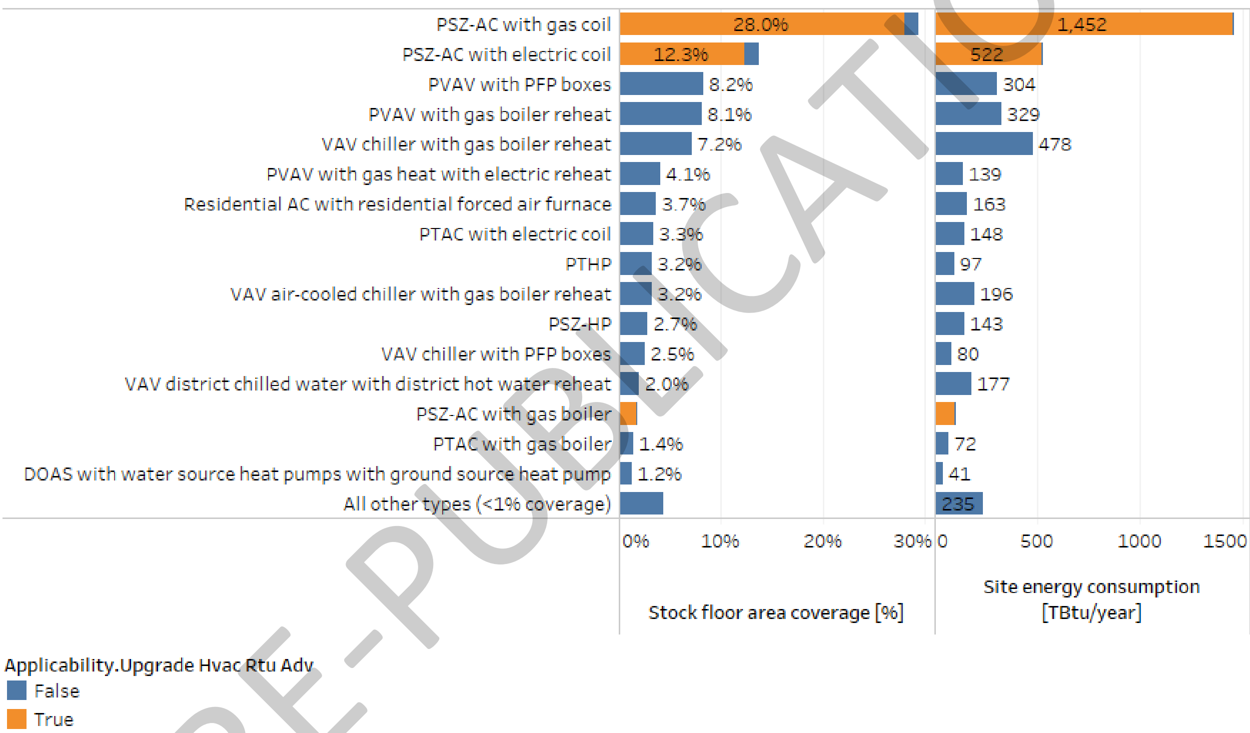





**Figure 2. ComStock HVAC system type prevalence by stock floor area.**

PTHP = packaged terminal heat pump; PTAC = packaged terminal air conditioner; PVAV = packaged variable air volume; DOAS = dedicated outdoor air system; PFP = parallel fan power

## 3.2 Measure Scenario Modeling Methodology

High-efficiency RTUs sold in the United States typically feature high energy efficiency ratio (EER) and integrated energy efficiency ratio (IEER) ratings, along with variable-speed compressors and supply fans that enhance part-load performance. They often include advanced digital controls and economizers for free cooling and are compatible with building automation systems. Enhanced heat exchangers and improved air filtration or indoor air quality features are also common. Many units offer factory-installed energy recovery, smart diagnostics, and remote monitoring capabilities. Overall, these features help high-efficiency RTUs reduce energy consumption, maintain peak performance, and meet utility rebate requirements. And the following sections describe the details of what we have chosen for modeling high-efficiency RTUs.

### 3.2.1 Cooling Performance Modeling

The cooling performance of RTUs is modeled in two aspects: rated performance leveraging EER (but modeled as coefficient of performance [COP]) and off-rated performance leveraging performance maps published by the manufacturers. Details of how the public data are translated into EnergyPlus/OpenStudio® are included in the following subsections.

#### 3.2.1.1 Rated Performance

Metrics reflecting the rated performance of RTUs sold in the United States are well documented in the AHRI certification directory [4]. We have extracted RTU data entries from the AHRI database and filtered the products based on the following criteria: (1) production status should be active and (2) must be sold in the United States. The final list of products used to extract average RTU performance included 2,847 products (or individual entries in the AHRI database) manufactured by 35 different manufacturers. Figure 3 to Figure 4 include snapshots of the data collected. As shown in Figure 3, products used for extracting rated performance range from 5–59 tons.

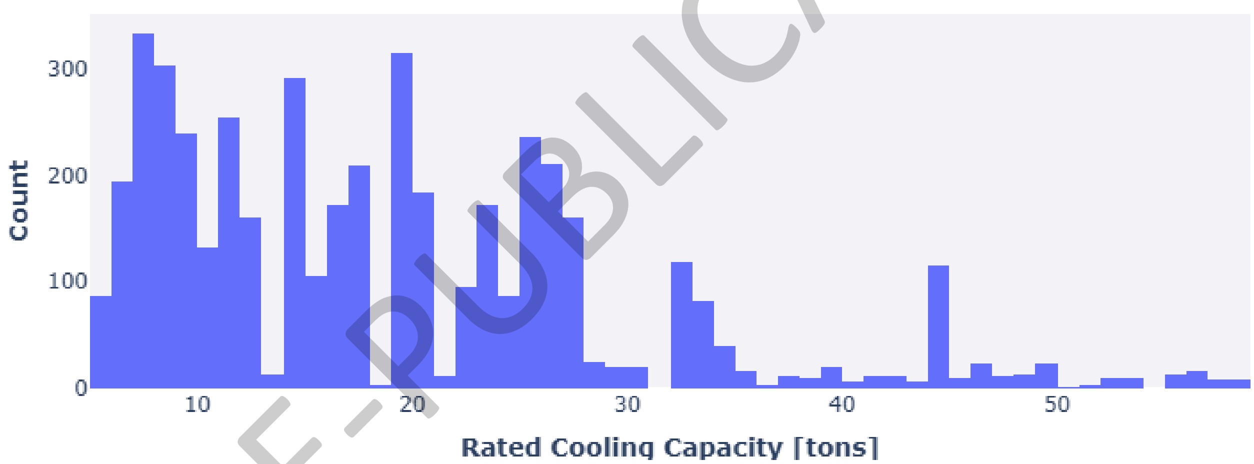



**Figure 3. Distribution of rated cooling capacities from data used for modeling**

To capture the relationship between unit size and rated efficiency (EER and IEER), three capacity bins were defined (following bin categories used in ASHRAE 90.1-2016 [11]) to reflect the typical decline in efficiency as RTU size increases, as illustrated in Figure 4. The first bin covers rated capacities from 0 to 135 kBtu/h (11.3 tons), the second from 135 to 240 kBtu/h (20 tons), and the third includes units with capacities above 240 kBtu/h. As shown in Figure 4, the latest ASHRAE 90.1-2016 [11] standard applied in ComStock sets the minimum product efficiency requirements for each capacity bin, with the lowest flat points in each bin representing these minimum thresholds. In other words, this analysis includes (1) only products that meet or exceed current building energy codes and represent the highest-performing models currently available on the market and (2) products that manufacturers identify as “high efficiency” as of July 31, 2025.

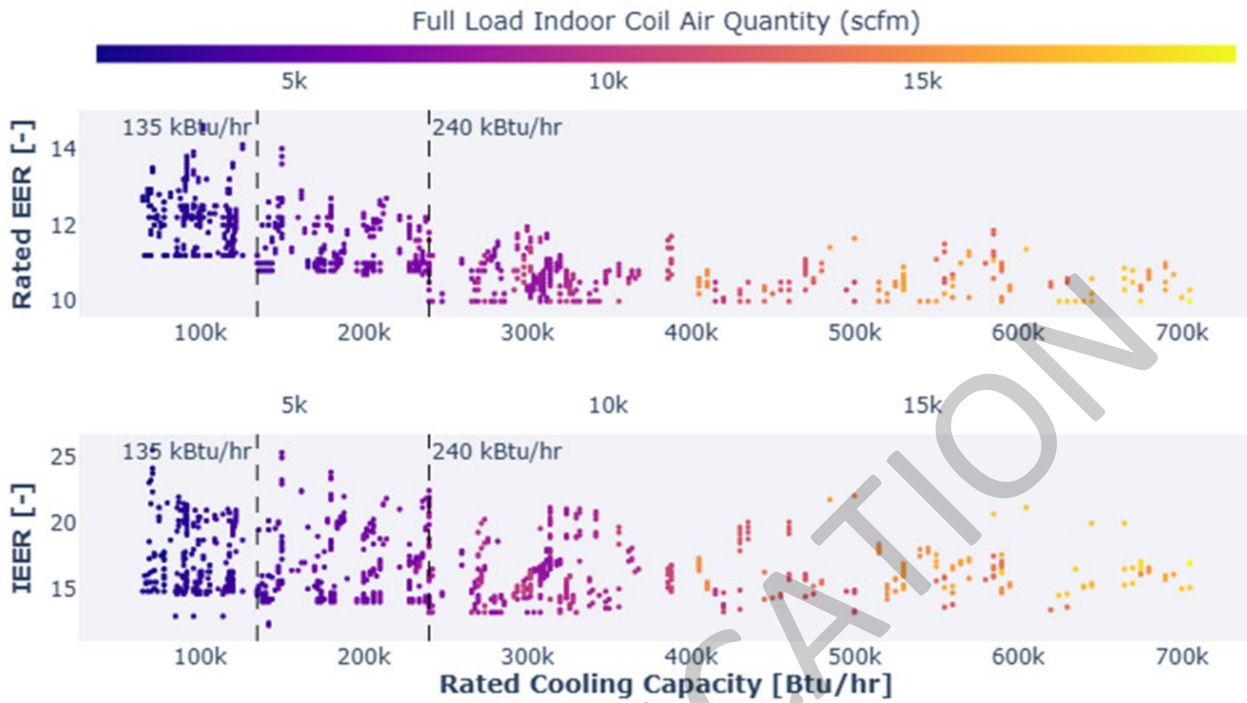



**Figure 4. Rated EER/IEER against rated cooling capacity from data used for modeling**

Figure 5 presents the final linear regression fits used to estimate the rated COP based on the rated capacity. The rated COP values in this figure are converted from the rated EER values shown in Figure 4, using the formula from the OpenStudio Standards, which accounts for condenser fan and excludes supply blower fan power from the rated EER. Regarding the measure execution sequence, the RTU model first undergoes the EnergyPlus sizing algorithm to determine its rated capacity. Then, based on this calculated rated capacity, the rated COP is computed and assigned using the linear equations depicted in Figure 5 (and in Figure 4); rated COPs generally decrease as rated capacity increases. Although there is noticeable variability among the data points compared to the linear regression lines, we have chosen to represent average rated COP performance using the three regression curves, one for each size category.

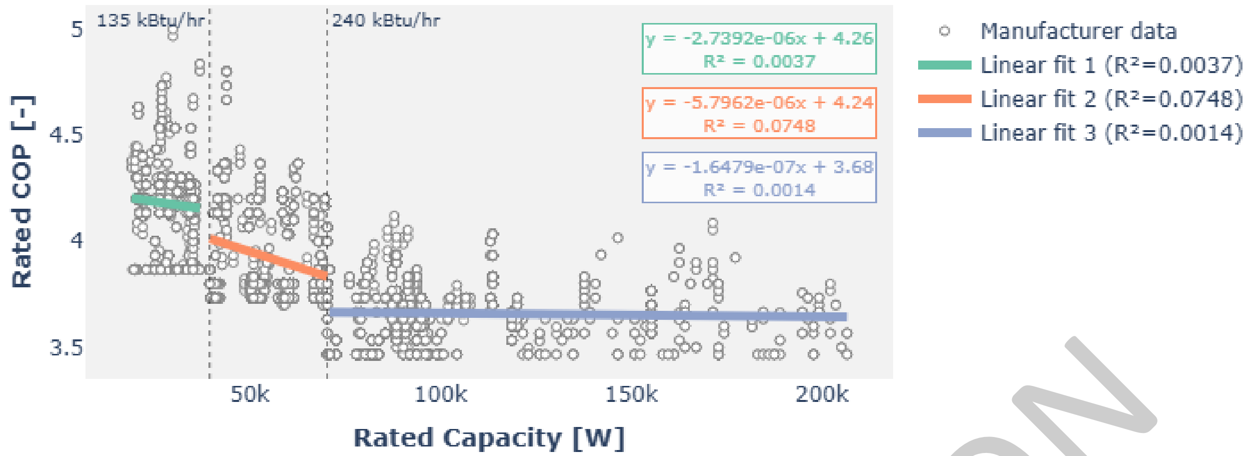



**Figure 5. Linear regressions for estimating rated COP from rated capacity**

One observation from this and previous research is that the rated COP values used (e.g., using Figure 5 based on rated capacity only) in EnergyPlus models often differ technically from those listed in manufacturer catalogs. This discrepancy arises because the term "rated" is not always used consistently between real-world product documentation and EnergyPlus modeling conventions. For example, manufacturer catalogs typically define rated conditions using specific values—such as 67°F evaporator inlet wet-bulb, 95°F condenser inlet dry-bulb, and a product-specific rated airflow. While the temperature conditions are usually easy to align in EnergyPlus, the rated airflow is often overlooked. This is because EnergyPlus determines airflow based on its auto-sizing algorithms, which are designed to ensure the system can meet the cooling or heating loads of the modeled building. Referring to the values shown in Figure 5, the rated COPs based on manufacturer data are tied to these catalog-rated airflows. Therefore, when applying these COP values in our models, we must adjust them to reflect the airflow conditions generated by the EnergyPlus sizing routines rather than use the manufacturer's rated airflow directly.

