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National Efficient Rooftop Unit Energy Modeling

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Executive Summary

This study presents a comprehensive analysis of commercial HVAC efficiency measures for various types of commercial rooftop unit (RTU) equipment and their energy savings potential across different climate zones to support development of RTU initiatives. The Northwest Energy Efficiency Alliance (NEEA) and the Center for Energy and Environment (CEE) contracted with Resource Innovations and A2 Efficiency to conduct this analysis. A project committee – comprising NEEA, CEE, Resource Innovations, A2 Efficiency and Nicor Gas (Nicor) – was formed to define the research scope and modeling methodology. The research assesses key measures individually and in combination, highlighting their implications for program development, market transformation, and influencing codes and standards. This study also provides actionable insights to further the research. By focusing on measures' combined impacts and addressing regulatory gaps, stakeholders can drive significant advancements in HVAC efficiency, leading to substantial energy and cost savings nationwide.

This study investigated the energy savings potential of commercial HVAC efficiency measures for various types of RTU equipment nationally. This study did not investigate energy pricing, cost savings, or carbon savings.

The analysis builds directly on the methodology NEEA and Nicor employed in two previous RTU energy modeling studies: one with similar measures, simulated predominantly in the Pacific Northwest;[1] and one to support the CSA P.8 test procedure development.[2] The Resource Innovations team worked with NEEA, Nicor, and CEE to select the following:

- Seven building types representing the most common applications of packaged RTUs.
- Eleven locations representing climate diversity for most of the population in the United States.
- Four RTU HVAC types representing the most common gas and electric RTU technologies available.
- Fifteen different energy-efficiency measures or combinations of measures.

Summaries follow of the study's high-level **Key Findings** and **Recommendations**.

[1] NEEA, "Energy Savings from Efficient Rooftop Units in Heating Dominated Climates," Cadeo Group, April 2022, https://neea.org/resources/energy-savings-from-efficient-rooftop-units-in-heating-dominated-climates
[2] NEEA, "Energy Modeling of Commercial Gas Rooftop Units in Support of CSA P.8 Standard," Cadeo Group, May 2020, https://neea.org/resources/energy-modeling-of-commercial-gas-rooftop-units-insupport-of-csa-p-8-standard

Key Findings

- **Energy savings vary by climate.** The effectiveness of HVAC efficiency measures differs significantly by climate zone. National average energy savings estimates provide useful insights, but they may mask regional differences.
- **In gas RTUs, heating consumption makes up a significant portion of the HVAC load, even in warm climates.** Even if units are cooling-dominated from a building load perspective, high heating consumption results from gas furnaces operating much less efficiently than cooling systems. Heating consumption is reduced in heat pump RTUs, but remains dominant in most climates. Heating energy should be considered the biggest opportunity for energy savings through RTUs.
- **Combined measure packages have very minor interactive effects in relation to energy savings potential.** Each individual measure will face its own challenges in installation or implementation, and should be considered individually, given short-term goals, long-term goals, and costs.
- **For gas RTUs, the addition of Energy Recovery Ventilation (ERV) – and therefore NEEA's Tier 2 measure – offers high energy savings potential.** ERVs have an HVAC energy savings potential of 6%-27% for gas RTUs, with potential savings up to 32% when accounting for increased ventilation. Lower ERV measure savings occur when installed in all-electric or dual-fuel heat pump RTUs.
- **The largest energy savings potential comes from replacing gas RTUs with standard heat pumps, dual-fuel heat pumps, or Cold Climate Heat Pumps (CCHP).** Depending on the climate zone and backup fuel type, converting a pre-existing gas RTU to a standard-practice heat pump RTU or CCHP can save 13%-59% of total HVAC energy usage. Total HVAC energy savings can reach even higher – up to 68% when incorporating NEEA Tier 1 and NEEA Tier 2 measure packages. Dual-fuel heat pumps can save a similar amount of energy with a less expensive backup source and without requiring electrical upgrades.
- **The Low Switchover Temperature and CCHP measures offer high energy savings potential in very cold climates.** Installing controls that allow the heat pump to condition at low temperatures serves as a low-cost upgrade. It is important, however, to note the additional cost in operating heat pump systems where heat pump loads replace gas backup heating. Moreover, installing a heat pump with CCHP performance introduces additional costs.
- **Nationally, the Efficient Cooling measure has the lowest total HVAC average energy savings percent.** While the Efficient Cooling measure offers substantial energy savings potential in hot climates, very little energy savings potential exists in mild and cold climates. When weighting results to create national savings estimates,

average HVAC potential savings are the lowest among all measures, ranging from 2%-3% of total HVAC energy savings.

- **Enclosure Insulation and Low-Leakage Dampers measures offer moderate energy savings potential individually, but packaged together (NEEA Tier 1) these measures offer more substantial energy savings for all HVAC types.** Depending on the climate zone and HVAC type, average HVAC potential energy savings for Enclosure Insulation and Low-Leakage Dampers range from 0%-8%. When these measures are combined through the NEEA Tier 1 measure package, the energy savings potential increases, ranging from 2%-14% of total average HVAC savings.
- **The Enclosure Leakage measure, which has never been previously modeled, could be used to inform future RTU specifications.** When weighting results to create national energy savings estimates, Enclosure Leakage offers considerable energy savings potential – similar to other enclosure measures such as Enclosure Insulation and Low-Leakage Dampers – ranging from 1%-8% of total HVAC energy use on average.

Recommendations

- **NEEA can use information from this research effort to support codes and standards efforts.** Currently, several measures demonstrating significant savings potential are neither valued by RTU test procedures nor federal regulations, and they are not required by code. This report's findings can be used to demonstrate the value of these features and to highlight gaps in coverage by codes and standards.
- **Prioritize heating performance in RTU program specifications.** Cooling efficiency may have reached a point of diminishing returns for all but the hottest climates, while features that reduce heating consumption (e.g., ERVs, controls) offer a substantial opportunity for energy savings. RTU specifications and programs should not only focus on heating *ratings* (e.g., furnace efficiency such as AFUE) but also on heating performance holistically, which could mean combining multiple energy-saving measures.
- **Consider combining multiple measures into a package to maximize savings.** Promote efficiency programs that support combinations of measures rather than focusing solely on individual upgrades to maximize energy savings. Programs should also consider installation barriers for each measure as well. For example, low-leak dampers provide a low-cost and easy-to-install upgrade, while ERVs remain expensive, heavy, and can be difficult to install.
- **Analyze existing simulation data for operating mode information.** Conduct an operating mode analysis of existing simulation results to gather detailed information

of RTU operation behaviors that can be used for codes and standards recommendations.

- **Collect data on RTU shipments by climate zone.** Conducting research to better understand how RTU shipments nationally could be used to update national weightings and savings potential estimates in this analysis.
- **Perform research and validation efforts.** Conduct field metering studies to verify simulated savings, compare results with similar studies for validation, and update data on RTU shipments by climate zone to better understand market trends and inform future efficiency programs.

1 Introduction

Efficient packaged Rooftop Unit (RTU) products present significant energy savings over conventional gas RTU equipment ubiquitous in the commercial sector. For several years, the Northwest Energy Efficiency Alliance (NEEA) has supported the research of efficient RTUs, including studying condensing gas RTUs in lab and field applications, supporting revisions to the Canadian Standards Association's (CSA) P.8 Commercial Warm-Air Furnace standard and test procedure, researching the gas RTU market, coordinating with gas RTU manufacturers, and developing gas RTU market transformation program specifications. NEEA's efficient RTU market transformation program also embeds building energy modeling analyses designed to quantify potential energy savings for implementing efficient RTU measures.

In April 2022, NEEA and Nicor Gas (Nicor) used building energy modeling to investigate potential measure-savings opportunities for efficient RTU systems in the Northwest and Midwest to support market transformation efforts ("the previous modeling effort" or "2022 RTU analysis").[3] This project sought to better understand different measures' impacts individually and when combined into tiers to account for interactive effects on energy usage in RTU systems. The project involved model development and simulated executions for five different commercial building types, five individual measures, and five tiers (i.e., combinations of measures included in measure packages) across five climate zones. This modeling work expanded on a 2020 energy-modeling analysis that supported CSA P.8 revisions that sought to determine how different efficient RTU measures, beyond thermal efficiency, can impact heating consumption.[4]

While modeling work conducted in April 2022 provided valuable insights into how different energy-efficiency measures or tiers affect efficient RTU energy savings in heating-dominated climates, it did not draw conclusions about the applicability of these measures nationally, specifically in hot and humid climates. Additionally, the project exclusively simulated gas-fueled RTUs and did not consider the relative measure impacts from fully electric, heat pump rooftop equipment or dual-fuel packaged Air-Source Heat Pumps (ASHP).

This report summarizes the energy modeling methodology and results developed by NEEA and the Center for Energy and Environment (CEE). The work was conducted by "the project team" – Resource Innovations and A2 Efficiency – under contract to NEEA and CEE. This work expanded on the 2022 modeling effort by creating more nationally representative

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[3] NEEA, "Energy Savings from Efficient Rooftop Units in Heating Dominated Climates," Cadeo Group, April 2022, https://neea.org/resources/energy-savings-from-efficient-rooftop-units-in-heating-dominated-climates

[4] NEEA, "Energy Modeling of Commercial Gas Rooftop Units in Support of CSA P.8 Standard," Cadeo Group, May 2020, https://neea.org/resources/energy-modeling-of-commercial-gas-rooftop-units-insupport-of-csa-p-8-standard

models, a more extensive range of packaged rooftop equipment, and a larger set of efficiency measures. This energy modeling analysis is intended to further support market transformation efforts by NEEA, CEE, and Nicor.

1.1 Research Goals

The project team performed the analysis described in this report to reinforce and expand the applicability of conclusions from the previous research efforts surrounding efficient RTUs. This latest research expands on previous scopes in terms of measures, climates, and building types simulated. By broadening these energy modeling efforts to cover a greater portion of the United States, the team enhanced its understanding of the way measure and tier impacts vary by climate region, which could eventually inform development of a national program applicable to the RTU market and representative federal efficiency metrics for this product. Moreover, the team sought to understand how additional measures, such as decreased enclosure leakage, optimized switchover controls, and cold climate heat pumps (CCHP) saved energy during the heating and cooling seasons nationally.

Primary project goals included the following:

- Understand how locations will impact the outcomes of efficient RTU measures.
- Understand which efficiency measures have the greatest impact on the heating and cooling energy consumption of RTUs by climate.
- Understand the effect on energy consumption from combining different measure tier requirements and how these effects vary, based on climate zones.
- Develop supporting evidence that can be used in advocating for changing RTU codes and standards to achieve regulatory goals, such as the development of a whole-box energy-efficiency metric.
- Determine key requirements to include in a future national program specification targeting annual performance for heating and cooling.

This study investigated the energy savings potential of commercial HVAC efficiency measures for various types of RTU equipment nationally. This study did not investigate energy pricing, cost savings, or carbon savings.

1.2 Research Design

The research approach used detailed building energy modeling to estimate performance outcomes for different efficiency measures applied to RTUs on buildings across a range of occupancies and locations. Critical dimensions of the simulations considered included the following:

- Climate Zones
- Building Types
- HVAC Systems
- Efficiency Measures

1.2.1 Climate Zones

To best represent climatic diversity nationally, the project team assigned geographical climate zone regions in alignment with climate zones from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 90.1. These climate zones are defined based on heating-degree days (HDD), cooling-degree days (CDD),[5] and humidity.[6] These definitions resulted in 16 different climate zones within The United States.

Because simulations rely on actual weather data as an input,[7] the team required weather file data from specific, representative locations in each region. These weather files specified key simulation inputs, such as air temperature, humidity, wind speed, and solar radiation levels (among others), all of which play a considerable role in determining simulation results. Weather from a particular analysis location also defined the capacity of HVAC equipment using design conditions based on statistical analyses of historical weather data. In addition to having the required historical weather data available, the location selected had to reflect a region's typical climatic conditions while accounting for the distribution of commercial buildings throughout the region (i.e., applying a bias in our selection towards the largest towns or cities in a region).

The project team sought to select the minimum number of regions required to (1) represent the national weather variability; and (2) account for most highly populated cities/regions in the United States. The locations used in this analysis, referred to as the "Reference City" for each region, have been based on those ASHRAE used for its simulation-based Codes and Standards impact analyses. The team aligned this project's Reference Cities with the ASHRAE 90.1 Reference Cities and those used during the 2022 Commercial Unitary Air Conditioners (CUAC) Test Procedure Appliance Standards and Rulemaking Federal Advisory Committee (ASRAC) working group for developing the Integrated Ventilation, Economizer, and Cooling (IVEC) metric,[8] with revisions representing climate zones 5A and

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[5] HDDs and CDDs measure how much heating or cooling a building is expected to need, based on how many days during the year the outdoor air temperature remains below or above 65°F, respectively.

[6] In the United States, ASHRAE divides the country by humidity classification: Marine (C), Dry (B), and Moist (A).

[7] This is so, even if the team uses "Typical Meteorological Year" weather as the TMY data sets are developed by measured weather data.

[8] Presentation to ASRAC WG by industry: https://www.regulations.gov/document/EERE-2022-BT-STD-0015-0019

6A for Chicago, IL, and Minneapolis, MN, respectively. This Reference City-based approach is commonly used for analyses that cover large geographic areas as it aligns the simulation effort with the analyses' overall precision, thus avoiding simulation of more models than needed.

Table 1 lists climate zones and Reference Cities the project team used to represent weather variability nationally as well as each climate zone's HDD (HDD65) and CDD (CDD74).[9] This list of 11 Reference Cities accounted for about 95% of RTU shipments[8] and the United States' population.[10] **Figure 1** maps climate zones and Reference Cities.

Table 1: Climate Zones and Reference Cities

ASHRAE 90.1 Climate Zone	Reference City	HDD65	CDD74
4C	Seattle, WA	4621	85
3C	San Diego, CA	1101	101
5B	Denver, CO	5874	421
6B	Great Falls, MT	7593	241
2B	Tucson, AZ	1328	1969
3B	El Paso, TX	2203	1393
3A	Atlanta, GA	2578	713
2A	Tampa, FL	481	1421
5A	Chicago, IL	6157	337
4A	New York City, NY	4761	283
6A	Minneapolis, MN	7396	295

[9] "2021 ASHRAE Handbook—Fundamentals," The American Society of Heating, Refrigeration, and Air-Conditioning Engineers, https://www.ashrae.org/technical-resources/ashrae-handbook/description-2021-ashrae-handbook-fundamentals

[10] The project team relied on state-level 2020 census data from the United States Census Bureau (https://www.census.gov/data/tables/2020/dec/2020-apportionment-data.html) and county-level 2024 census data from World Population Review (https://worldpopulationreview.com/states/wisconsin/counties) to determine rough population estimates.

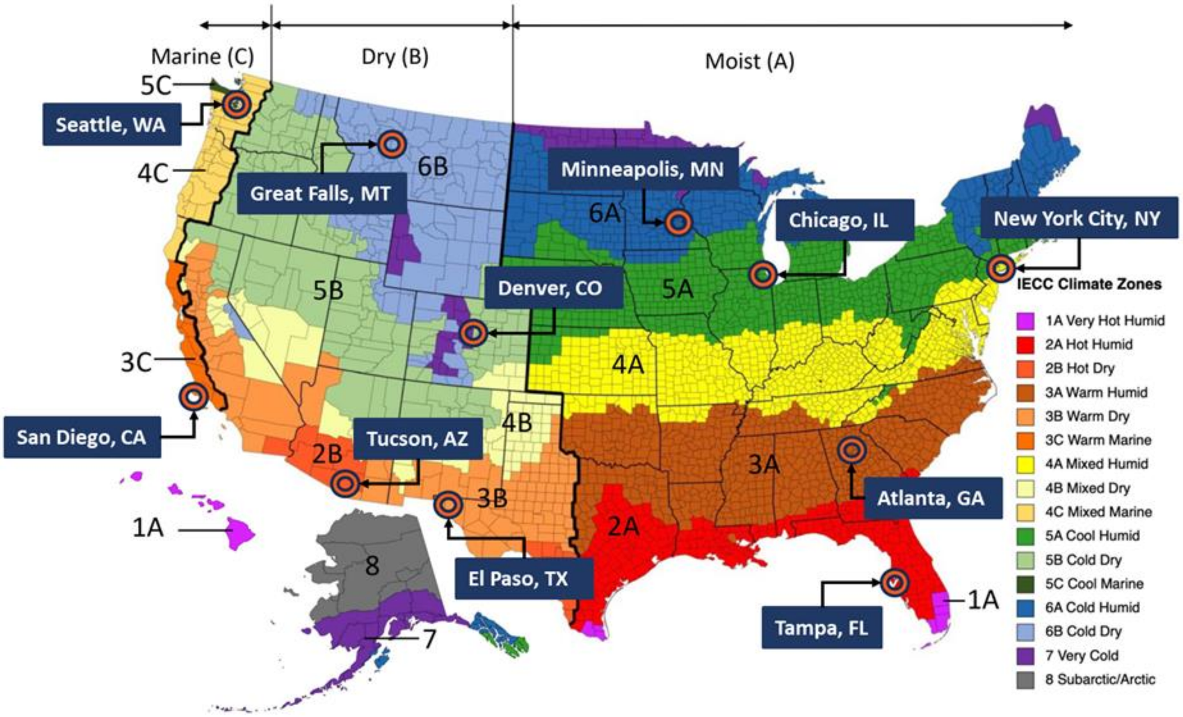


Figure 1: Mapped Climate Zones and Reference Cities

Due to low population densities or small geographical footprints, the team did not include the following five climate zones in this analysis:

- 1A (Miami, FL)
- 4B (Albuquerque, NM)
- 5C (Port Angeles, WA)
- 7 (International Falls, MN)
- 8 (Fairbanks, AK)

To align with the April 2022 modeling approach, the team ran all simulations with TMY3 weather data.

1.2.2 Building Types

A building's type represents a key segmentation variable that strongly correlates to schedules and non-HVAC load assumptions. Building types can significantly impact different efficiency-measures' outcomes, therefore it was important for this analysis to include a range of building types where RTUs can be most commonly found.

Consequently, the team carefully selected building types to reflect the majority of typical RTU installations while balancing that adding or changing building types can significantly impact project timelines and budget requirements. In the previous modeling effort, the project team used regional building characteristic data from the Commercial Building Stock Assessment (CBSA)[11] to identify building types that "most commonly" have installed packaged RTUs in the Northwest, employing the following metrics:

- Building Type by the greatest number of sites employing RTUs.
- Building Type by the most floor area conditioned with RTUs.
- Building Type with the greatest installed RTU capacity.

Using these metrics, CBSA data analysis resulted in the following U.S. Department of Energy (DOE) Commercial Reference Building (prototypes),[12] simulated in the previous modeling effort:

- Medium Office
- Single-Story Medium Office[13]
- Stand-alone Retail
- Strip-mall Retail
- Grocery

All building types, except for the custom-built Single-Story Medium Office prototype, are based on DOE prototypes, which were developed by the Pacific Northwest National Laboratory (PNNL) to create representative commercial building models that match common geometric, operational, and building performance characteristics for 16 different building types.

The project team and NEEA decided that a national study should at least employ the five building types used in the previous modeling effort. To ensure that building type selection based on the CBSA reflected the country as a whole, the project team reviewed building types with the most floor area conditioned by gas packaged RTUs in the 2018 Commercial Building Energy Consumption Survey (CBECS).[14] The team found that the third-greatest portion of building square footage conditioned by gas packaged RTUs in the United States are education buildings (15%). As gas packaged RTUs occur so frequently in education

[11] CBSA is a regional study, funded by NEEA, which seeks to understand drivers of energy consumption in commercial buildings by collecting detailed information on building characteristics, installed equipment, and energy consumption for buildings throughout the Northwest. https://neea.org/data/commercial-building-stock-assessments

[12] DOE, "Commercial Reference Buildings," https://www.energy.gov/eere/buildings/commercial-reference-buildings

[13] This altered version of the Medium Office prototype is one-story rather than three-story. Unlike the three-story Medium Office model, this version of the office building is more likely to be served by single-zone packaged RTU systems.

[14] The CBECS is a national survey conducted every five to seven years to understand energy consumption and energy-related commercial building characteristics. https://www.eia.gov/consumption/commercial/data/2018/

buildings nationally, the project team added the Primary School prototype to this project's scope. Similarly, the team added the Warehouse prototype to the project's scope as warehouses accounted for 10% of the square footage conditioned by gas RTUs nationally.