To make this adjustment, we modify the rated COP based on the difference between the airflow sized by EnergyPlus and the reference airflow from product data. This is done by calculating the ratio of actual to reference airflow and then applying a performance curve—specifically, an EIR modifier curve that is a function of flow fraction (described in the following section)—to estimate how the airflow difference affects energy consumption. Once the adjustment factor is determined from the curve, it is applied to the rated COP derived from Figure 5. The adjusted COP better reflects the actual operating conditions in the building model, resulting in a more accurate simulation of system performance. Because the COP values in Figure 5 are based on real product data, we also fit a corresponding rated cubic feet per minute per ton (cfm/ton) (as shown in Figure 6) to estimate each product's rated airflow, which is then aligned with the rated capacity calculated by EnergyPlus.

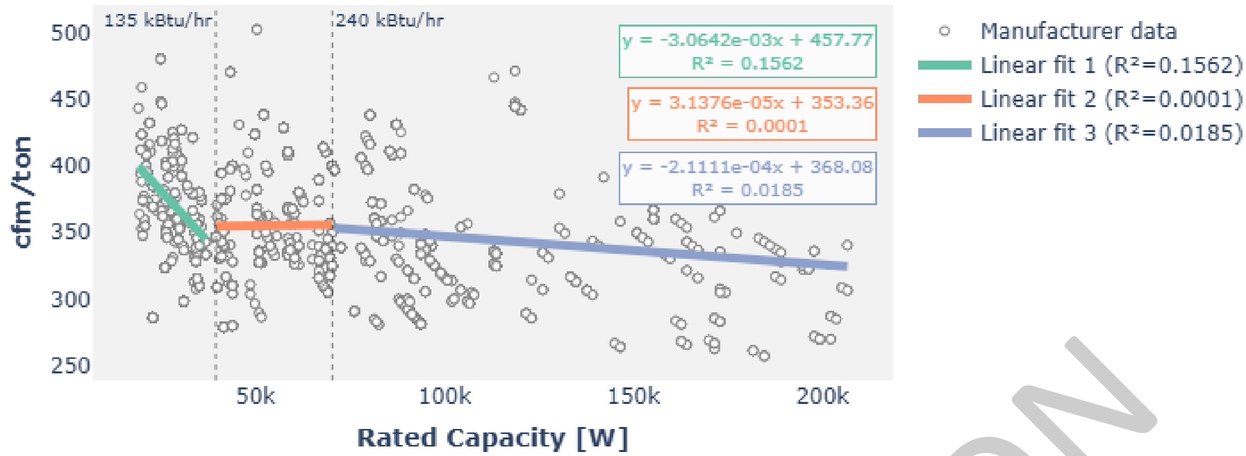



**Figure 6. Linear regressions for estimating rated cubic feet per minute per ton (cfm/ton) from rated capacity**

For EnergyPlus modeling, inputs such as sensible heat ratio (SHR) and reference COP at reduced compressor speeds are necessary to accurately simulate lower-stage equipment performance. To derive these values, we filtered manufacturer performance data (from three different manufacturers and across 28 different products) at standard rated conditions—specifically, 67°F evaporator inlet wet-bulb temperature, 95°F condenser inlet dry-bulb temperature, and the corresponding rated airflow for each product. Based on this filtered dataset, we calculated the relative changes in SHR and COP for each stage of operation, as summarized in Table 1.

**Table 1. Modeling Assumptions for Lower-Stage Sensible Heat and Reference COP Ratios**

| | Low Stage | Middle Stage | High Stage |
|---|---|---|---|
| SHR (from data / actual simulation) | 0.81 / 0.7 | 0.74 / 0.64 | 0.73 / 0.63 |
| Reference COP ratio | 1.13 | 1.10 | 1 (rated) |

As shown in Table 1 and based on manufacturer data representing high-efficiency RTUs—which includes two-stage (only for very small units), three-stage, and variable-speed systems, with three-stage systems being the most commonly available in public catalogs—we chose to model a variable-speed system in EnergyPlus using separate performance characteristics for each stage. EnergyPlus represents variable-speed systems through discrete stages, so to align with this modeling approach, we incorporated intermediate-stage performance data. While the manufacturer data include variable-speed systems, they also provide detailed performance information for many three-stage systems. We leverage this intermediate-stage data to effectively represent the performance of a variable-speed system within the EnergyPlus framework.

However, while extracting SHR values for each stage from the manufacturer's data, we noticed that the values did not initially align well with the EnergyPlus simulations. This discrepancy arose because the SHR values provided in the data went beyond the limits of those calculated by EnergyPlus using psychrometric principles. We suspect that this stems from differences in the humidity conditions of the inlet air entering the evaporator—specifically, between the conditions assumed in the manufacturer data (which is not specified) and those used by EnergyPlus during simulation. Since EnergyPlus generated frequent warnings with the original SHR values (listed as "from data" in Table 1), leading to increased simulation time, we made an engineering decision to reduce the SHR values consistently across all three stages (as shown under "actual simulation" in Table 1). We believe this adjustment has minimal impact on air property modeling, as it prevents throwing the air outlet properties beyond 100% relative humidity.

As shown in Table 1, the SHR (from data) increases at lower-speed stages (e.g., from 0.73 at high speed to 0.81 at low speed). This trend is expected because at lower compressor speeds, the evaporator coil operates at higher temperatures and the airflow often decreases, reducing the coil's ability to condense moisture from the air. As a result, latent cooling capacity drops more than sensible capacity, causing the SHR to rise.

Similarly, the reference COP increases at lower stages, with the low-speed COP reaching 1.13 times the rated high-speed COP. This improvement in efficiency is primarily due to lower compressor power draw, reduced fan power, and improved heat exchanger effectiveness at part-load conditions. Since the system operates more efficiently under reduced load—with less energy input per unit of cooling delivered—the part-load COP surpasses the full-load rated COP.

#### *3.2.1.2 Performance Under Various Operating Conditions*

While rated capacities and efficiencies are commonly available from public resources, data on performance variation under off-rated operating conditions are relatively scarce. When such data exist, they often lack the detail needed to implement the performance in EnergyPlus or OpenStudio models. Additionally, this information is not well organized or documented in a format that others can easily download and process like the structured data available in the AHRI database.

To address this challenge, we conducted a comprehensive review of 15 catalogs featuring high-efficiency (designated by manufacturers) RTUs from three major manufacturers to identify suitable performance map data [12]–[26]. Table 2 summarizes how fragmented information from each catalog was interpreted and translated into EnergyPlus-compatible performance curves.

**Table 2. Mapping of Data Sources to RTU Performance Curves**

**From data source**

| **Manufacturer** | A | B | C |
|---|---|---|---|
| **Rated capacities available?** | Yes for some units | Yes | No |
| **Rated power available?** | Yes | No | No |
| **Rated airflow available?** | Yes for some units | Yes | No |
| **Reference capacities (for lower stages) available?** | No | No | No |
| **Reference power (for lower stages) available?** | No | No | No |
| **Reference airflow (for lower stages) available?** | No | No | No |
| **Off-rated performances of highest stage cooling capacities available?** | Yes | Yes | Yes |
| **Off-rated performances of highest stage compressor power available?** | Yes | No | No |
| **Off-rated performances of lower stage cooling capacities available?** | No | Yes | No |
| **Off-rated performances of lower stage compressor power available?** | No | No | No |

**To EnergyPlus**

| | Stage / Size | Low Stage | Med Stage | High Stage | Low Stage | Med Stage | High Stage | Low Stage | Med Stage | High Stage |
|---|---|---|---|---|---|---|---|---|---|---|
| **Total Cooling Capacity Function of Temperature Curve derived from** | Larger Units | | | O | Δ | Δ | O | | | Δ |
| | Smaller Units | Δ | Δ | O | Δ | Δ | O | | | |
| **Total Cooling Capacity Function of Air Flow FractionCurve derived from** | Larger Units | | | O | Δ | Δ | O | | | Δ |
| | Smaller Units | Δ | Δ | O | Δ | Δ | O | | | |
| **Energy Input Ratio Function of Temperature Curve Name derived from** | Larger Units | | | O | | | | | | |
| | Smaller Units | Δ | Δ | O | | | | | | |
| **Energy Input Ratio Function of Air Flow Fraction Curve Name derived from** | Larger Units | | | O | | | | | | |
| | Smaller Units | Δ | Δ | O | | | | | | |
| **Part Load Fraction Correlation Curve Name** | Larger Units | | | | | | | | | |
| | Smaller Units | O | O | O | | | | | | |

* Circle means sufficient data, triangle means data available but insufficient for curve development, and blank means no data.



The "From Data Source" section outlines the type of specific data required by EnergyPlus and whether that data were available from each manufacturer. For example, while Manufacturer A provided rated power data (including compressor and condenser fan power), similar information was not available in Manufacturer B's catalogs.

The "To EnergyPlus" section illustrates which EnergyPlus performance curves were informed by public data from each source. For instance:

- Both Manufacturers A and B provide sufficient information to develop the capacity modifier (function of temperatures) curve for full-load operation (highest stage), particularly for larger units (shown with circle symbol).
- Manufacturer A did not include enough data to generate capacity modifier curves for lower-stage operation and for larger units (shown as blank).
- Manufacturer B offered data showing how capacity varies with temperature but lacked the reference capacity values needed to create normalized capacity modifier curves for lower-stage operation and for larger units (shown with triangle symbol).

EnergyPlus performance curves for modeling RTUs require normalizing actual capacity, power, and airflow. To do this, both rated values (at full-load operation) and reference values (at lower stages) are needed. While the absence of reference values for lower stages was expected, rated values were also occasionally missing, as shown in Table 2—particularly for these high-efficiency products. These values were more commonly available for flagship or lower-tier models. As a result, certain assumptions were made during the normalization process—for example, estimating rated capacity based on the product's nameplate tonnage.

Among the reviewed data, only one manufacturer (Manufacturer A) provided performance maps for larger RTUs (25 to 150 tons) that included both capacity and power variations under varying indoor/outdoor temperatures and airflow rates, as shown in Table 2. In contrast, the other manufacturers reported only capacity variations, which are insufficient for deriving power-related (i.e., EIR) curves. Consequently, we developed normalized off-rated performance curves—focused on power consumption at the highest stage of operation—based on detailed maps from Manufacturer A.

Also, the larger, high-efficiency RTUs from Manufacturer A are variable-speed units equipped with three or four compressors and two refrigerant circuits. Their catalogs provide performance maps only for the highest stage of operation (i.e., no data for lower-stage performance). In contrast, EnergyPlus requires performance maps for intermediate stages to accurately simulate lower-stage performance in variable-speed systems.

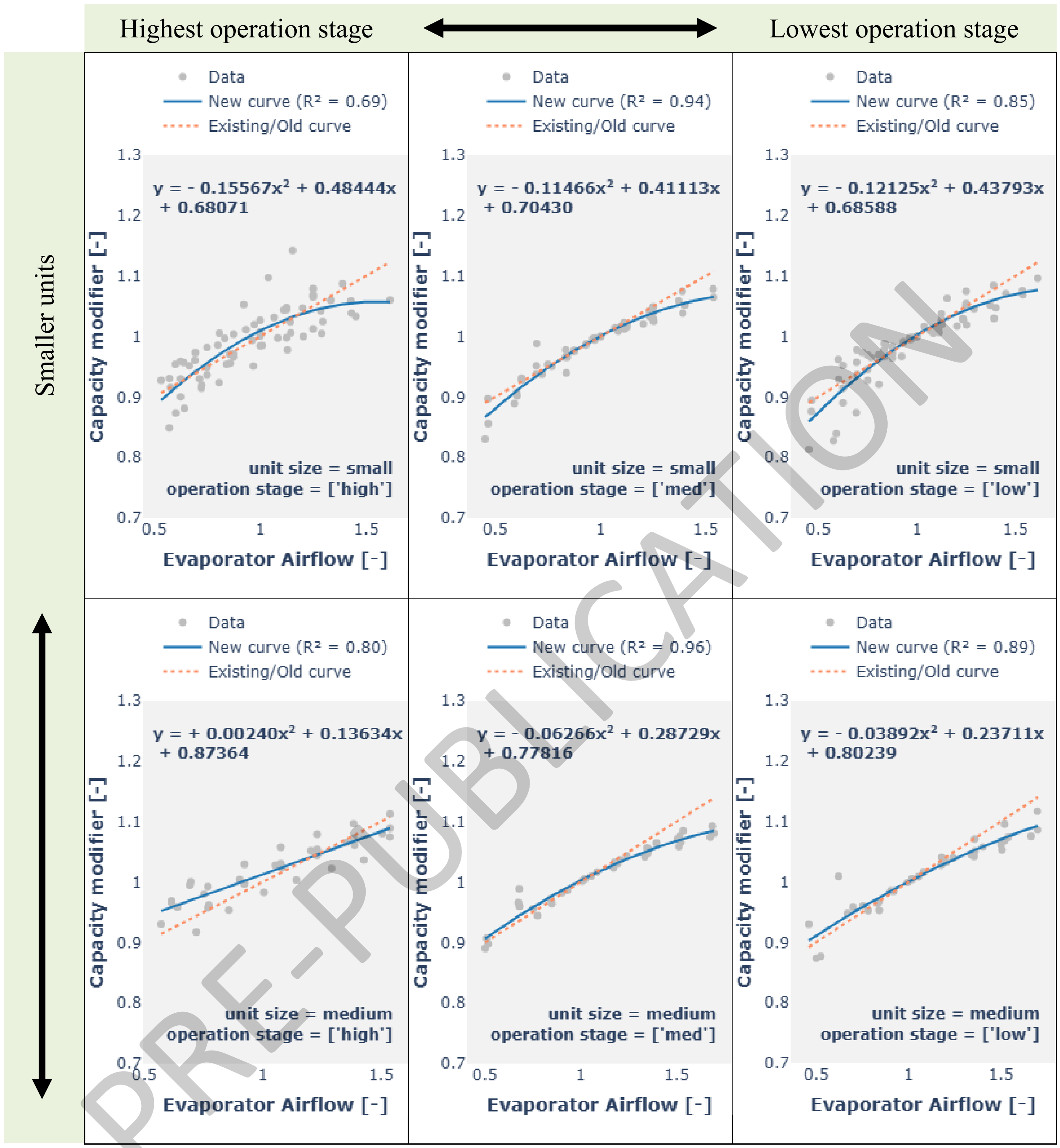
As shown in Table 2, lower-stage capacity data for larger units are available only from Manufacturer B. A further challenge with these lower-stage data is the lack of "reference" values for capacity, power, and airflow. As previously noted, EnergyPlus performance maps must be normalized, meaning that EnergyPlus determines the rated/reference capacity and airflow (via the sizing algorithm), and the normalized performance data are scaled accordingly based on these "reference" values.