Including the original five building types plus Education and Warehouse accounted for roughly 68% of total floor area conditioned by RTUs in the United States. This collection of building types also captured five of the top six building types served by gas RTUs; "Other" buildings accounted for roughly 19% of conditioned square footage served by gas RTUs. However, no representative prototype exists for "Other" buildings, and several buildings binned in this category could likely be proxied by office or retail buildings (e.g., the geometric characteristics of a bowling alley could be proxy-simulated using the retail standalone building, though internal loads and schedules would vary). **Table 2** shows the distribution of commercial floor area conditioned by RTUs in these building types, according to CBECS .

Table 2: Most Common Building Types with RTUs According to CBECS

Building Type	Correlated Building Types in CBECS[15]	Percent of Conditioned Square Footage Served by Gas RTUs in United States
Standalone Retail	Retail other than mall, religious worship, public assembly	24%
Primary School	Education	15%
Medium Office	Office, public order and safety	15%
Warehouses	Nonrefrigerated warehouse, refrigerated warehouse	10%
Strip shopping center	Enclosed mall	2%
Grocery	Food Sales	2%
RTU Floor Area of Building Types Included in Scope		**68%**

Table 3 summarizes the square footage and key characteristics for each prototype. Characteristics provided in this section do not vary between baseline and measure scenarios; these inputs remain constant during measure model runs. All buildings have been simulated using the entire occupied floor area conditioned by RTUs with air conditioning,[16] except for the front-entrance zone of the Retail Standalone building, which is

[15] As several building types did not have associated DOE commercial reference building prototypes, the team matched these buildings with existing prototypes, based on geometrical and operational attributes as proxies.

[16] The Warehouse DOE Commercial Reference Building does not have air conditioning provided in the large bulk storage zone. The team added cooling to this zone for this analysis to reflect that (1) new construction warehouses are likely to have the entire building square footage conditioned; and (2) warehouses in hot climates are likely to have air conditioning throughout the entire building.

served by a small, zonal electric-resistance heater without cooling. All RTUs are modeled as single-zone configurations.[17]

In the previous modeling effort,[18] the project team modeled each Medium Office building with three multi-zone[19] RTU units (one unit serving each floor), based on an engineering judgement that multi-zone systems operate more typically for office buildings that are greater than two-stories and with floor areas around 50,000 square feet. However, the Regional Technical Forum (RTF) recently analyzed NEEA's CBSA and found that most Medium Office buildings had single-zone RTU systems (about 73% of buildings[20] from the CBSA 2014[21] and CBSA 2019[22]). The RTF developed three different, single-zone Medium Office buildings, calibrated to billing data from both CBSAs.[23] The project team decided to align this study's RTU configuration for Medium Office buildings with RTF models by simulating single-zone RTU systems.

[17] Singe-zone RTUs have one thermostat to control the unit and often have single-speed fans. Single-zone RTU units are only capable of heating and conditioning one zone individually.

[18] NEEA, "Energy Savings from Efficient Rooftop Units in Heating Dominated Climates," Cadeo Group, April 2022, https://neea.org/resources/energy-savings-from-efficient-rooftop-units-in-heating-dominated-climates

[19] Multi-zone RTUs typically have multiple thermostats. Each one controls a variable air volume (VAV) box. The VAV box provides a variable amount of air to its zone, depending on its setpoint. The variable air flow to each space is typically provided by a variable-speed fan on the RTU. Multi-zone RTU units are capable of heating and conditioning multiple zones within a building.

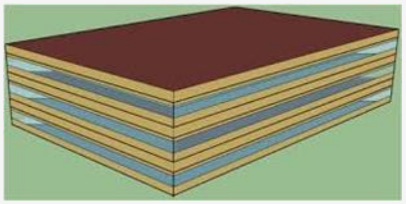
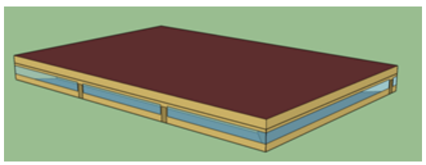
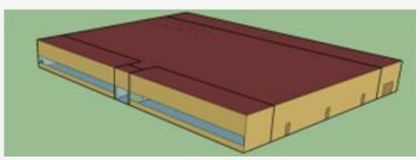
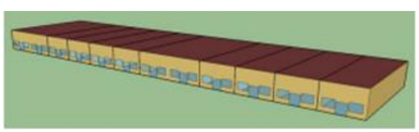
[20] This figure is unweighted as it accounts for buildings in both the CBSA 2014 and CBSA 2019; the team did not attempt to combine weights from the separate data sources.

[21] "2014 CBSA Final Report," The National Energy Efficiency Alliance, https://neea.org/resources/2014-cbsa-final-report

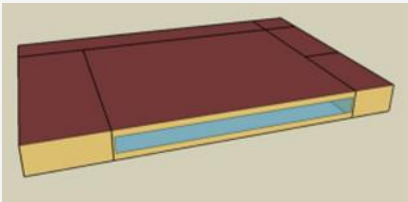
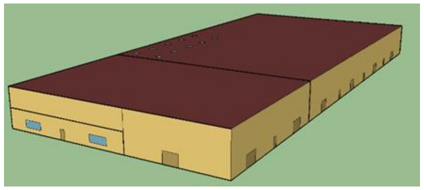
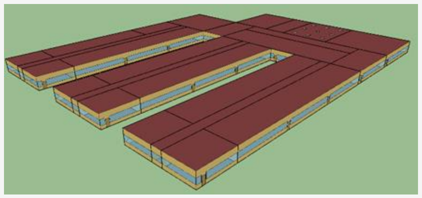
[22] "CBSA 4 (2019) Final Report," The National Energy Efficiency Alliance, https://neea.org/resources/cbsa-4-2019-final-report

[23] "Commercial Building Simulation Models," RTF, https://rtf.nwcouncil.org/commercial-building-simulation-models/

Table 3: Building Types and Prototype Characteristics

Building Type	Image	Square Footage (ft²)	Window/Wall Ratio	Number of RTUs Modeled[24]	Other Characteristics
Medium Office		53,600	31%	15	• Three-stories. • One interior zone and four perimeter zones per floor. • Modeled in the previous analysis with three multi-zone RTUs (one per floor).
Single-story Medium Office		17,000	31%	5	• One-story. • One interior zone and four perimeter zones. • Modeled in the previous analysis with five single-zone RTUs (one per zone). • Custom-built prototype.
Stand-alone Retail		25,000	11%	5	• One-story. • Large interior zone, register zones, entrance zone, and storage zones. • Modeled in the previous analysis with four single-zone RTUs.
Strip-mall Retail		22,500	20%	10	• One-story. • Ten small stores making up individual zones. • Modeled in the previous analysis with ten single-

[24] The team assumes the maximum size for a single RTU as 25 tons. Zones in which capacity requirements fall below 25 tons have one RTU per zone. In the remainder of zones, the minimum number of RTUs are modelled to meet the zonal capacity requirements.

Building Type	Image	Square Footage (ft^2)	Window/Wall Ratio	Number of RTUs Modeled[24]	Other Characteristics
					zone RTUs (one per zone/store).
Grocery		45,000	8%	8	• One-story. • Large interior zone, several smaller storage zones. • Modeled in the previous analysis with six single-zone RTUs (one per zone).
Warehouse		52,000	6%	5	• One-story. • One large and one small storage zone, small office zone. • Not modeled in the previous analysis.
Primary School		74,000	22%	25	• One-story. • Most diverse building type in terms of types of zones, including gyms, kitchens cafeterias, classrooms, hallways, etc. • Not modeled in the previous analysis

The DOE prototypes align code-influenced inputs to ASHRAE 90.1-2004 standards. In the previous modeling effort,[25] the project team selected these prototypes to approximate an existing building, aligning with an approximate 15-year end-of-life for RTUs. For this analysis, the team maintained the approach of aligning code-regulated inputs to ASHRAE 90.1-2004.

In the previous modeling effort, envelope and fenestration characteristics were tailored to individual climate zones. For this study, however, the project team standardized all code-influenced inputs to meet climate zone 6 criteria for the following reasons:

- **Minimizing Variability.** Varying non-measure-related inputs introduced unnecessary savings differences when comparing savings across climate zones.
- **Limited Variation Requirements.** While fenestration requirements changed across climate zones, envelope insulation requirements remained largely consistent between climate zones 2 through 6.[26]
- **Conservative Estimates.** Aligning inputs to climate zone 6 regulation requirements ensured all surfaces meet code-minimum insulation levels. Therefore, models with higher-than-code fenestration levels yielded conservative savings estimates.
- **Modeling Effort.** The previous modeling effort simulated fewer building types, climate zones, and HVAC systems (approximately 200 models) compared to this study (over 2,000 models). Given the preceding reasons, reducing the modeling effort by standardizing code-influenced inputs provided a clear modeling simplification.

Prototype ventilation rates align with ASHRAE 62.1-2004, ensuring consistency with the code year used for other regulated inputs and with the previous modeling effort.

Appendix A provides values for code-regulated inputs, such as water-heater efficiency, fenestration insulation, and ventilation rates.

Appendix B includes non-code-regulated inputs, such as schedules, water-heating flow rates, and heating/cooling setpoints. These inputs, while more difficult to define, are based on values from the DOE prototypes and are nationally representative of each building type.

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[25] NEEA, "Energy Savings from Efficient Rooftop Units in Heating Dominated Climates," Cadeo Group, April 2022, https://neea.org/resources/energy-savings-from-efficient-rooftop-units-in-heating-dominated-climates

[26] The team only simulated buildings in climate zone 2 through 6. Only "Mass" construction insulation requirements changed in these climate zones, going from "not required in climate zone 2" to "an R-value of 1.7 in climate zone 6." This construction only impacted Stand-alone Retail and Grocery buildings.

1.2.3 HVAC Systems

The project team, NEEA, Nicor, and CEE decided to include four packaged RTU systems in this project's scope, as listed and detailed in **Table 4**.

Table 4: HVAC System Types

HVAC System Type	Description
Gas Packaged RTU with AC	This system type is the "typical" RTU. Based on NEEA interviews with RTU manufacturers, 70%-90% of RTUs sold presently belong to this type.
Gas Packaged RTU with AC High-Ventilation	This system type uses the same equipment as the gas-packaged RTU with an AC, but uses ventilation rates higher than code minimums. As discussed in the **Building Types** section (**1.2.2**), ventilation rates for other HVAC systems are set to ASHRAE 62.1-2004 levels. For this system type, the team set ventilation rates equal to LEED v4.1 requirements, equating to 30% higher outside air ventilation above ASHRAE 62.1-2016 requirements. The primary research purpose of these HVAC types is to assess the potential energy savings increase for the Energy Recovery Ventilation (ERV) measure, given ventilation rates typically higher than code minimum requirements, especially after the COVID-19 pandemic
Packaged ASHP with Electric Resistance Backup	This all-electric RTU type uses an electric heat pump as the main heating component and provides electric resistance back up for auxiliary heating.
Packaged ASHP with Gas Backup	In this system, the heat pump serves as the main heating component, but the unit includes a gas furnace as the backup or auxiliary option. This system type is also called a dual-fuel unit or hybrid unit.

1.2.4 Efficiency Measures

The project team ran two model scenarios to quantify efficiency measures' impacts:

1. **Baseline models.** Inputs reflect "current practice" RTUs that meet regulated efficiencies.
2. **Measure models.** Inputs reflect either individual RTU energy-saving features or combinations of features.

The difference in energy use between the two model scenarios define the measure impacts. As addressed in the **Building Types** section (**1.2.2**), inputs unrelated to RTU baseline and measure specifications, such as code-regulated inputs (e.g., envelope, fenestration, ventilation) and non-code-regulated inputs (e.g., building internal loads, occupancy, thermostat setpoints) are held constant through both model scenarios.

In coordination with NEEA, Nicor, and CEE, the project team developed the list of efficiency measures shown in **Table 5,** which also provides a description of the technology or intervention.

Table 5: Efficiency Measures

Measures	Description
Enclosure Insulation	Two enclosure insulation levels are considered for this measure: 1. **R8 Insulation:** A moderate amount of enclosure insulation. 2. **R12 Insulation:** A high amount of enclosure insulation.
Low-Leakage Dampers	This measure modeled outside air dampers with damper leakage rates equal Air Movement and Control Association (AMCA) Class 3 from AMCA Standard 500-D.[27]
Enclosure Leakage	Reduced air leakage from a RTU enclosure meeting Class-Leakage 24 from AHRI 1350, Table 2: Casing Air Leakage Rating Class.[28]
Efficient Cooling	Cooling efficiencies (EER/IEER) that meet Advanced Tier specifications from the Consortium of Energy Efficiency Unitary AC Specs.[29]
ERV	An additional heat exchanger component capable of recovering energy and moisture from the exhaust air stream and transferring it to the incoming outside air stream.
NEEA Tier 1	This measure, which aligns with NEEA's Efficient RTU Specification, combines individual measures for R12 insulation and low-leak dampers.
NEEA Tier 2	This measure combines individual measures for R12 enclosure insulation, low-leak dampers, and ERV.
Low Switchover Temperatures	Two switchover setpoints are considered for this measure, with other HVAC specifications defined for each HVAC type by setpoint: 1. **Compressor Lockout #1:** A low compressor lockout of 15˚F. 2. **Compressor Lockout #2:** A very low compressor lockout of 5˚F.
Cold-Climate Heat Pump	This measure estimates the combined impacts of: 1. Removing the compressor lockout entirely. 2. Allowing backup heating to turn on at lower temperatures (packaged ASHP with gas backup only). 3. Improving performance of heat pump units at cold climates.
Low Switchover Temperature with NEEA Tiers	This measure combines all criteria for (1) Low Switchover Temperature with Compressor Lockout #1; and (2) NEEA Tier 1 and Tier 2.
Cold-Climate Heat Pump with NEEA Tiers	This measure combines all criteria for the (1) Cold Climate Heat Pump, and (2) NEEA's Tier 1 and Tier 2.

27 AMCA Standard 500-D: Laboratory Methods of Testing Dampers for Rating. AMCA International, Inc.

28 AHRI, "Mechanical Performance Rating of Central Station Air-handling Unit Casings," https://www.ahrinet.org/system/files/2023-06/ANSI_AHRI_Standard_1350_I-P_2014_with_Addendum_1_0.pdf

29 Consortium for Energy Efficiency. (2024). *Commercial Air-Conditioning and Heat Pumps Unitary Specification: Unitary Air Conditioner Specifications*. Consortium for Energy Efficiency. https://cee1.org/images/pdf/CEE_CommACHP_UnitarySpec2024_corrected.pdf

To answer key research questions while balancing the modeling effort, the project team chose not to model every measure with every HVAC system type. Rather, the team selected the measure set for each HVAC type based on measure applicability and combinations best suited to answering the analysis' research questions. For example, the team modeled the HVAC system type "gas packaged RTU with AC high-ventilation" using only measures involving energy recovery, given the primary goal of modeling this system type was to quantify measure savings in light of increased ventilation rates due to lingering impacts from the COVID pandemic, which had less impact on the outcomes of other measures, such as increased enclosure insulation. **Table 6** shows the combinations of measures and HVAC system types.

Table 6: Measure Segmentation by HVAC System Type

HVAC System Type	Measures
Gas Packaged RTU with AC	Enclosure Insulation (R8 & R12)
	Enclosure Leakage
	Low-Leakage Dampers
	Efficient Cooling
	ERV
	NEEA Tier 1
	NEEA Tier 2
	ERV
Gas Packaged RTU with AC High-Ventilation	ERV
Packaged ASHP with Electric Resistance Backup	Enclosure Insulation (R8 only)
	Low-Leakage Dampers
	Efficient Cooling
	ERV
	NEEA Tier 1
	NEEA Tier 2
	Low Switchover Temperatures
	Cold Climate Heat Pump
	Low Switchover Temperature + NEEA Tiers
	Cold Climate Heat Pump + NEEA Tiers
Packaged ASHP with Gas Backup	Enclosure Insulation (R8 only)
	Low-Leakage Dampers

HVAC System Type	Measures
	Efficient Cooling
	ERV
	NEEA Tier 1
	NEEA Tier 2
	Low Switchover Temperatures
	Cold Climate Heat Pump
	Low Switchover Temperature + NEEA Tiers
	Cold Climate Heat Pump + NEEA Tiers

1.3 About This Report

This report contains the following four sections, which describe the project team's methodology, results, and recommendations:

Modeling Approach

Model Results

Findings, Recommendations, and Next Steps

Conclusion

2 Modeling Approach

This section provides the methodology for developing all building simulations as well as methods that the team used to perform quality assurance and quality control (QAQC) activities.

2.1 Overview

Figure 2 broadly outlines the steps used in conducting the approach described in this report.

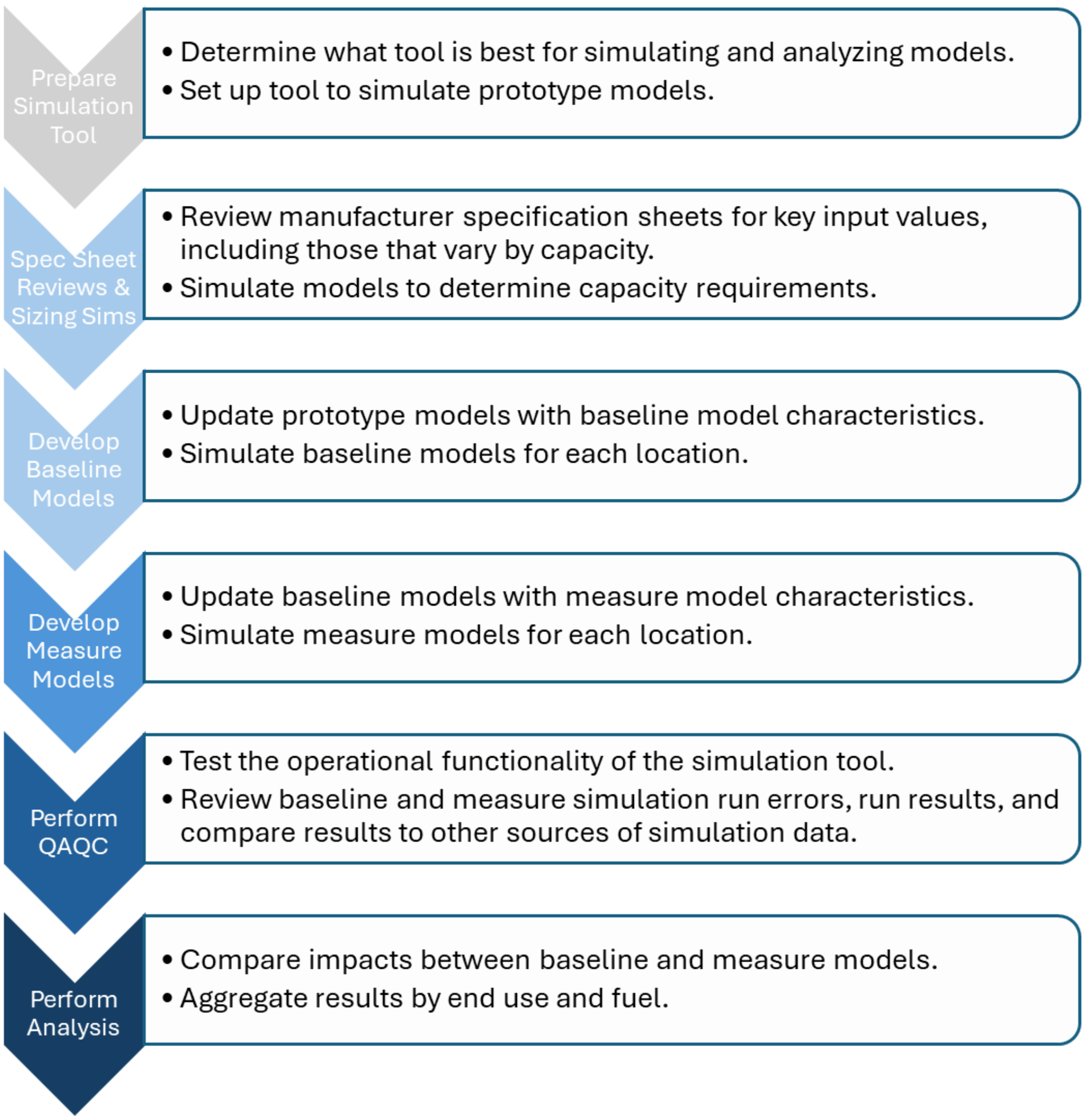

Figure 2: Modeling Approach Overview

2.2 Tool Selection and Preparation

The project team developed all models using the EnergyPlus modeling framework Modelkit Flannel (Modelkit), using the simulation engine EnergyPlus version 22.1 as the program "back-end." Modelkit is a customizable parametric analysis framework that Big Ladder Software originally built for the RTF's Pacific Northwest commercial building simulation efforts.[30] In the previous modeling study conducted by Cadeo Group and NEEA, EnergyPlus was used directly to simulate each baseline and measure model a-la-carte. This approach proved more manageable in the previous study as that effort included about 300 models, whereas this study included over 3,300 models. With Modelkit's parametric capability and customization features, the team efficiently streamlined model runs and aggregate results.