To estimate the reference capacity, power, and airflow values for lower-stage operation, we approximated the location of the reference condition within the performance map using parameters similar to those of the full-load rated condition. For instance, standard rated temperatures are 67°F for the evaporator inlet wet-bulb and 95°F for the condenser inlet dry-bulb. The remaining unknown—rated airflow—was not consistently available across all products, as shown in Table 2. However, when rated capacity became available (with approximation) but rated airflow was missing, we estimated airflow by interpolating within the available data. In other words, based on (1) the estimated position of the rated airflow within the airflow range of the highest-stage performance maps and (2) the consistent use of rated temperature conditions, we extracted the reference capacity and power values for the lower-stage performance maps.

When simulating system behavior in tools like EnergyPlus, data gaps across manufacturers often force engineers to stitch together performance curves using fragmented information. Since no single source provides comprehensive data covering all operating conditions—full-load and part-load capacities, compressor power, airflow dependencies, and temperature sensitivities—we must combine partial datasets like a patchwork quilt. This approach is not ideal, but it is often the only option for capturing any semblance of real-world operation in these behaviors.

Based on engineering judgment using the available data, Figure 7 to Figure 11 present the performance assumptions applied in this simulation study. The key highlights from these figures are summarized below:

- Figure 7 to Figure 11: The existing/old curves are sourced from OpenStudio Standards ASHRAE 90.1-2019 data, representing some of the better performance levels typically found in existing buildings.
- Figure 7 to Figure 11: With the exception of very small units (≤ 5 tons), products with multistage data included up to three stages. Accordingly, we applied engineering judgment to model variable-speed units using performance data distinguished across three stages.
- Example of an operating COP determination based on performance maps shown:
    - If rated COP = 4.2 (small unit shown in Figure 5) and
    - EIR = 0.5 (small unit, lower stage, and colder temperature in Figure 10), then
    - off-rated COP = 4.2 / 0.5 = 8.4.
- Figure 7 and Figure 8: Off-rated performance of high-efficiency RTUs (based on airflow) is similar to reference/existing curves.
- Figure 9 and Figure 10: Off-rated performance of high-efficiency RTUs (based on temperature) is slightly better than reference/existing curves.
- Figure 11: Part-load performance of high-efficiency RTUs is better than reference/existing curves. But we still use the new curves in Figure 11.
- Overall: High-efficiency RTUs generally perform better.
- Key drivers of benefits: The modeled benefits of high-efficiency RTUs primarily stem from (1) higher rated efficiency, (2) reduced cycling with variable-speed systems, and (3) improved performance under off-rated operating conditions.


Highest operation stage
Lowest operation stage
Smaller units
Data
New curve (R² = 0.69)
Existing/Old curve
y = - 0.15567x² + 0.48444x + 0.68071
unit size = small
operation stage = ['high']
Capacity modifier [-]
Evaporator Airflow [-]
Data
New curve (R² = 0.94)
Existing/Old curve
y = - 0.11466x² + 0.41113x + 0.70430
unit size = small
operation stage = ['med']
Capacity modifier [-]
Evaporator Airflow [-]
Data
New curve (R² = 0.85)
Existing/Old curve
y = - 0.12125x² + 0.43793x + 0.68588
unit size = small
operation stage = ['low']
Capacity modifier [-]
Evaporator Airflow [-]
Data
New curve (R² = 0.80)
Existing/Old curve
y = + 0.00240x² + 0.13634x + 0.87364
unit size = medium
operation stage = ['high']
Capacity modifier [-]
Evaporator Airflow [-]
Data
New curve (R² = 0.96)
Existing/Old curve
y = - 0.06266x² + 0.28729x + 0.77816
unit size = medium
operation stage = ['med']
Capacity modifier [-]
Evaporator Airflow [-]
Data
New curve (R² = 0.89)
Existing/Old curve
y = - 0.03892x² + 0.23711x + 0.80239
unit size = medium
operation stage = ['low']
Capacity modifier [-]
Evaporator Airflow [-]

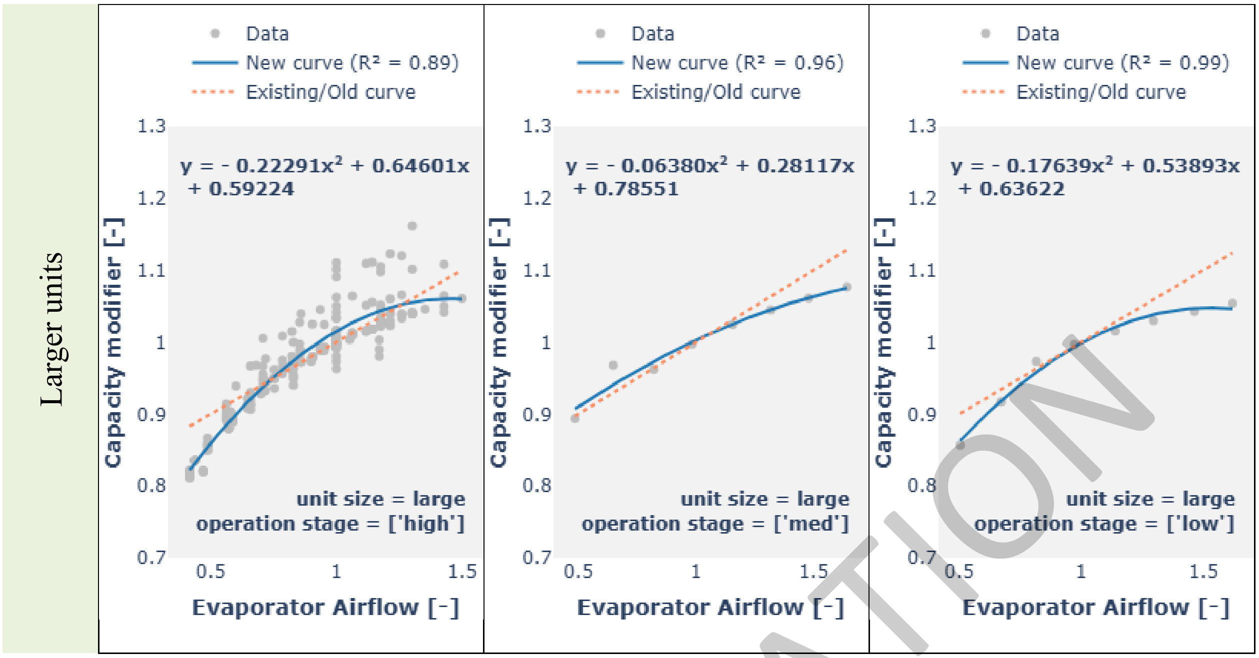
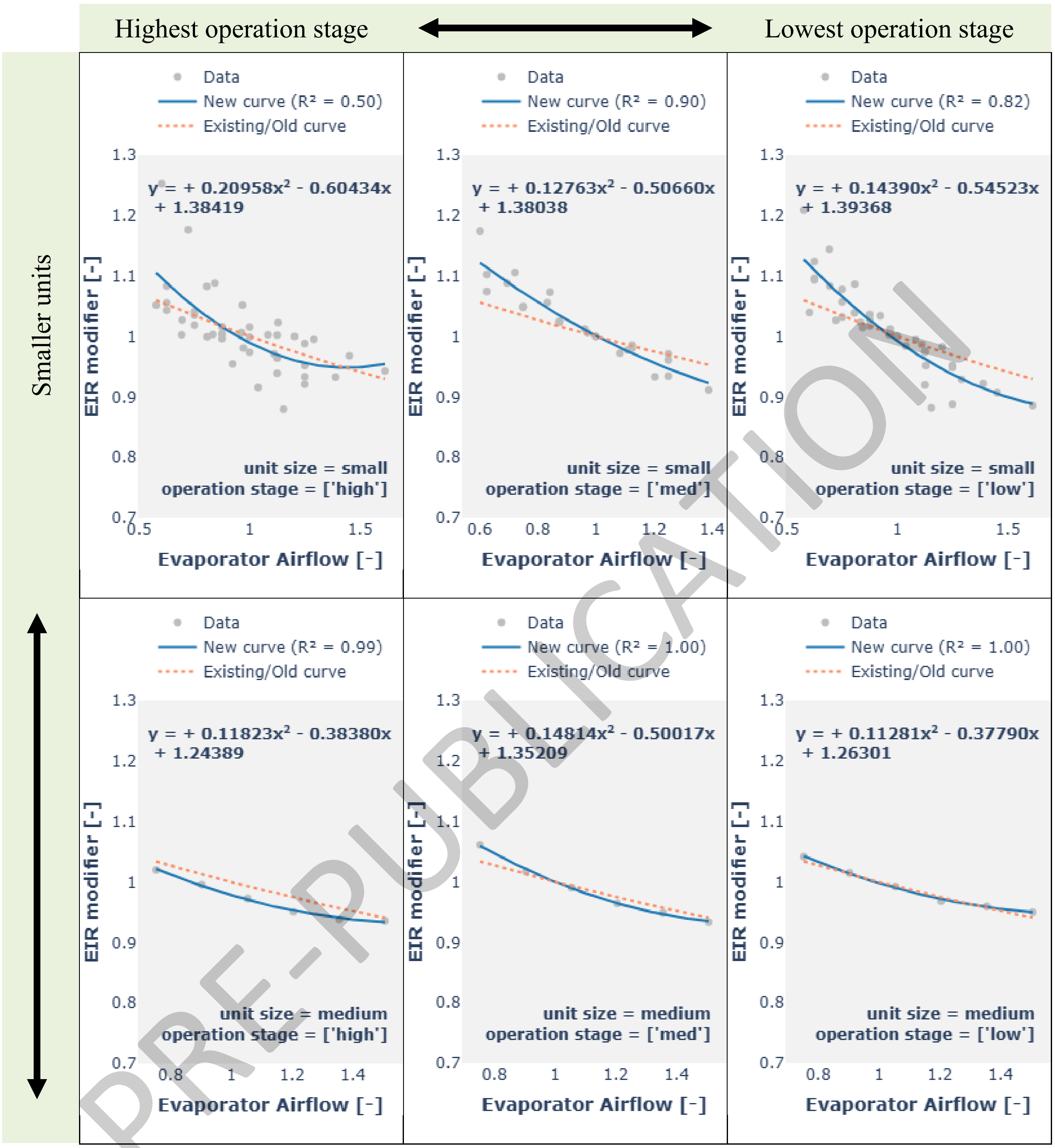



**Figure 7. Performance curves used in the study: capacity modifier function of fraction of airflow**



Highest operation stage
Lowest operation stage
Smaller units
Data
New curve ($R^2$ = 0.50)
Existing/Old curve
y = + 0.20958x² - 0.60434x + 1.38419
unit size = small
operation stage = ['high']
Data
New curve ($R^2$ = 0.90)
Existing/Old curve
y = + 0.12763x² - 0.50660x + 1.38038
unit size = small
operation stage = ['med']
Data
New curve ($R^2$ = 0.82)
Existing/Old curve
y = + 0.14390x² - 0.54523x + 1.39368
unit size = small
operation stage = ['low']
Data
New curve ($R^2$ = 0.99)
Existing/Old curve
y = + 0.11823x² - 0.38380x + 1.24389
unit size = medium
operation stage = ['high']
Data
New curve ($R^2$ = 1.00)
Existing/Old curve
y = + 0.14814x² - 0.50017x + 1.35209
unit size = medium
operation stage = ['med']
Data
New curve ($R^2$ = 1.00)
Existing/Old curve
y = + 0.11281x² - 0.37790x + 1.26301
unit size = medium
operation stage = ['low']
EIR modifier [-]
Evaporator Airflow [-]