Modelkit employs a "templating" technique, where EnergyPlus objects are categorized into individual text files (template files). This approach enables users to easily adjust objects or input assumptions related to a building model or HVAC system through an Excel interface while running multiple simulations simultaneously. Some efficiency measures fell outside the native capability of the EnergyPlus simulation engine. EnergyPlus, however, includes an Energy Management System (EMS) capability that allows custom calculations.

The team developed an EnergyPlus template for an RTU to account for each efficiency measure and component fuel type (gas heating or heat pump heating) and to manipulate inputs for each configuration evaluated. The RTU template built out several additional components using the EMS in EnergyPlus to account for the following RTU features that EnergyPlus did not directly consider or include:

- RTU box enclosure thermal leakage and insulation.
- RTU box enclosure air leakage.
- RTU damper air tightness and air leakage.

These custom RTU templates allowed the team to simulate the complex RTU specifications described in the **Baseline Model Development** (**2.4**) and **Measure Model Development** (**2.5**) sections while leveraging Modelkit's parametric capability.

To verify that custom RTU templates worked as intended, the team performed various QAQC activities, detailed in the **Quality Assurance and Quality Control** section (**2.6**).

[30] "Commercial Building Simulation Models", RTF, https://rtf.nwcouncil.org/commercial-building-simulation-models/

2.3 Manufacturer Specification Sheet Review and Sizing Simulation Runs

Several key inputs for baseline and measure models, varied by RTU capacity, were determined through manufacturer cut sheets (spec sheet), reviews and simulation sizing runs. The spec sheet review defined the following variables:

- Exterior surface area of RTUs.
- Percentage of RTUs before/after the heating section.
- Damper area of RTUs.
- Cooling efficiency.
- Cooling compressor speeds.
- ERV fan efficiency.
- Non-fan energy used by the ERV.

For the spec sheet review and for defining the inputs shown above, the team determined RTU units commonly sold nationally for 5-ton, 10-ton, 15-ton, or 25-ton unit capacity categories. Based on DOE's 2024 Technical Support Document for CUAC, nine original equipment manufacturers offer RTUs in the United States.[31] A 2017 RTU Market Characterization report by CEE found that three manufacturers (Carrier, Lennox, and Trane) accounted for approximately three-quarters (75%) of RTUs in Minnesota and over one-half (52%) of the installed capacity.[32] While the distribution may vary for other states, these three manufacturers are anecdotally known to dominate the RTU market. Therefore, the team selected products from Trane, Carrier, and Lennox for the spec sheet review.

The team then performed simulation sizing runs to determine zonal capacity requirements by simulating gas and heat pump RTUs across all building types and climate zones. These simulation runs, along with findings from the spec sheet reviews, allowed the team to assign 5-ton, 10-ton, 15-ton, and 25-ton units to each zone and subsequently define inputs that depend on unit capacity. In this report the entire analysis of reviewing manufacturer spec sheets and running simulation sizing runs is called "simulation sizing runs."

The exterior surface area of the RTUs varies by unit capacity. Surface areas are defined for the area before the fan (the mixed air portion of the RTU, also called the negative pressure section) and after the fan/heating coil (the supply air portion of the RTU, also called the positive pressure section). These were determined through sizing simulation runs. **Table 7**

[31] DOE 2024 CUAC Direct Final Rule Technical Support Document, Chapter 3.5.2.1, Manufacturers. https://www.regulations.gov/document/EERE-2022-BT-STD-0015-0096

[32] Characteristics and Performance of Commercial Rooftop Units. Chapter "RTU Characteristics" Table 8: RTU manufacturers. https://www.mncee.org/final-report-characteristics-and-performance-commercial-rooftop-units

shows the final surface areas by RTU capacity. The project team also averaged the surface area proportion for each section of the RTU, as shown in **Table 8**.

Table 7: RTU Exterior Surface Area by Capacity

RTU Capacity (tons)	Before the Fan Exterior Surface Area (ft²)	After the Fan/Heating Coil Exterior Surface Area (ft²)
5	68	25
10	101	37
15	153	57
20	176	65
25	199	74
30	267	99

Table 8: RTU Zone Proportions

Section of RTU	Proportion of RTU
Before the fan (the negative pressure section)	73%
After the fan/heating coil (the positive pressure section)	27%

The total damper area component of the effective leakage area varies by RTU size capacity. Simulation sizing run analysis resulted in the team developing a damper area-to-RTU size ratio of 0.5 damper surface square footage per ton. **Table 9** shows the final damper areas by RTU capacity.

Table 9: Damper Surface Area by RTU Capacity

RTU Capacity (tons)	Damper Surface Area (ft²)
5	2.5
10	5
15	7.5
20	10
25	12.5
30	15

Lastly, compressor speeds, also based on RTU capacity, were determined through sizing simulation runs. **Table 10** shows the resulting compressor speeds by RTU capacities, which remain constant between baseline and measure RTUs.

Table 10: RTU Compressor Speeds

RTU Capacity (tons)	Compressor Speeds
5	1
10	2
15	2
25	3
30	3

2.4 Baseline Model Development

The baseline energy models represent existing buildings where owners have replaced their original equipment with a current practice baseline RTU without applying any of the measures studied. To reflect the current practice for baseline equipment, the project team updated gas and heat pump RTU performance in the prototype models, based on ASHRAE 90.1-2022. Key updates included burner efficiency, heating coil coefficient of performance (COP), and cooling coil COP. As EnergyPlus requires efficiency inputs in terms of the COP rather than typical ASHRAE performance metrics (HSPF2, SEER2, and IEER ratings), the team converted these values from ASHRAE to the COP for simulation purposes.

Table 11 and **Table 12** summarize the resulting baseline efficiency values for gas and heat pump RTUs, respectively.

Table 11: Gas RTU Baseline HVAC Efficiency Values

RTU Capacity (tons)	Burner Efficiency (AFUE)	Cooling Efficiency (COP)
5	81%	3.84
10	81%	3.72
15	81%	3.65
25	81%	3.31

Table 12: Heat Pump RTU Baseline HVAC Efficiency Values

RTU Capacity (tons)	Heating Efficiency (COP)	Cooling Efficiency (COP)
5	4.01	3.84
10	3.40	3.65
15	3.30	3.52
25	3.20	3.14

ASHP performance curves were adopted from the DOE prototypes, ensuring consistency with widely accepted performance assumptions.

Beyond updating RTU performance, the project team incorporated several modifications to align prototype models with measure specifications. These adjustments addressed components such as enclosure leakage, pressure drops, damper performance, and compressor configuration. **Table 13** summarizes these changes, including their rationale and sources. All key inputs that vary by RTU capacity are available in the **Manufacturer Specification Sheet Review and Sizing Simulation Runs** section (**2.3**).

Table 13: Baseline Model Changes to Align with Measure Modeling Specifications

Variable	Applicable Measure(s)	Baseline Value	Reasoning	Source
RTU Enclosure Insulation R-Value	Enclosure Insulation Measures	2	Common enclosure insulation R-value, value used in prior study (assumes ½ inch fiberglass insulation).	CSA P.8 Test Procedure committee, manufacturer interviews.
RTU Enclosure Surface Area (ft²)	Enclosure Insulation Measures, Enclosure Leakage Measure	Varies by capacity (dependent on zone, building type, and climate zone), defined for the RTU area before the fan and after the heating coil.	RTU surface area will increase as zonal capacity requirements increase. Areas of the RTU vary by portion that contain mixed air vs. supply air.	Sizing simulation runs, spec sheet review.
RTU Enclosure Leakage Schedule	Enclosure Leakage Measure	Varies by section of the RTU. The section of the RTU before the fan (the negative pressure section) exhibits leakage only when dampers are closed (unoccupied hours). The section of the RTU after the fan (the positive pressure section) has leakage at all times.	Due to differences in pressure and temperature within different RTU sections, the team cannot model leakage uniformly for the whole RTU unit.	Engineering judgement.
Total Internal and External RTU Pressure Drop (in. w.c.)	Enclosure Leakage Measure, ERV Measure	3.2	Considers all components of the RTU, internal and external.	2019 California codes presentation.[33]
Damper Effective Air Leakage Area (ft²)	Low-Leakage Dampers	Varies by capacity (dependent on zone, building type, and climate zone).	RTU damper area will increase as zonal capacity requirements increase.	Sizing simulation runs, spec sheet review, NEEA Tier 1 requirements.
Effective Damper Leakage Rate (cfm/ft² at 1.0 in. of water)	Low-Leakage Dampers	40	Align with ASHRAE on common effective damper leakage rates for all climate zones.	ASHRAE 90.1-2019.
Normalized Effective Air Leakage Area (in²/ft²)	Low-Leakage Dampers	0.14	Align with AMCA on common, normalized, effective air leakage area for all climate zones.	AMCA Class 3 from AMCA Standard 500-D.[34]

[33] California Energy Codes and Standards, "California Statewide Codes and Standards Enhancement Team's Stakeholder Meeting on Nonresidential and Single Family HVAC Proposals (Part 1)", 2019, https://title24stakeholders.com/wp-content/uploads/2020/01/2022_T24_NR_SF-HVAC-Part-1_Stakeholder-Meeting-Presentation_20200312_PPT_FINAL.pdf

[34] AMCA, AMCA Standard 500-D: Laboratory Methods of Testing Dampers for Rating, AMCA International, Inc.

Variable	Applicable Measure(s)	Baseline Value	Reasoning	Source
Damper Leakage Schedule	Low-Leakage Dampers	On during unoccupied building hours.	To capture the damper leakage in the closed position (unoccupied hours).	Engineering judgement.
Casing Leakage (CL) Rates (cfm/ft²)	Enclosure Leakage	Varies by section of the RTU and operating mode, equal to AHRI 1350 CL_{100} specifications.	Leakage varies by RTU section (mixed air section vs. heated section), outdoor airflow rate (i.e., if dampers are open), and fan operation.	AHRI 1350 Table 2: Casing Air Leakage Rates.[35]
Compressor Lockout	Low Switchover Temperatures (ASHP only)	30°F	Most observed switchover control in several states.	Heat pump program data, default lockout temperature for some ASHP RTU manufacturers, and contractor outreach.
Gas Backup Switchover Control	Low Switchover Temperatures (ASHP only)	Hard-Switchover.	Most observed switchover control in several states.	Heat pump program data, default lockout temperature for some ASHP RTU manufacturers, and contractor outreach.
Gas Backup Allowed Temperature for Backup Heating	Low Switchover Temperatures (ASHP only)	35°F	Most observed switchover temperature in several states.	Heat pump program data, default switchover temperature for some ASHP RTU manufacturers, and contractor outreach.
Electric Resistance Backup Switchover Control	Low Switchover Temperatures (ASHP only)	Backup allowed to provide supplemental heating when needed to meet load.	Typical control configuration for systems with electric resistance backup.	Engineering judgement.
Electric Resistance Allowed Temperature for Backup Heating	Low Switchover Temperatures (ASHP only)	35°F	Most representative allowance for backup heating; default assumption in prototype models.	DOE/PNNL prototype models.[36]
ASHP Performance Curves	Enclosure Insulation, Low-Leakage Dampers, Efficient Cooling, ERV, NEEA Tier 1, NEEA Tier 2, Low Switchover	Same as heat pump performance curves developed by DOE and PNNL for the development of Commercial Reference Buildings.	Most representative heat pump performance curves for existing ASHP RTUs.	DOE/PNNL prototype models.[36]

[35] AHRI, "Mechanical Performance Rating of Central Station Air-handling Unit Casings," https://www.ahrinet.org/system/files/2023-06/ANSI_AHRI_Standard_1350_I-P_2014_with_Addendum_1_0.pdf

[36] DOE, "Commercial Reference Buildings," https://www.energy.gov/eere/buildings/commercial-reference-buildings

Variable	Applicable Measure(s)	Baseline Value	Reasoning	Source
	Temperatures, Cold Climate Heat Pump			
Fan Speed	All	Variable speed.	To remove potential savings from fan speed improvements.	Engineering judgment.
Compressor Configuration	All	Varies by capacity (dependent on zone, building type, and climate zone).	Compressor configuration changes and system sizes change.	Sizing simulation runs, spec sheet review.

The total static pressure drop variable accounted for both internal and external RTU components. **Table 14** breaks down the pressure contributions from each system component, resulting in a total static pressure of 3.2 in. w.c. for baseline systems (without an energy recovery ventilator).

Table 14: RTU Total Static Pressure Drop Components

Internal/External Components	Component	Pressure Contribution (in. w.c.)	Source
Internal	Air blender	0.2	2019 CA codes presentation.
	Economizer damper	0.2	2019 CA codes presentation.
	Filters	0.6	2019 CA codes presentation.
	DX/HP coil	0.6	2019 CA codes presentation.
	Auxiliary heating coil	0.2	2019 CA codes presentation.
External	Supply duct	0.8	Engineering judgement.
	Return duct	0.6	Engineering judgement.

2.5 Measure Model Development

This section details the project team's approach for developing all measure models.

2.5.1 Enclosure Insulation Measures

The Enclosure Insulation measure captures energy savings resulting from increasing the insulation levels of the rooftop package equipment itself, as shown in **Figure 3**. The team simulated two insulation levels for the Enclosure Insulation measure:

- **R-8 Insulation:** A moderate amount of enclosure insulation.
- **R-12 Insulation:** A high amount of enclosure insulation.

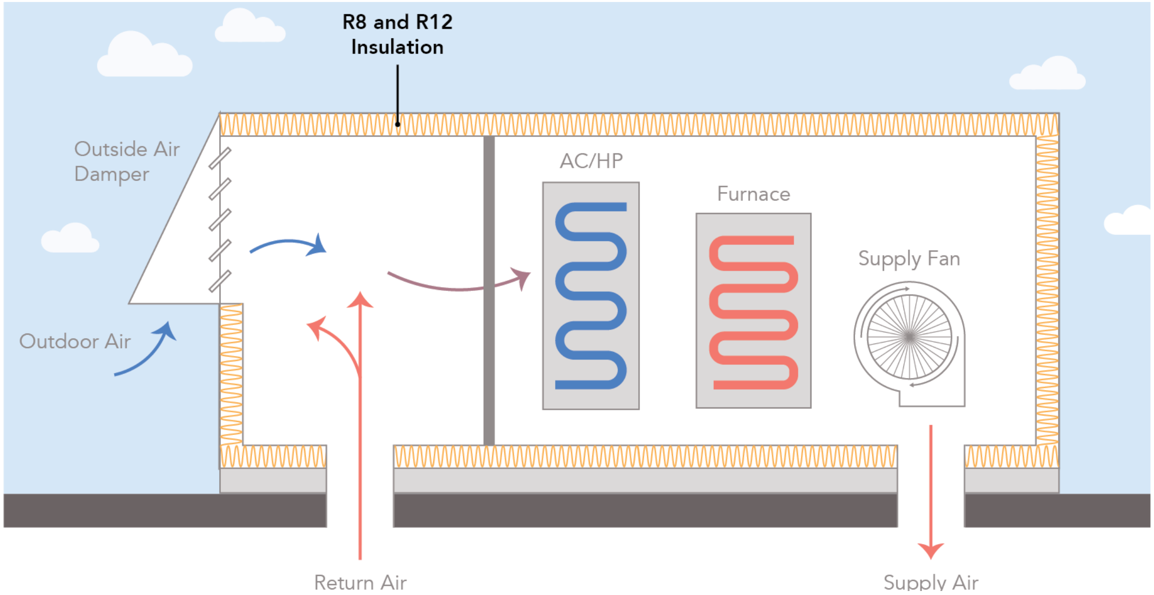

Figure 3: Packaged RTU Enclosure Insulation Diagram

Table 15 shows key variables for this measure, including baseline and measure enclosure insulation values.

Table 15: Enclosure Insulation Measure Key Variables and Sources

Variable	Value	Reasoning	Source
Baseline R-Value	2	Common enclosure insulation R-value, value used in prior study (assumes ½ inch fiberglass insulation).	CSA P.8 Test Procedure committee, manufacturer interviews.
R-8 Measure	8	Measure description.	Measure description.
R-12 Measure	12	Measure description.	Measure description.
RTU Enclosure Surface Area (ft^2)	Varies by capacity (dependent on zone, building type, and climate zone), defined for the RTU area before the fan and after the heating coil.	RTU surface area will increase as zonal capacity requirements increase. Areas of the RTU vary by portion that contain mixed air vs. supply air.	Sizing simulation runs, spec sheet review.
Fan Configuration	Draw-through.	Uniform air flow across the heating coil.	Engineering judgement.

Simulating this measure in EnergyPlus-based software presented a challenge as no direct EnergyPlus object or parameter existed for enclosure insulation levels. To address this, the project team developed an approach to calculate conductive heat gains and losses from an enclosure based on the RTU's surface area and the temperature at each timestep of the analysis inside and outside of the box. **Figure 4** shows calculated heat gains or losses were included as an additional thermal load served.

To accomplish this, the conductive calculation broke the RTU box into two thermal regions:

1. **Portion of the box at the mixed air temperature.**
2. **Portion of the box at the supply air temperature.**

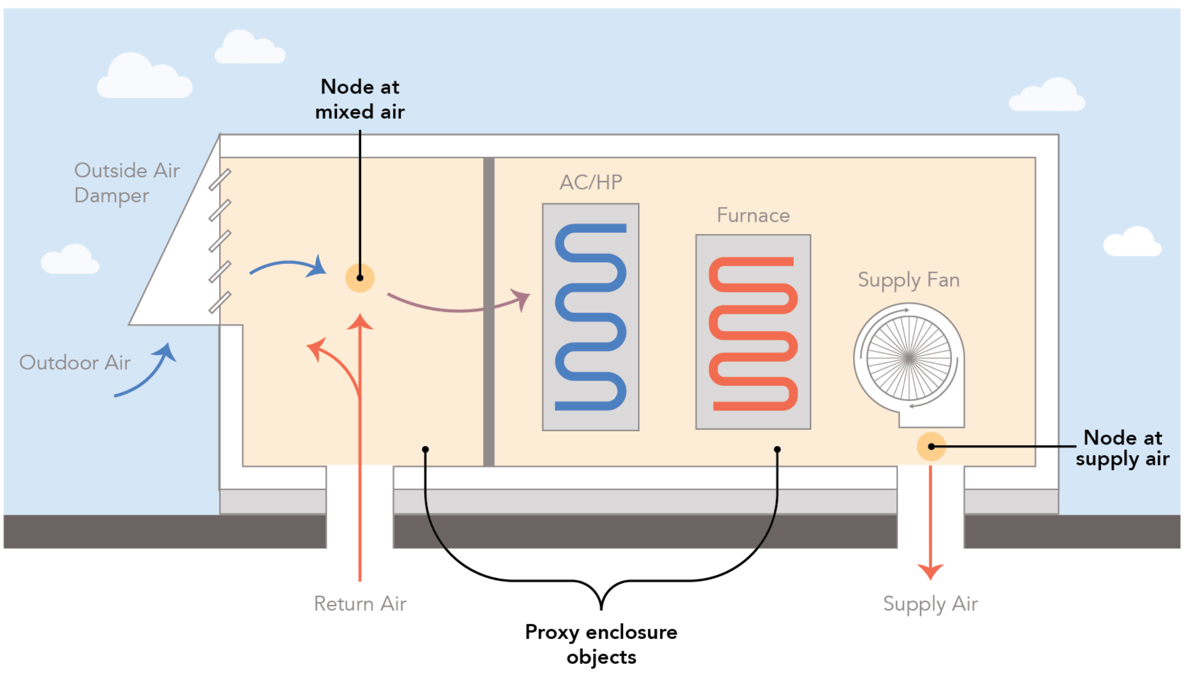

Figure 4: Enclosure Insulation Measure Approach Diagram

Defining the RTU surface areas required analysis of sizing simulation runs, given the RTU surface area varied, based on the size capacity of the RTU, which was a function of the building type, location, and zone that the system serves. Surface areas were defined for the area before the fan (the RTU's mixed air portion) and after the heating coil (the RTU's supply air portion). The model then dynamically calculated the heat loss and gain on each simulated timestep from internal temperatures and applied this heat to the conditioned space, affecting energy use. **Table 7** provides final RTU surface area values by capacity.