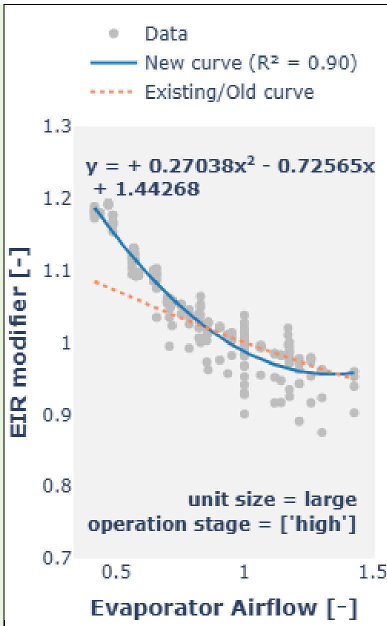
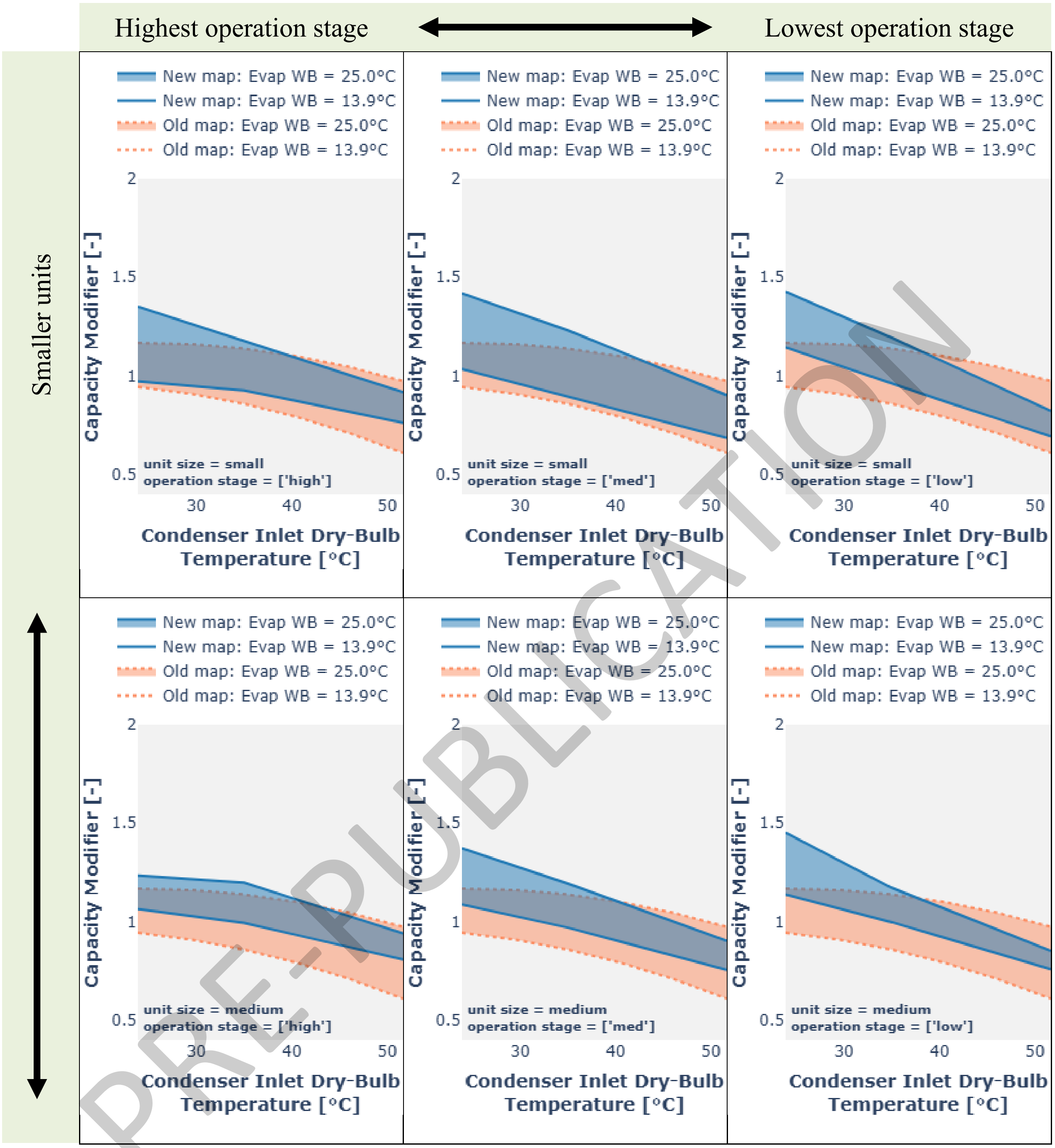
| | | | |
|---|---|---|---|
| Larger units |  | **No data available for curve development**<br><br>**Use curve on the left** | **No data available for curve development**<br><br>**Use curve on the left** |

**Figure 8. Performance curves used in the study: EIR modifier function of fraction of airflow**


Highest operation stage
Lowest operation stage
Smaller units
New map: Evap WB = 25.0°C
New map: Evap WB = 13.9°C
Old map: Evap WB = 25.0°C
Old map: Evap WB = 13.9°C
Capacity Modifier [-]
Condenser Inlet Dry-Bulb Temperature [°C]
unit size = small
operation stage = ['high']
unit size = small
operation stage = ['med']
unit size = small
operation stage = ['low']
unit size = medium
operation stage = ['high']
unit size = medium
operation stage = ['med']
unit size = medium
operation stage = ['low']

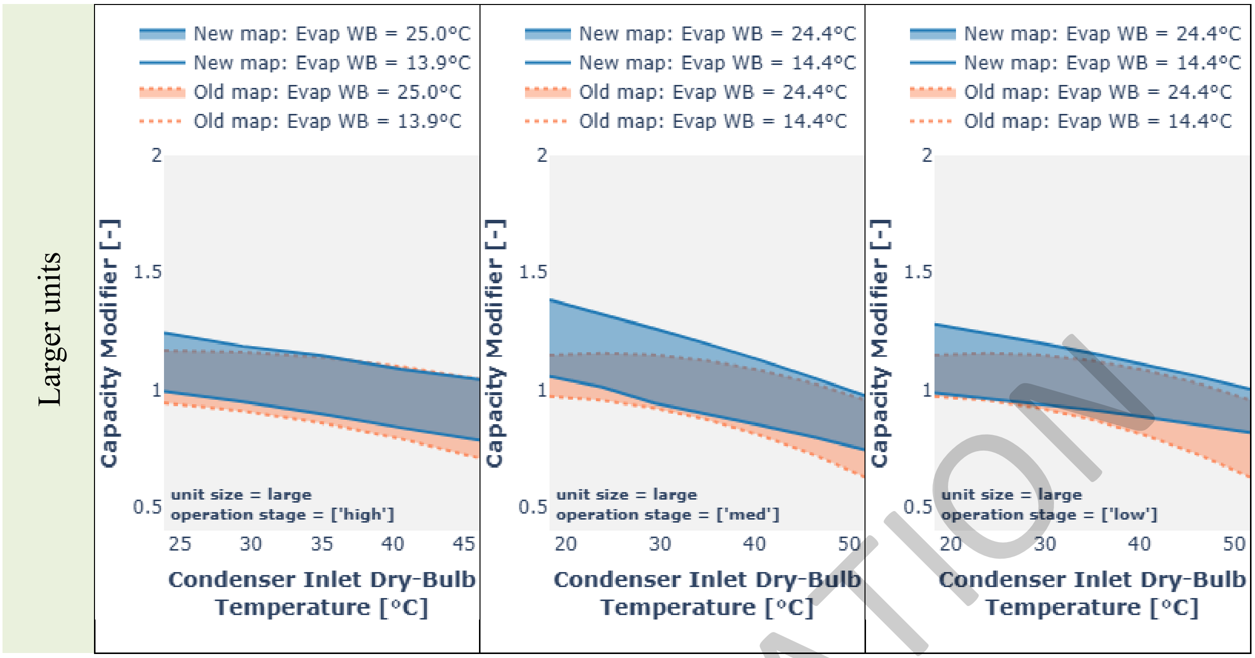
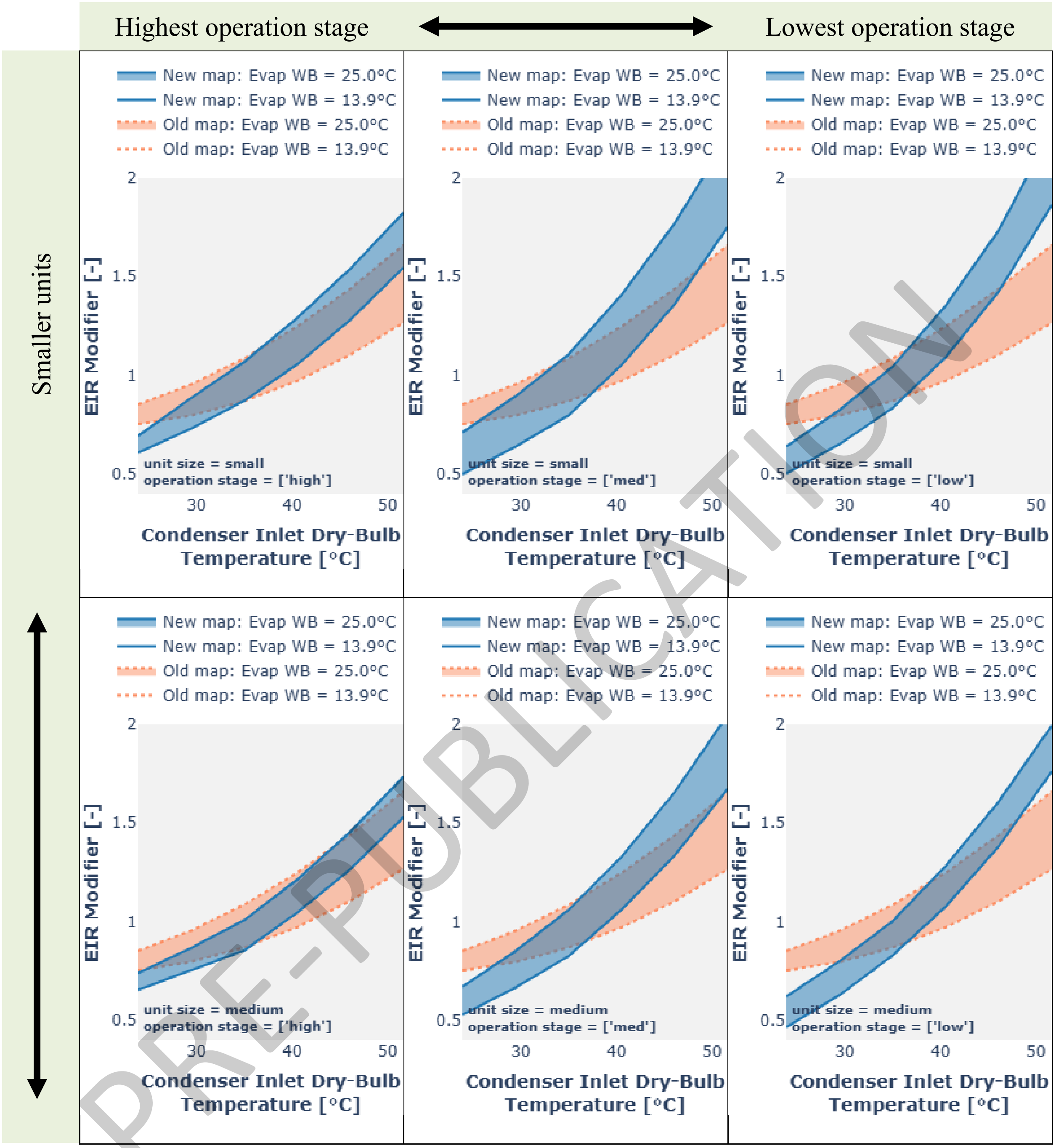



**Figure 9. Performance curves used in the study: capacity modifiers function of fraction of temperatures**



Highest operation stage
Lowest operation stage
Smaller units
New map: Evap WB = 25.0°C
New map: Evap WB = 13.9°C
Old map: Evap WB = 25.0°C
Old map: Evap WB = 13.9°C
EIR Modifier [-]
Condenser Inlet Dry-Bulb Temperature [°C]
unit size = small
operation stage = ['high']
operation stage = ['med']
operation stage = ['low']
unit size = medium

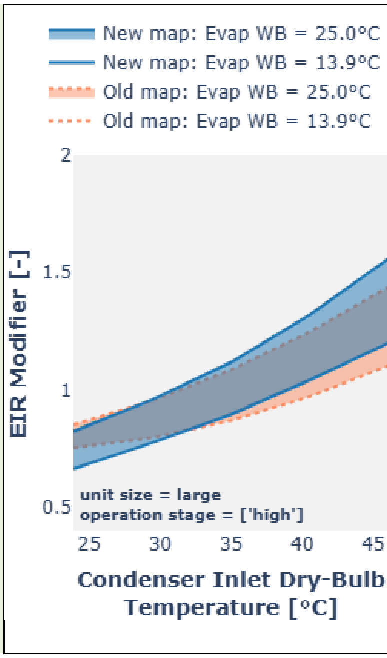
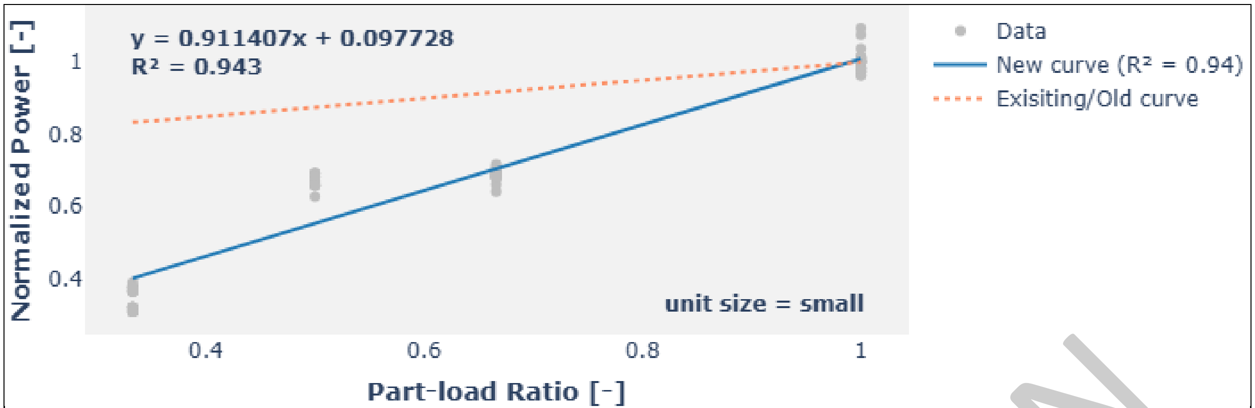
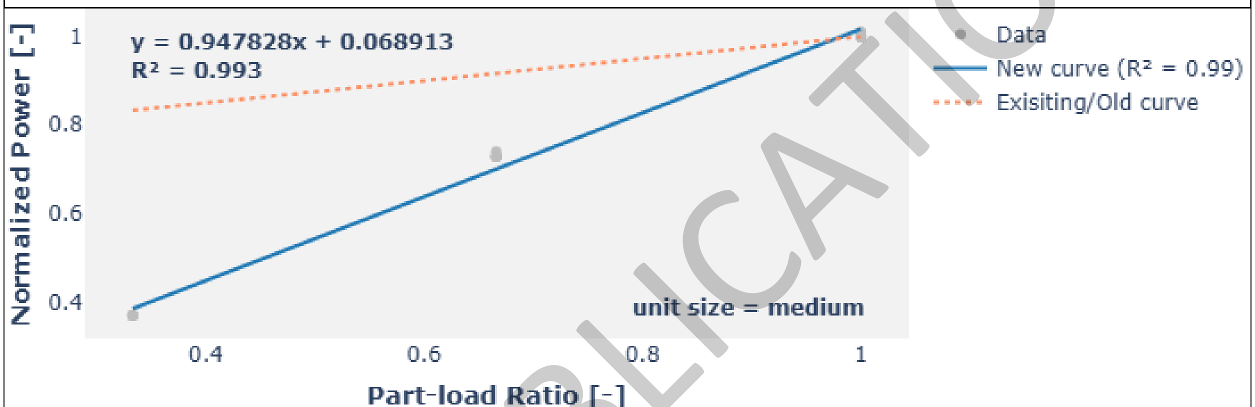
| | | | |
|---|---|---|---|
| Larger units |  | **No data available for lookup table development**<br><br>**Using map on the left** | **No data available for lookup table development**<br><br>**Using map on the left** |