2.5.2 Enclosure Leakage Measure

The Enclosure Leakage measure estimates energy savings from reducing air leakage through the RTU enclosure. This measure only applied to gas RTUs.

Due to pressure and temperature differences within different sections of the RTU, the team could not model leakage uniformly for the whole RTU unit. To model this measure, the team created two zone infiltration EnergyPlus objects to proxy-simulate leakage through two sections of the RTU: **the negative pressure section** (the section before the supply fan); and **the positive pressure section** (the section after the heating coil/supply fan), as shown in **Figure 5**. Each infiltration object depended on two key, high-level variables:

- **Surface area of the RTU section.** As with the Enclosure Insulation measure, defining the surface areas of the two RTU sections required analysis of sizing simulation runs as the RTU surface area varied based on the RTU's size capacity, a function of building type, location, and zone that the system serves. Final exterior surface area proportions for each RTU zone averaged across RTU capacities, as shown in **Table 8**.
- **Enclosure leakage rate.** The team used enclosure leakage rates from Air Conditioning, Heating, and Refrigeration Institute (AHRI) 1350 Table 2: Casing Air Leakage Rating Class.[37] Specifically, the team defined baseline leakage as Class-Leakage 100 (CL_{100}) and measure leakage as Class-Leakage 24 (CL24). These defined levels for baseline and measure leakage rates aligned with NEEA and Natural Resources Canada (NRCan) lab testing of enclosure leakage from 2021. To calculate the final enclosure leakage rate, the team utilized **Equation 1**.

[37] AHRI, "Mechanical Performance Rating of Central Station Air-handling Unit Casings," https://www.ahrinet.org/system/files/2023-06/ANSI_AHRI_Standard_1350_I-P_2014_with_Addendum_1_0.pdf

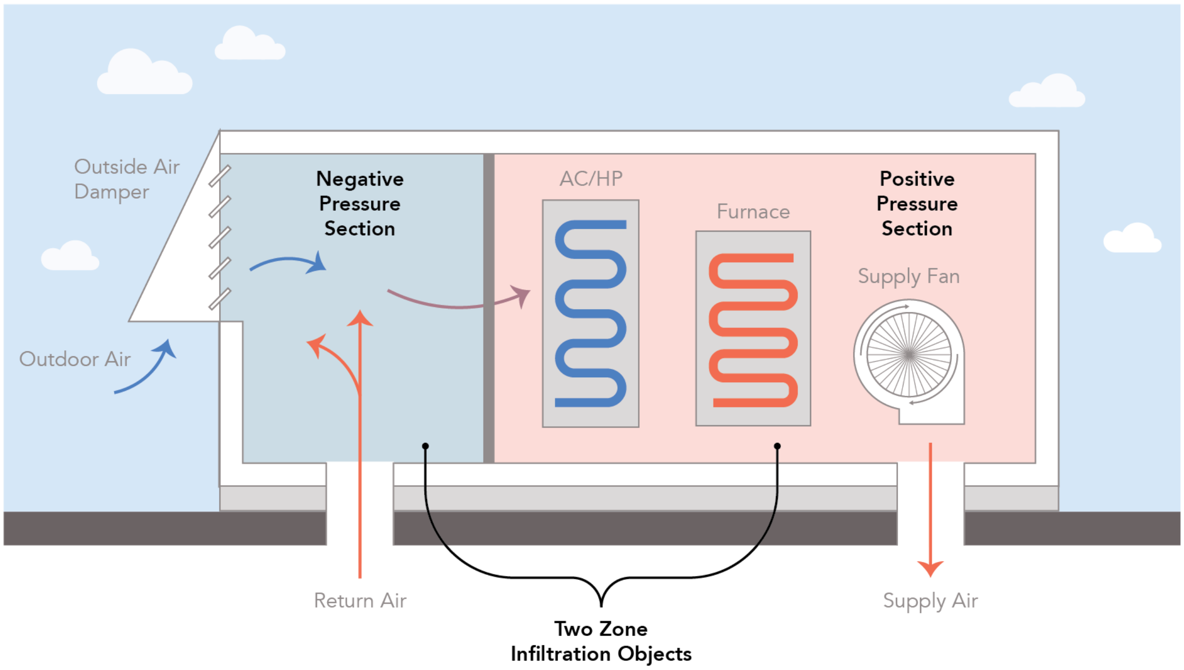

Figure 5: Enclosure Leakage Measure Diagram

Equation 1: Casing Air Leakage Rate

$$CL = CL_m * (\frac{P_m}{P_r})^{-0.65}$$

Where,

CL = Casing air leakage rate (cfm/100ft^2)

CL_m = Measured leakage (cfm/100ft^2)

P_m = Absolute value of test differential pressure (in. H_2O)

P_r = Reference pressure (1.0 in. H_2O)

2.5.2.1 Negative Pressure Section

The RTU's internal section before the fan (the negative pressure section) is subject to fresh air entering through the dampers. The team assumed leakage rates in this section depended on two instances:

- **When dampers are open:** The team assumed no leakage in this RTU section as any fresh air leakage would be negligible to fresh air entering through the dampers. This instance occurred during building occupied hours.
- **When dampers are closed:** The team modeled leakage through the enclosure, assuming a pressure of 4 Pa, or 0.2 in. w.c. due to stack effects. This instance occurred during non-occupied hours.

Table 16 outlines this measure's baseline and measure characteristics for this section of the RTU.

Table 16: Enclosure Leakage Measure Key Variables for Negative Pressure Section

Scenario	Damper Open/Closed	Pressure	Leakage	Reasoning
Baseline	Open	NA	NA	Sufficient outdoor airflow such that leakage is negligible.
	Closed	4 Pa (0.2 in. w.c.)	7 cfm/100ft^2	Modification to CL_{100} using Equation 1 and defined pressure.
Measure	Open	NA	NA	Sufficient outdoor airflow such that leakage is negligible.
	Closed	4 Pa (0.2 in. w.c.)	2 cfm/100ft^2	Modification to CL_{24} using Equation 1 and defined pressure.

2.5.2.2 Positive Pressure Section

The RTU's internal section after the heating coil/supply fan (i.e., the positive pressure section) is always under some pressure, which varies in two instances:

- **When the supply fan is on:** The team assumed a total static pressure of 3.2 in. w.c., in alignment with the baseline total static pressure drop (both internal and external) of the RTU, also shown in **Table 14**. This instance occurred during building occupied hours.
- **When the supply fan is off:** The team assumed a pressure of 4 Pa, or 0.2 in. w.c. due to stack effects, in alignment with the assumed pressure when dampers are closed, which occured at the same time as this instance (during non-occupied hours).

Table 17 outlines baseline and measure characteristics for this measure in this RTU section.

Table 17: Enclosure Leakage Measure Key Variables for Positive Pressure Section

Scenario	Fan On/Off	Pressure	Leakage	Reasoning
Baseline	On	3.2 in. w.c.	213 cfm/ft^2	Modification to CL_{100} using Equation 1 and defined pressure.
	Off	4 Pa (0.2 in. w.c.)	7 cfm/100ft^2	Modification to CL_{100} using Equation 1 and defined pressure.
Measure	On	3.2 in. w.c.	51 cfm/ft^2	Modification to CL_{24} using Equation 1 and defined pressure.
	Off	4 Pa (0.2 in. w.c.)	2 cfm/100ft^2	Modification to CL_{24} using Equation 1 and defined pressure.

2.5.3 Low-Leakage Dampers Measure

As shown in **Figure 6**, the Low-Leakage Dampers measure calculates energy savings from reducing air leakage rates from inside the RTU to the outside through the RTU's outside air dampers.

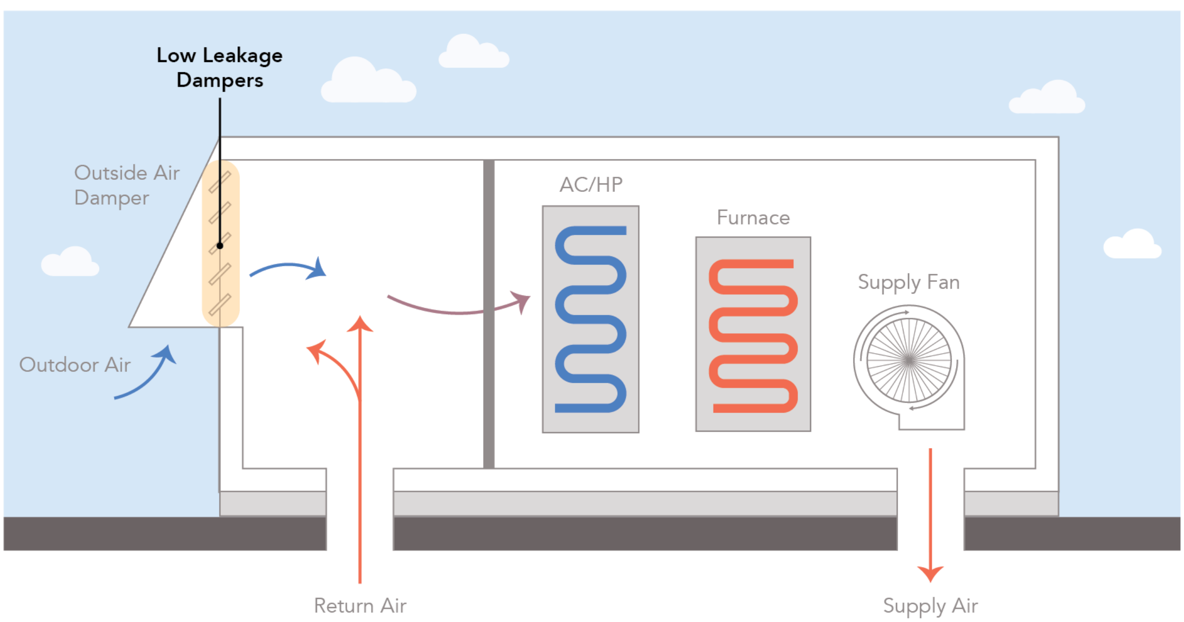

Figure 6: Low-Leakage Dampers Measure Diagram

As shown in **Table 18**, the project team defined the baseline damper leakage rate as equal to AMCA Class 3 from AMCA Standard 500-D[38] in all buildings, locations, and HVAC systems. The measure damper leakage rates, on the other hand, equaled ASHRAE 90.1 2019 damper leakage rates[39] and varied by ASHRAE 90.1 climate zones.[40]