**Figure 10. Performance curves used in the study: EIR modifiers function of fraction of temperatures**




(a) Small (rated capacity ≤ 135 kBtu/h) size units




(b) Medium (135 kBtu/h < rated capacity ≤ 240 kBtu/h) size units

**No data available for curve development.**

**Use the curve above.**

(c) Large (rated capacity > 240 kBtu/h) size units

**Figure 11. Performance curves used in the study: Power modifier function of part-load ratio**



### *3.2.2 Heating Performance Modeling*

The RTUs considered as upgrades in this study will use the same heating fuel that is already used in the existing building. Thus, if the building currently uses gas for space heating, the upgraded RTU will be equipped with a gas furnace (with typical ~80% efficiency). If the building uses electricity for space heating, the RTU will include electric resistance heating. Refer to the ComStock Reference Documentation for more details on how heating fuel is determined in the ComStock baseline [10].

## 3.3 Utility Bills

ComStock provides utility bill estimates for several fuel types in buildings: electricity, natural gas, propane, and fuel oil. The current implementation represents utility bills circa 2022, which is the most current year of utility data available from the U.S. Energy Information Administration (EIA). This section provides a high-level overview of the methodology behind utility bills in ComStock, but more detailed information is available in the ComStock Reference Documentation [10]. Summary statistics from this implementation are shown in Table 3. Note that ComStock does not currently estimate utility bills for district heating and cooling.

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

| Fuel Type | Minimum Price ($) | Average Price ($) | Maximum Price ($) |
|---|---|---|---|
| Natural gas | $0.007/kBtu ($0.70/therm) | $0.012/kBtu ($1.20/therm) | $0.048/kBtu ($4.80/therm) |
| Propane | $0.022/kBtu ($2.20/therm) | $0.032/kBtu ($3.20/therm) | $0.052/kBtu ($5.20/therm) |
| Fuel oil | $0.027/kBtu ($2.70/therm) | $0.033/kBtu ($3.30/therm) | $0.036/kBtu ($3.60/therm) |
| Electricity | $0.003/kBtu ($0.01/kWh) | $0.035/kBtu ($0.12/kWh) | $3.530/kBtu ($12.04/kWh) |

Natural gas bills are estimated using 2022 EIA averages by state. 2022 U.S. EIA Natural Gas Prices - Commercial Price and U.S. EIA Heat Content of Natural Gas Delivered to Consumers are used to create an energy price in units of $/kBtu [27].

Propane and fuel oil bills are estimated using 2022 EIA averages by state. Residential No. 2 Distillate Prices by Sales Type and U.S. EIA residential Weekly Heating Oil and Propane Prices (October - March) and EIA assumed heat content for these fuels are used to create an energy price in units of $/kBtu [28]. 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 [29]. The URDB rates include detailed cost features such as time-of-use pricing, demand charges, ratches, 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 [30]. While this method does not reflect the detailed rate structures and demand charges, it is a fallback for the 15% of buildings in ComStock with no utility assigned.

## 3.4 Limitations and Concerns

Comprehensive RTU performance maps, which are required for detailed energy modeling, are somewhat publicly available but not enough to reflect all manufacturers' products. RTU modeling is sensitive to performance assumptions given the strong dependency of both efficiency and capacity on outdoor air temperature (both dry-bulb and wet-bulb). 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 RTU operation and performance. These will notably impact results. Please consider these assumptions.

- Stock savings are sensitive to ComStock baseline assumptions. Refer to the ComStock Reference Documentation for details of how current/baseline RTUs are modeled in the ComStock baseline [10].
- After collecting performance maps for high-efficiency RTUs from three major manufacturers, we found that only one provided input power data (in kilowatts) across various operating conditions, including different indoor/outdoor air temperatures and airflow rates. Therefore, we made an engineering judgment to use only the performance maps from that manufacturer, as it offered sufficient detail to model both capacity and power variations. While the rated performance values reflect 2,847 products from 35 manufacturers, the normalized performance under variable conditions is based solely on the detailed information from this single manufacturer.
- When deriving SHR values for each stage based on manufacturer data, we found that these values initially did not correspond well with the results from EnergyPlus simulations. The mismatch appears to result from the SHR values in the data exceeding the bounds expected by EnergyPlus, which calculates SHR based on psychrometric relationships. This issue is likely due to inconsistencies in the assumed inlet air humidity conditions—the manufacturer's assumptions (which were not specified) differ from those applied within EnergyPlus. Due to frequent warnings triggered by the original SHR inputs (shown as "from data" in Table 1), which also slowed down simulation performance, we made an engineering judgment to uniformly lower the SHR values across all three stages (reflected under "actual simulation" in Table 1). This adjustment ensures the outlet air conditions remain physically valid (i.e., not exceeding 100% relative humidity) and is expected to have negligible impact on the accuracy of air property modeling.

# 4 Output Variables

Table 4 includes a list of output variables that are calculated in ComStock. These variables are important for understanding the differences between buildings with and without the upgrade 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 4. Output Variables Calculated From the Measure Application**

| Variable Name | Description |
| --- | --- |
| out.params.hvac_count_dx_cooling_0_to_30_kbtuh | Count of DX cooling equipment in size range |
| out.params.hvac_count_dx_cooling_135_to_240_kbtuh | Count of DX cooling equipment in size range |
| out.params.hvac_count_dx_cooling_240_to_760_kbtuh | Count of DX cooling equipment in size range |
| out.params.hvac_count_dx_cooling_30_to_65_kbtuh | Count of DX cooling equipment in size range |
| out.params.hvac_count_dx_cooling_65_to_135_kbtuh | Count of DX cooling equipment in size range |
| out.params.hvac_count_dx_cooling_760_plus_kbtuh | Count of DX cooling equipment in size range |
| out.params.dx_cooling_average_cop | DX cooling COP during operation averaged across all cooling coils |
| out.params.dx_cooling_capacity_tons | Sum of DX cooling capacity |
| out.params.dx_cooling_design_cop | DX cooling COP at rated conditions averaged across all cooling coils |
| out.params.dx_cooling_design_eer_135_to_240_kbtuh | Design EER of DX cooling coils for 135–240 kBtu/h equipment |
| out.params.dx_cooling_design_eer_240_to_760_kbtuh | Design EER of DX cooling coils for 240–760 kBtu/h equipment |
| out.params.dx_cooling_design_eer_65_to_135_kbtuh | Design EER of DX cooling coils for 65–135 kBtu/h equipment |
| out.params.dx_cooling_design_eer_760_plus_kbtuh | Design EER of DX cooling coils for 760+ kBtu/h equipment |
| out.params.dx_cooling_design_ieer_135_to_240_kbtuh | Design IEER of DX cooling coils for 135–240 kBtu/h equipment |
| out.params.dx_cooling_design_ieer_240_to_760_kbtuh | Design IEER of DX cooling coils for 240–760 kBtu/h equipment |
| out.params.dx_cooling_design_ieer_65_to_135_kbtuh | Design IEER of DX cooling coils for 65–135 kBtu/h equipment |
| out.params.dx_cooling_design_ieer_760_plus_kbtuh | Design IEER of DX cooling coils for 760+ kBtu/h equipment |

| Variable Name | Description |
|---|---|
| out.params.dx_cooling_design_seer_0_to_30_kbtuh | Design seasonal EER of DX cooling coils for 0–30 kBtu/h equipment |
| out.params.dx_cooling_design_seer_30_to_65_kbtuh | Design seasonal EER of DX cooling coils for 30–65 kBtu/h equipment |
| out.params.dx_cooling_electric | Total DX cooling equipment electric use |
| out.params.dx_cooling_load | Total DX cooling equipment cooling load served |

# 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 analyze the performance of a small office building model in St. Louis, Missouri (climate zone 4A) to demonstrate the application of the measure scenario to a single building. Figure 12 illustrates the impact of the upgrade by comparing the baseline and upgrade models, using hourly data for operating/cooling COP and runtime fraction throughout the year in relation to outdoor air temperature. The baseline RTU is equipped with a single-speed DX system with a rated cooling COP of 3.0 and a constant air volume fan. In contrast, the upgraded model features a variable-speed DX system with a higher rated cooling COP of 4.4 and a single-zone variable air volume fan.

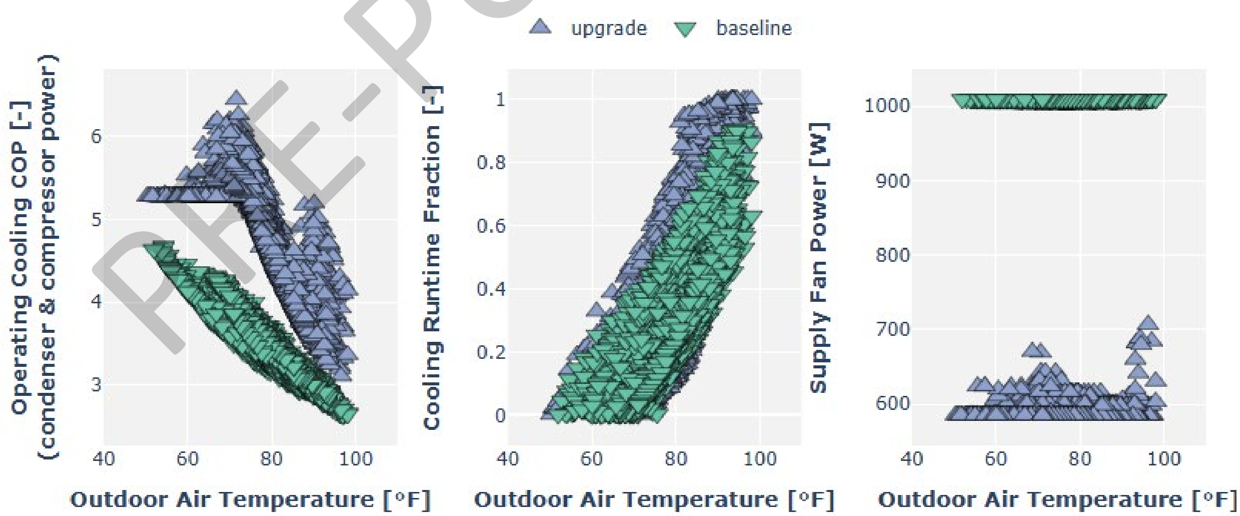



**Figure 12. Single-building model example with upgrade measure**

As shown in Figure 12, the baseline single-speed DX unit shows limited improvement in operating COP as outdoor temperatures decrease, indicating it benefits less from colder air than the upgraded system. In contrast, the upgraded unit maintains higher COPs across the full range of outdoor temperatures, including the rated condition of 95°F. The performance gap between the two systems widens at lower outdoor air temperatures.

This improvement is driven by several factors: (1) higher rated COP, (2) better efficiency at lower speeds, (3) better performance across operating temperatures, and (4) improved part-load performance. Collectively, these advantages enable the upgraded RTU to operate more efficiently than the baseline model. As indicated in Figure 9 and Figure 10, the performance maps employed in this study are limited to outdoor air dry-bulb temperatures of 75°F (23.9°C). This limitation accounts for the plateau observed in the operating cooling COP below that temperature in Figure 12. The second graph in Figure 12 also shows that cooling runtime fractions are much smaller below 75°F, minimizing the influence of this plateau.

Figure 12 also compares the runtime fractions between the baseline and upgrade scenarios. The runtime fraction (also known as the duty factor) represents the proportion of time the cooling coil (or the compressor and condenser fan) is actively operating relative to the total time it is available to run for a given time period. It is based on the part-load ratio, defined as the ratio of the cooling load (part-load capacity) to the coil's full or steady-state capacity. As expected for a single-speed DX unit compared to a variable-speed system, the baseline unit shows lower runtime fractions across the temperature range, indicating more frequent short cycling and less continuous operation. In contrast, the variable-capacity systems operate more continuously at lower compressor speeds, reducing cycling losses associated with short run times.

The RTU upgrade also delivers fan energy savings by incorporating a variable-speed supply fan. As shown in Figure 12, the constant-speed fan used in the baseline system operates at a fixed speed whenever it is on, providing steady airflow regardless of the actual heating or cooling demand. In contrast, the upgraded system includes multiple fan power levels, allowing it to reduce speed—and therefore power consumption—during periods of lower load. While the constant-speed fan is simpler to control and generally less expensive up front, it is less efficient under part-load conditions because it consumes the same amount of energy even when full airflow is unnecessary. The variable-speed fan, on the other hand, adjusts airflow to match the required load, improving energy efficiency, enhancing occupant comfort through more consistent temperature and humidity control, and reducing system wear caused by frequent cycling.

Table 5 summarizes the modeled annual electricity use and operating performance for the baseline and upgraded RTU systems (heating is served with an electric resistance coil in this example). Overall, the upgrade scenario achieves an 11.4% reduction in total electricity consumption, primarily driven by savings in cooling (43.8%) and fan energy (24.9%). These improvements reflect the combined benefits of a higher-efficiency variable-speed DX system and a variable-speed supply fan, which reduces energy use by modulating airflow to match real-time cooling demand. Despite these overall savings, heating energy usage increased slightly by 1.9%. This is attributed to the improved fan efficiency in the upgraded system: Unlike the baseline's constant-speed fan, which adds more waste heat to the airstream during operation, the variable-speed fan introduces less incidental heat. As a result, the system must compensate with additional mechanical heating to meet space heating loads. The upgrade also yields a notable improvement in annual cooling system performance, with the average operating COP (including compressor and condenser fan power only) increasing from 3.5 to 4.8 (a 37.1% improvement), along with gains in minimum and maximum COP across the cooling season. The higher standard deviation of COP observed in the upgraded system reflects its broader range of efficient part-load operation, enabled by variable-speed modulation.

**Table 5. Annual Summary of Baseline vs. Upgrade Measure Scenarios**

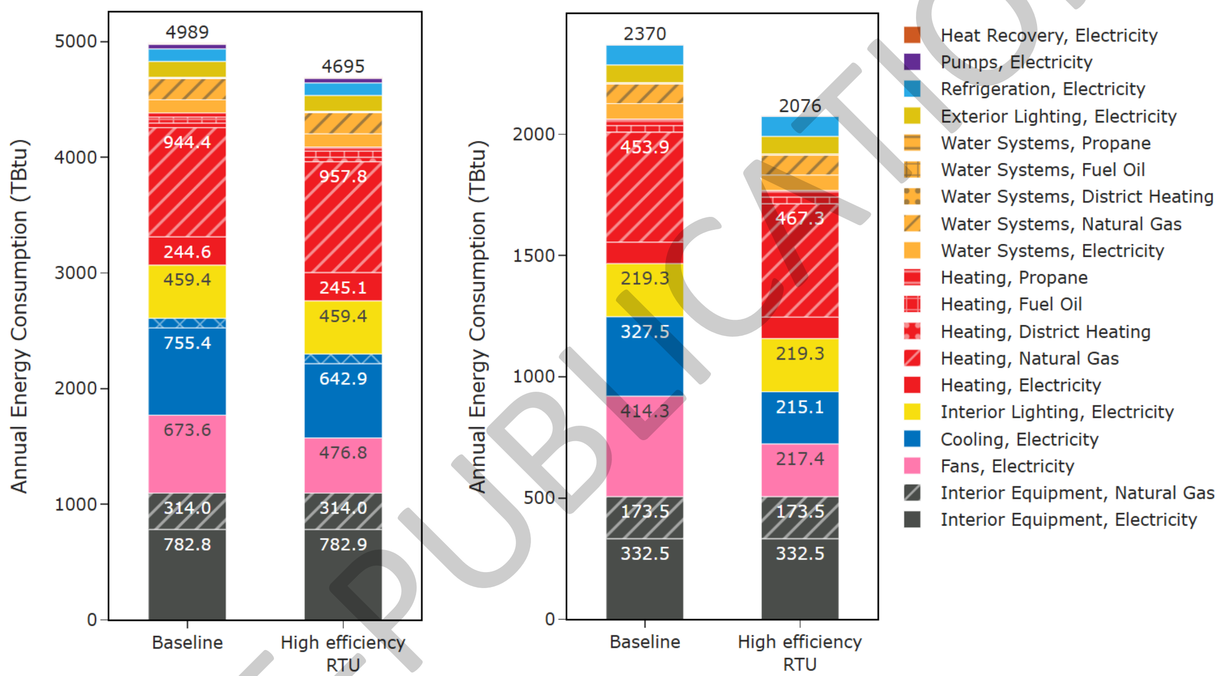
| | | Baseline | Upgrade | Improvement |
|---|---|---|---|---|
| Electricity Usage [GJ] | Heating | 43.15 | 43.95 | -1.9% |
| | Cooling | 19.43 | 10.92 | 43.8% |
| | Interior Lighting | 3.58 | 3.58 | 0.0% |
| | Exterior Lighting | 10.62 | 10.62 | 0.0% |
| | Interior Equipment | 24.87 | 24.87 | 0.0% |
| | Fans | 31.82 | 23.9 | 24.9% |
| | Water Systems | 3.54 | 3.54 | 0.0% |
| | Total | 137.01 | 121.38 | 11.4% |
| Annual Operating COP | Average | 3.5 | 4.8 | 37.1% |
| | Minimum | 2.6 | 3.1 | 19.2% |
| | Maximum | 4.7 | 6.4 | 36.2% |
| | Standard deviation | 0.37 | 0.63 | 70.3% |

## 5.2 Stock Energy Impacts

Table 6 and Figure 13 show the comparison of annual site energy consumption between the baseline and upgrade scenarios for the entire building stock and buildings that are only applicable to the upgrade, respectively. The high-efficiency RTU upgrade measure results in a 6% reduction in total site energy consumption—equivalent to 295 TBtu—across the U.S. commercial building stock modeled in ComStock, including buildings not applicable to the upgrade scenario (the measure is only applicable to buildings with existing RTUs). The majority of these savings are driven by a 29% reduction in fan electricity use (197 TBtu) and a 15% reduction in cooling electricity use (112 TBtu), partially offset by a 1.4% increase in heating natural gas use (-13 TBtu). As discussed in Section 5.1, this trend reflects the improved efficiency of variable-speed RTUs, which reduce electricity demand for fans and cooling. However, the reduced waste heat from more efficient fan operation leads to a slight increase in heating requirements, contributing to the observed rise in natural gas consumption.

**Table 6. Summary of Site Energy Savings From Upgrade Measure Application vs. the ComStock Baseline**

| End Use/Fuel Type | Percent Site Energy Savings (All Buildings) | Percent Site Energy Savings (Applicable Buildings Only) | Absolute Site Energy Savings (TBtu) |
|---|---|---|---|
| Total natural gas | -0.93% | -1.9% | -13.4 |
| Total electricity | 9.3% | 19.3% | 309 |
| Electric fans | 29.2% | 47.5% | 197 |
| Electric cooling | 14.9% | 34.3% | 112 |
| Natural gas heating | -1.4% | -3% | -13.4 |



(a) Entire building stock (b) Applicable models only

**Figure 13. Comparison of annual site energy consumption between the ComStock baseline and the upgrade measure scenario.**

Energy consumption is categorized both by fuel type and end use. (a) The entire building stock modeled in ComStock; (b) only models applicable to the upgrade measure.



## 5.3 Stock Utility Bill Impacts

This section includes a comparison of annual utility bills for buildings using different energy sources (i.e., electricity, natural gas, propane, fuel oil) and for the entire building stock. Because we apply many electricity utility rate structures that are available for a building located in a certain geographical location, our data include many annual utility bills per building model.

Table 7 compares utility bill savings between the baseline and upgrade (high-efficiency RTU) measure scenarios. For detailed information regarding utility rate implementation, refer to the ComStock Reference Documentation [10]. Site energy savings and utility bill savings do not necessarily align due to cost differences between fuel types as well as primary energy conversion factor differences. Figure 13 shows aggregated "site" energy consumption, which does not reflect the "primary" energy perspectives. Thus, the annual aggregated cost comparisons, shown in Table 7, can also tell us the primary energy consumption comparisons between different scenarios.

**Table 7. Summary of Key Results for Annual Utility Bill Savings**

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. "Applicable" buildings are those that receive the upgrade based on criteria defined for this study.

| End Use/Fuel Type | Percent Savings (All Buildings) | Percent Savings (Applicable Buildings Only) | Absolute Savings (million USD, 2022) |
|---|---|---|---|
| Electricity | 9.2% | 19.1% | 10.2 |
| Natural gas | -0.68% | -1.4% | -0.11 |
| Fuel oil | -1.3% | -2.6% | -0.024 |
| Propane | -0.25% | -0.33% | -0.0031 |
| **Total** | **7.8%** | **16%** | **10.1** |

As shown in Table 7, across the entire commercial building stock, the upgrade yields an 8% reduction in total utility costs, resulting in an annual savings of approximately $10.1 million per year. This is primarily driven by a 9% reduction in electricity costs, equating to $10.2 million in savings. These electricity savings are partially offset by modest increases in costs for other fuel types, including natural gas (+$0.11 million), fuel oil (+$0.024 million), and propane (+$0.003 million), reflecting the slight increase in heating energy use discussed previously. When isolating only the buildings applicable to the upgrade, the total utility cost savings increase to 16%, highlighting the greater economic benefit in targeted deployment scenarios.

Figure 14 illustrates the percentage of utility bill savings across different climate zones, considering only the models applicable to the high-efficiency RTU upgrade. As expected, the upgrade—which primarily improves cooling and fan performance—delivers greater cost savings in hotter climates, such as climate zone 1A. In this climate, the interquartile range of savings spans approximately 10% to 30%. In contrast, colder climates like climate zone 8 exhibit more modest savings, with an interquartile range of approximately 0% to 7%. These results reflect the greater cooling demand—and thus higher potential for energy and cost reductions—in warmer regions.

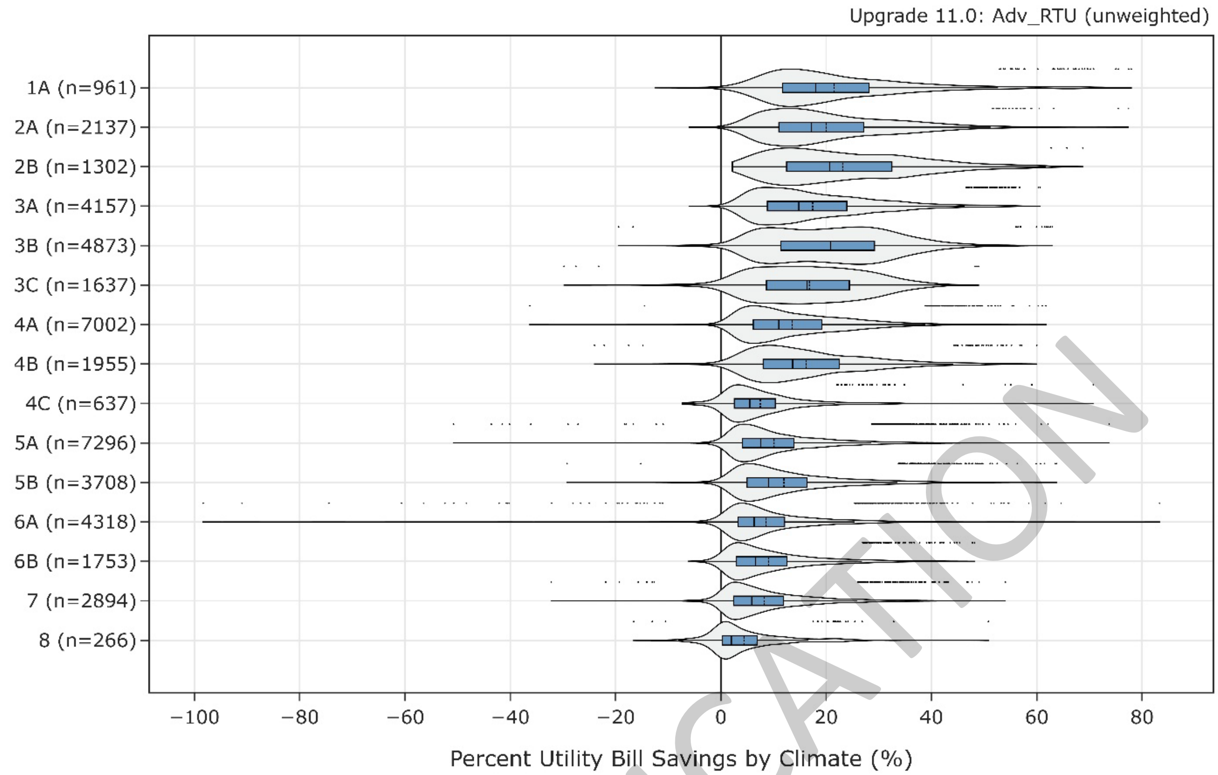



**Figure 14. Percentage annual utility bill savings distribution for ComStock models with the upgrade measure scenario by climate zone.**

Results shown in this plot are the savings for the average available utility rate per building. 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 unweighted ComStock models that were applicable for energy savings for the fuel type category.



## 5.4 Site Energy Savings Distributions

This section discusses site energy consumption for quality assurance/quality control purposes. Site energy savings can be useful for these (and possibly other) purposes, but additional factors should be considered when drawing conclusions, as site energy savings do not necessarily translate proportionally to source energy savings or energy costs, which vary widely across the United States. Savings shown in this section are based on comparisons between the baseline and the high-efficiency RTU upgrade.

Figure 15 to Figure 17 show distributions of the applicable baseline ComStock models versus the upgrade scenario for percentage site energy or site energy use intensity savings with different climate zones, fuel types, or end uses. Percentage savings provide relative impact of the measure at the individual building level, whereas site energy use intensity savings provide an absolute (or aggregated) scale of impact. The data points that appear above some of the distributions indicate outliers in the distribution, meaning they fall outside 1.5 times the interquartile range. The value for *n* indicates the number of ComStock models that were applicable for energy savings for the fuel type category. It should also be noted that these pairwise comparisons represented with distributions only calculate percentage savings for buildings where the baseline included some prevalence of end use/fuel type. Thus, the electric heating savings only shows buildings that originally used some amount of electric heating and does not represent buildings where natural gas was the only heating fuel.

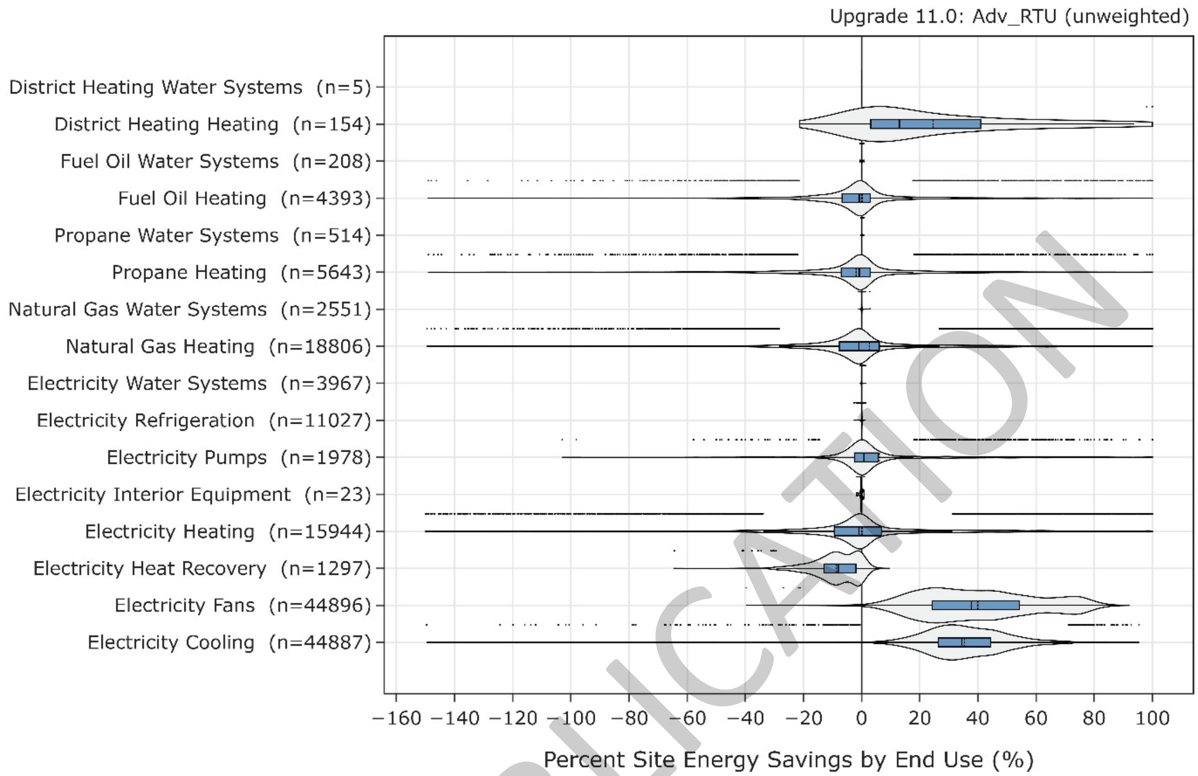



**Figure 15. Percentage site energy savings distribution for ComStock models with applied measure scenario by end use and fuel type.**

The data points that appear above some of the distributions indicate outliers in the distribution, meaning they 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.

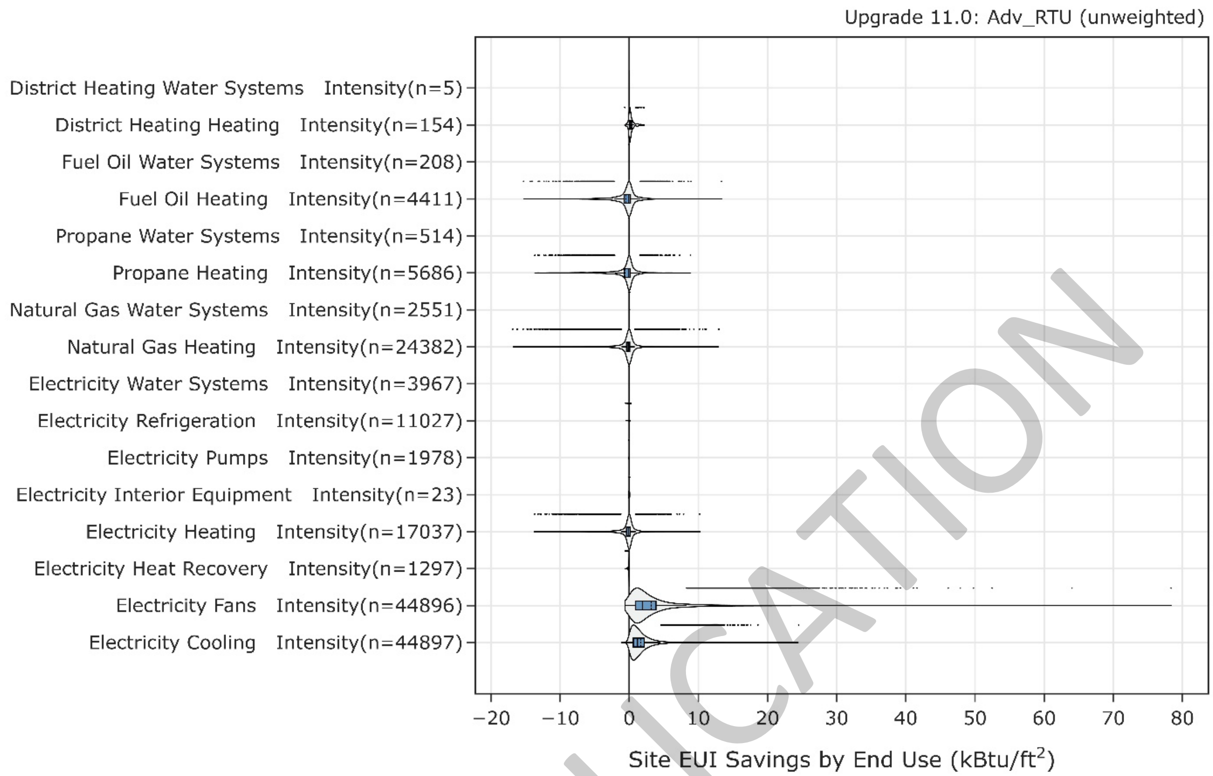



**Figure 16. Percentage site energy use intensity savings distribution for ComStock models with the applied measure scenario by end use and fuel type.**

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

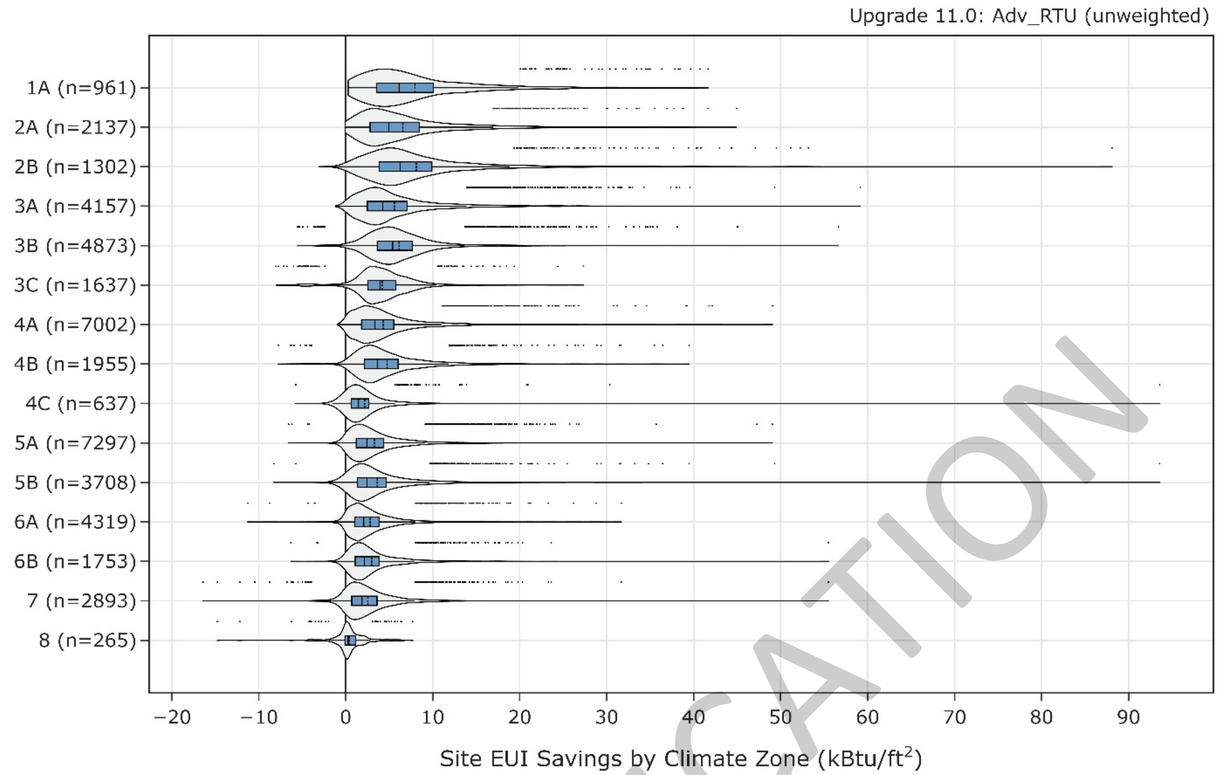



**Figure 17. Percentage site energy use intensity savings distribution for ComStock models with the applied measure scenario by climate zone.**

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



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

- Positive electricity fan savings (Figure 15 and Figure 16):
  - The primary savings come from replacing older RTU fans with newer and more efficient models (higher rated efficiencies and part-load efficiencies with variable-speed fans).
  - This upgrade accounts for the largest share of total site energy savings.
- Positive electricity cooling savings (Figure 15 and Figure 16):
  - The second largest savings also results from replacing outdated RTUs with higher-efficiency units (higher rated and part-load efficiencies and less cycling losses with variable-speed compressors).
- Negative savings in space heating:
  - Heating-related savings (e.g., natural gas heating) show mostly negative values within the interquartile ranges (Figure 15). The variable-speed fan introduces less incidental heat. As a result, the system must compensate with additional mechanical heating to meet space heating loads.

- However, in absolute terms (as shown by site energy use intensity), these losses are outweighed by fan and cooling savings (Figure 16).
- Impacts on climate zones (Figure 17):
    - Hotter climates, where cooling demand is higher, realize greater savings from high-efficiency RTU upgrades than colder climates.

## 5.5 Other Findings

This section presents additional, more detailed findings specific to the high-efficiency RTU measure that were not covered in the preceding sections. Figure 18 highlights the details of improved variable-speed fan operation in the RTU upgrade by comparing fan efficiencies and minimum flow fractions between the baseline and upgrade scenarios for applicable models only. As illustrated in Figure 18, the use of more efficient fans combined with variable-speed drives capable of modulating down to 40% of rated flow—compared to constant-speed fans in the baseline—results in a noticeable reduction in fan electricity consumption.

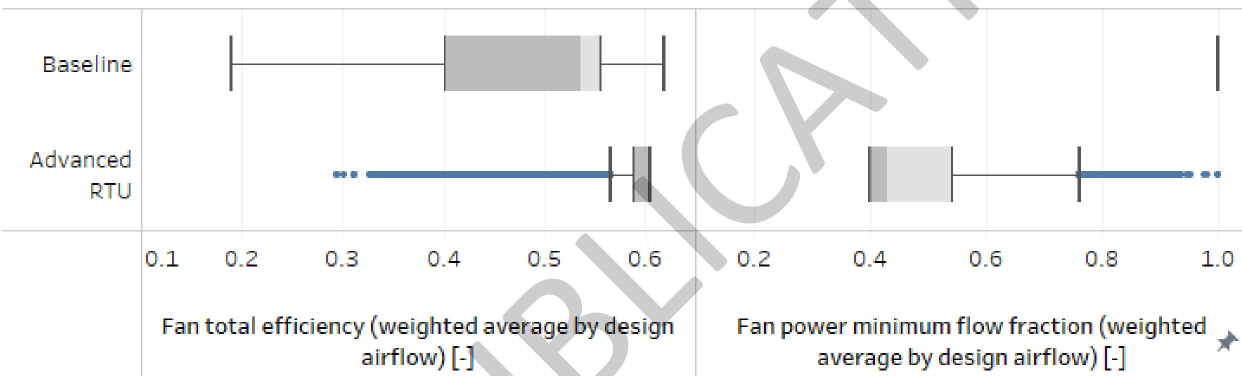



**Figure 18. Distribution of fan efficiency and minimum flow fraction between the baseline (left) and high-efficiency RTU (right) scenarios for applicable models only**

Figure 19 compares DX unit performance between the baseline and upgrade scenarios for applicable models only, highlighting both rated COPs and annual average operating COPs. The median rated COP increases from 3 in the baseline to 4 in the upgrade scenario, representing a 34% improvement. More notably, the median annual average operating COP—which reflects real-world, part-load operation—improves from 3.7 to 5.2, yielding a 42% increase in overall cooling efficiency. Annual average operating COPs are higher than rated COPs because cooling systems rarely operate at full load. Most hours occur under milder conditions where compressors and fans run more efficiently at part load, leading to higher effective COPs throughout the year.

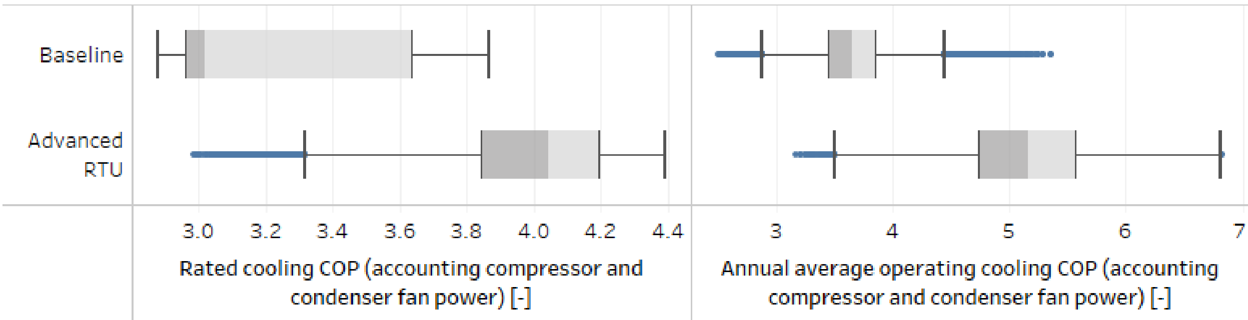



**Figure 19. Distribution of rated and operating COPs between the baseline (left) and high-efficiency RTU (right) scenarios for applicable models only**

To highlight geographical variations in the performance of DX units, Figure 20 presents the annual average operating COP for the median building in both the baseline and upgrade scenarios, focusing on applicable models only. The 42% overall operating COP improvement at the stock level, as shown in Figure 19, is now broken down by state to reflect the impact of different climates. In terms of operating performance, hotter regions such as Nevada, Arizona, and Texas experience COP improvements ranging from 36% to 38%, while colder regions like Minnesota see a 45% improvement. However, due to the significantly higher cooling demand in hotter states, the absolute energy savings are greater in those regions.

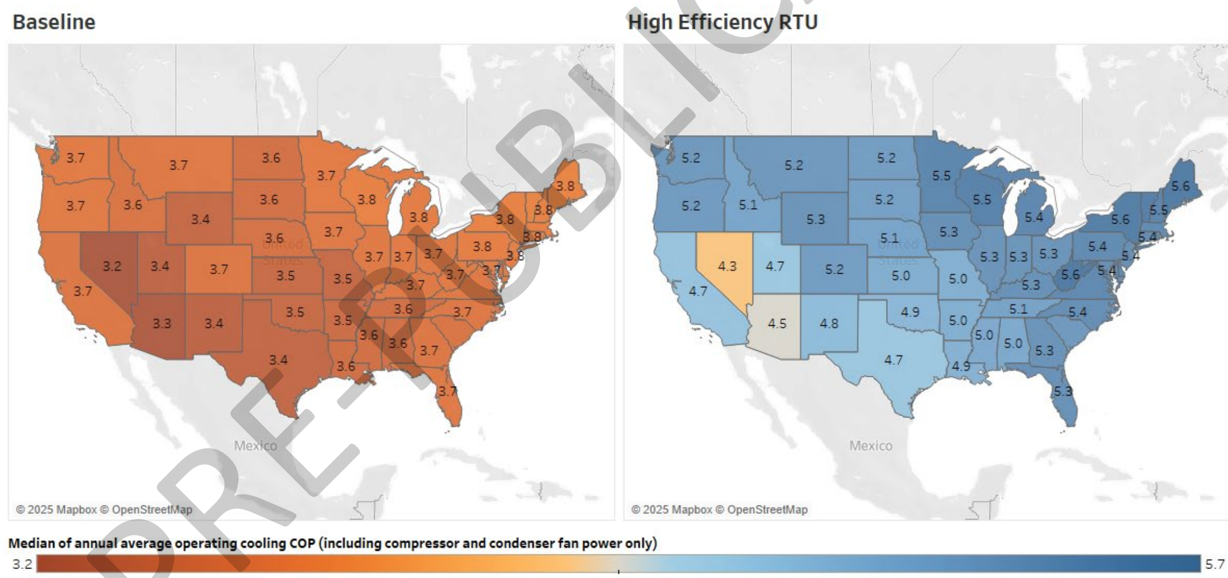



**Figure 20. Annual average operating cooling COP for the median building between the baseline (left) and high-efficiency RTU (right) scenarios for applicable models only**

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# Appendix A.

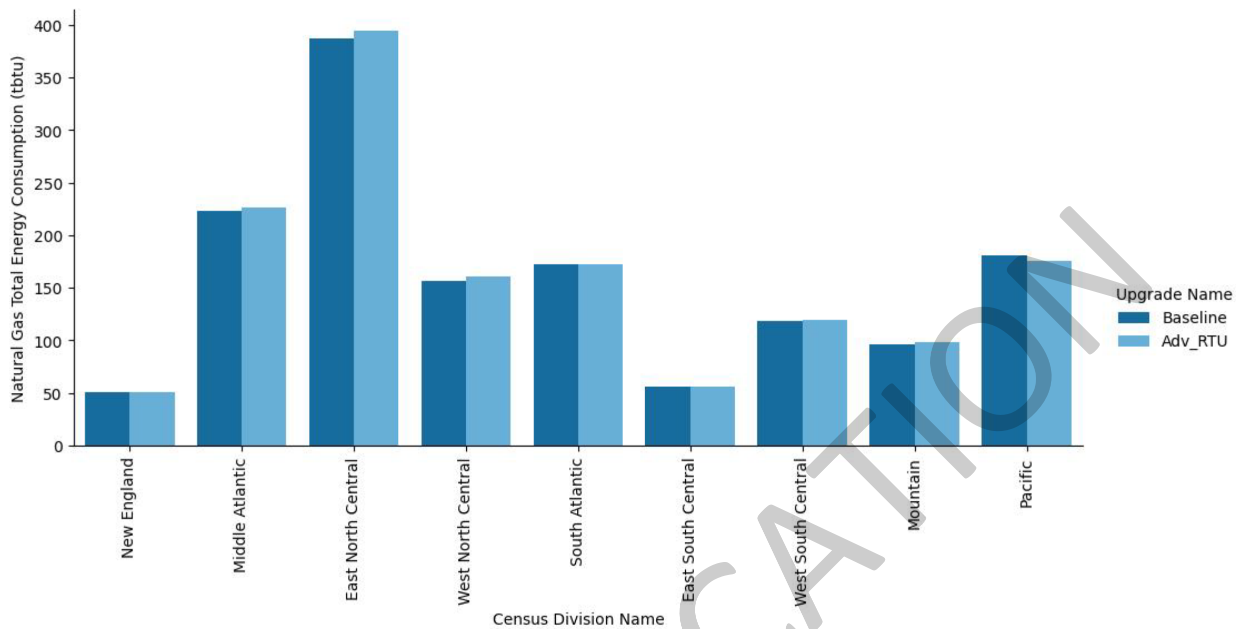


**Figure A-1. Site annual natural gas consumption of the ComStock baseline and the measure scenario by census division**

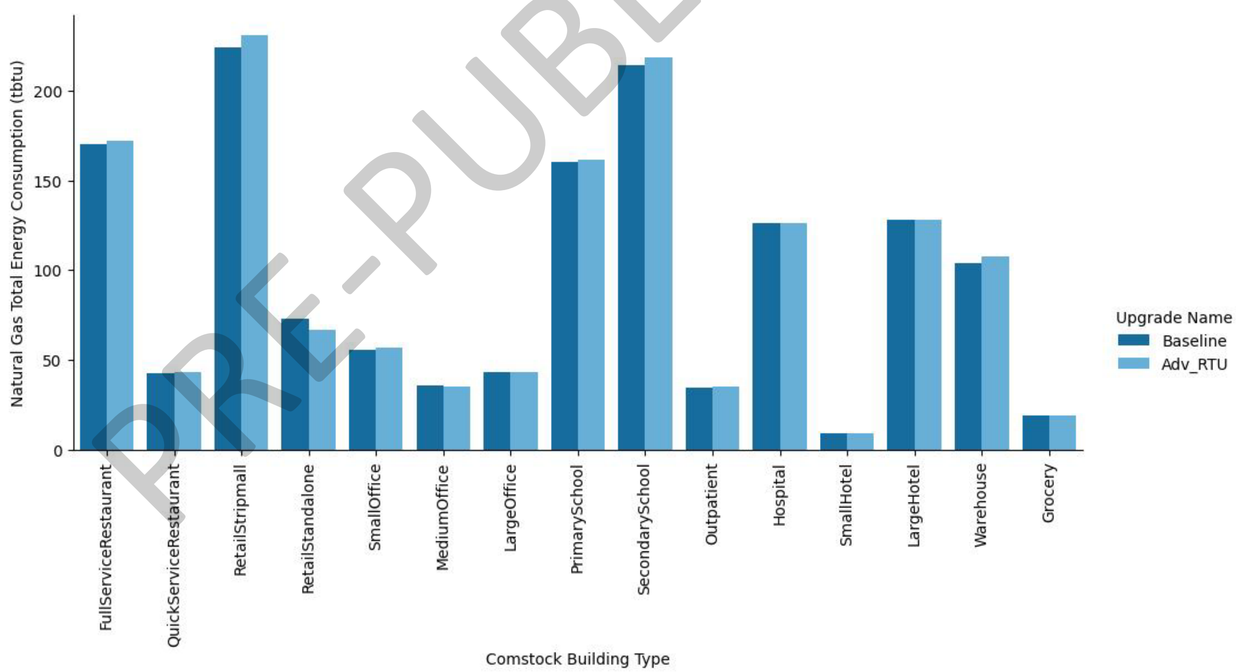


**Figure A-2. Site annual natural gas consumption of the ComStock baseline and the measure scenario by building type**

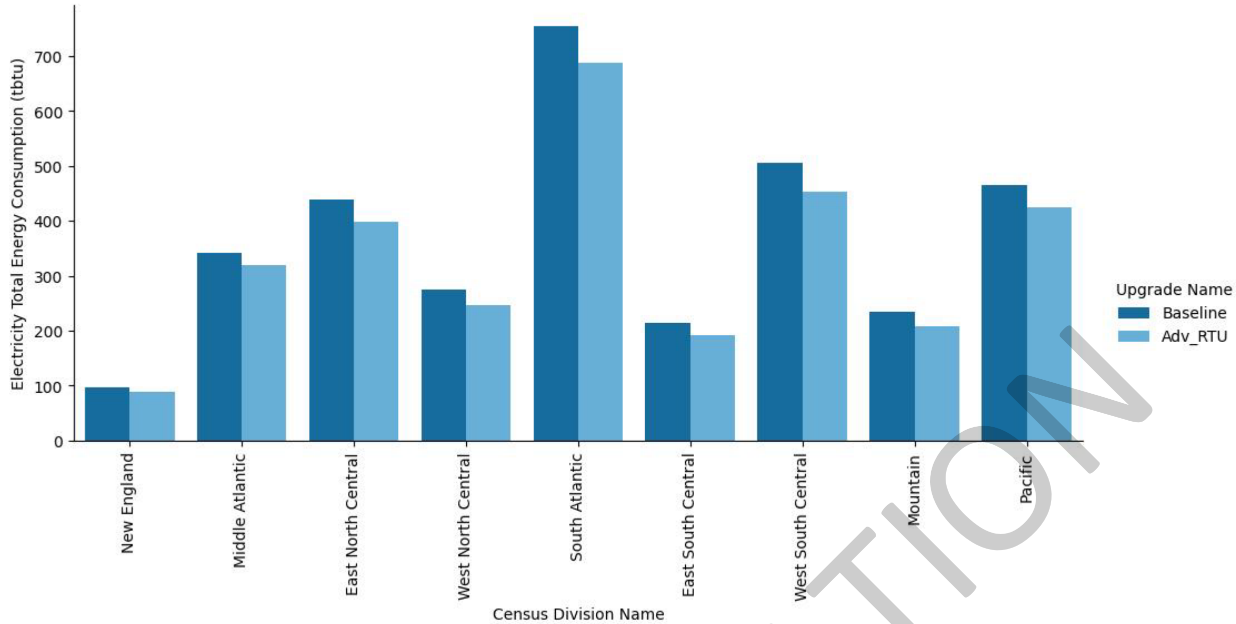


**Figure A-3. Site annual electricity consumption of the ComStock baseline and the measure scenario by census division**

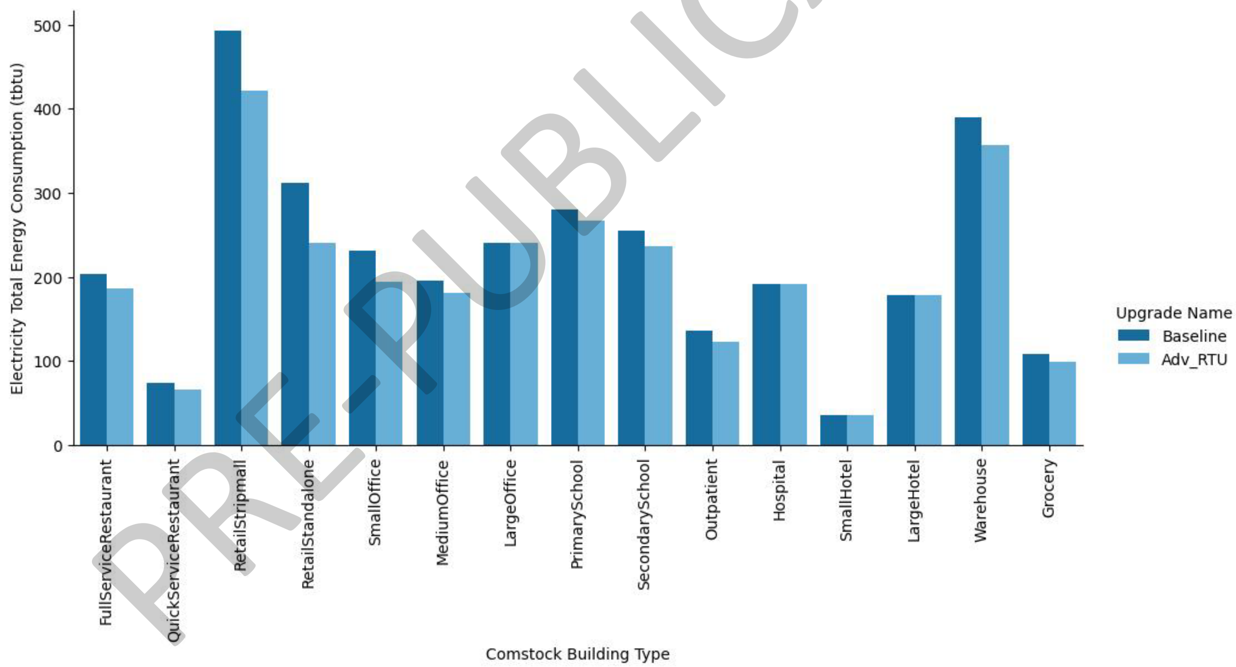


**Figure A-4. Site annual electricity consumption of the ComStock baseline and the measure scenario by building type**