Table 18: Baseline and Measure Effective Damper Leakage Rates for the Low-Leakage Dampers Measure

Scenario	Climate Zones	Effective Damper Leakage Rate (cfm/ft^2 at 1.0 in. of water)
Baseline	All	40
Measure	3, 4, 5B, 5C	10
Measure	5A, 6	4

Similarly to the RTU enclosure insulation, EnergyPlus did not have a parameter for defining damper leakage. To simulate this measure, the team created a proxy-zone around the RTU outside air dampers (shown in **Figure 6**) using an EnergyPlus zone infiltration object. The team then simulated damper leakage using the effective air leakage area EnergyPlus parameter. **Table 19** lists key variables for defining the damper proxy-zone. The damper effective air leakage area is a key variable, requiring analysis of simulations sizing runs to define as this area depends on the RTU's size.

Table 19: Low-Leakage Dampers Measure Proxy-Zone Key Variables and Sources

Variable	Value	Source
Damper Leakage schedule	Unoccupied buildings schedule to capture the damper in a closed position.	Engineering Judgement.
Stack Coefficient	Varies by building type.	2017 ASHRAE Handbook–Fundamentals (SI), Chapter 10.
Wind Coefficient	Varies by building type.	2017 ASHRAE Handbook–Fundamentals (SI), Chapter 10.
Damper Effective Air Leakage Area	Varies by RTU size.	Simulation runs, manufacturer specification sheets, NEEA Tier 1 requirements.

[38] AMCA. AMCA Standard 500-D: Laboratory Methods of Testing Dampers for Rating. AMCA International, Inc.

[39] "Energy Standard for Buildings Except Low-Rise Residential Buildings (I-P Edition)" Table 6.4.3.4.3: Maximum Damper Leakage, cfm per ft^2 at 1.0 in. of water, ANSI ASHRAE/IES Standard 90.1-2019, https://ashrae.iwrapper.com/ASHRAE_PREVIEW_ONLY_STANDARDS/STD_90.1_2019

[40] The project team assumed a motorized damper outdoor air intake.

The damper's effective air leakage area, which varies by zone, building type, and climate zone, depends on two variables, shown in **Equation 2**:

1. **The total damper area.**
2. **The normalized effective leakage area.**

Equation 2: Damper Effective Air Leakage Area

$$DALA = DA * NELA$$

Where,

$DALA$ = Damper effective air leakage area (in^2)

DA = Total damper area (ft^2)

$NELA$ = Normalized effective leakage area (in^2/ft^2)

The total damper area component of the effective leakage area varies by RTU size capacity, a function of the building type, location, and zone that the system serves. Therefore, the project team used sizing simulation runs of baseline systems to define the total damper area. This analysis resulted in the team developing a damper area-to-RTU size ratio of 0.5 damper-surface square footage per ton. **Table 9** provides the final total damper areas by RTU capacity. The normalized effective leakage area was determined using the equation shown in **Equation 3** and varied by the baseline and measure case. Solving for the normalized effective leakage area in **Equation 3** using the air mass flow rates and pressures defined in AMCA Standard 500-D[41] generated the results shown in **Table 20**.

Equation 3: Damper Effective Air Leakage Area

$$m = NELA * C_d\sqrt{2\rho} * (\Delta P_r)^{0.5-n} * (\Delta P)^n$$

Where,

m = Air mass flow rate (cfm/ ft^2)

$NELA$ = Normalized effective leakage area in^2 per ft^2)

P = Air density (0.0765 lb/ft^3)

ΔP_r = Reference pressure difference (Pa)

ΔP = Pressure difference across damper (Pa)

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[41] AMCA, AMCA Standard 500-D: Laboratory Methods of Testing Dampers for Rating, AMCA International, Inc.

C_d = Discharge coefficient (dimensionless)

n = Air mass flow exponent (dimensionless)

Table 20: Normalized Effective Leakage Area by Run, Climate Zone

Scenario	Climate Zones	AMCA Class	Effective Leakage Area per ft^2
Baseline	All	Class 3	0.14 in^2
Measure	3, 4, 5B, 5C	Class 2	0.36 in^2
Measure	5A, 6	Class 1	1.41 in^2

2.5.4 Efficient Cooling Measure

The Efficient Cooling measure estimates the impacts of increasing RTU units' cooling efficiency. **Table 21** lists all key variables considered for defining this measure. Efficiency values and compressor configurations were informed by zonal unit capacity requirements from the sizing simulation runs.

Table 21: Efficient Cooling Measure Key Variables and Sources

Variable	Value	Reasoning	Source
Baseline Efficiency	Current federal minimum values (SEER2, IEER ratings) converted to COP. Dependent on unit capacity. Values available in **Table 11** and **Table 12** for gas RTUs and ASHP RTUs, respectively.	Representative of the least-efficient units manufactured today.	Federal minimum values, sizing simulations.
Measure Efficiency	Advanced Tier from the Consortium of Energy Efficiency 2024 Unitary AC Specs.[42]	Representative of the most-efficient units manufactured today.	Consortium of Energy Efficiency's Unitary AC specs, consistency with products currently in the field.

Table 22 shows the resulting measure-level cooling efficiency values by capacity for gas RTUs and heat pump RTUs. Heating efficiency values remained unchanged between baseline and measure models for this measure.

[42] CEE, 2024, *Commercial Air-Conditioning and Heat Pumps Unitary Specification: Unitary Air Conditioner Specifications*. https://cee1.org/images/pdf/CEE_CommACHP_UnitarySpec2024_corrected.pdf

Table 22: Measure Cooling Efficiency Values

RTU Capacity (tons)	Cooling Efficiency (COP)
5	4.24
10	4.23
15	4.06
25	3.58

As the analysis included humid climates, an additional control was added to the system to ensure indoor humidity did not exceed 60% of the relative humidity at 75°F. When the indoor humidity exceeded this threshold, air conditioning removed moisture and reheated the air as needed to maintain the room thermostat's setpoint.

2.5.5 ERV Measure

The ERV measure assesses the impact of installing a heat exchanger component capable of recovering energy and moisture from the exhaust air stream and transferring it to the incoming outside air stream. **Table 23** lists all key variables considered for defining this measure.

Table 23: ERV Measure Key Variables & Sources

Variable	Value	Reasoning	Source
Sensible Effectiveness	70%	In alignment with recent proposed code changes in Minnesota as well as the CSA P.8 Test Procedure committee.	CSA P.8 Test Procedure committee, industry insight.
Latent Effectiveness	60%	In alignment with recent proposed code changes in Minnesota as well as the CSA P.8 Test Procedure committee.	CSA P.8 Test Procedure committee, industry insight.
Total Static Pressure Drop	4.0 in. w.c.	Considers all RTU components internal and external.	2019 California codes presentation, ASHRAE 90.1 2022.
Total Fan Efficiency	60%	In alignment with the previous modeling effort, confirmed through the spec sheet review.	Engineering judgement, manufacturer spec sheets.
Non-Fan Energy Used by the ERV	0.14 W/ft^3 per minimum air flow	In alignment with the previous modeling effort.	Engineering judgement.
Heat Exchanger Type	Rotary	Many energy-recovery ventilators utilize rotary recovery wheels that enable sensible and latent recovery.	Engineering judgement.

Variable	Value	Reasoning	Source
Heat Exchanger Frost Control Strategy	Exhaust-Only	At low temperatures, ventilation will bypass the heat exchanger device to mitigate frost formation.	Manufacturer insight.

The total static pressure drop accounted for the pressure drop of all RTU components, internal and external. **Table 14** displays the assumed pressure drop and source for each baseline system component, resulting in total static pressures of 3.2 in. w.c. without an ERV. For the ERV measure, the team assumed a static pressure drop of 0.8 in. w.c. due to addition of the ERV (0.4 in. w.c. for both the supply-side and the return-side of the ERV), in accordance with ASHRAE 90.1-2022, resulting in a total static pressure drop of 4.0 in w.c. for the measure-system.

The total static pressure drop, total fan efficiency, and non-fan energy variables inform the supply fan's nominal electric power for this measure, as shown in **Equation 4**. The fan's nominal electric power is the additional supply fan power required from installing an ERV and is used directly as an input to EnergyPlus.

Equation 4: Fan Nominal Electric Power

$$Nominal\ Electric\ Power\ (W) = \frac{\Delta P x Q}{\eta}$$

Where,

ΔP = Total pressure drop in Pascals (Pa)

Q = Volumetric airflow rate in cubic meters per second (m^3/s)

η = Fan efficiency (a dimensionless value between 0 and 1)

As the analysis included humid climates, an additional control was added to the system to ensure indoor humidity did not exceed 60% of the relative humidity at 75°F. When the indoor humidity exceeded this threshold, the air conditioning removed moisture and reheated the air as needed to maintain the room thermostat's setpoint.

2.5.6 NEEA Tier 1 Measure

The NEEA Tier 1 measure estimates the combined impacts of the following measures for gas and ASHP RTU units:

- **R-12 Enclosure Insulation**, as defined in the **Enclosure Insulation Measures** section (**2.5.1**).
- **Low-Leakage Dampers**, as defined in the **Low-Leakage Dampers Measure** section (**2.5.3**).

2.5.7 NEEA Tier 2 Measure

The NEEA Tier 2 measure estimates the combined impacts of the following measures for gas and ASHP RTU units:

- **R-12 Enclosure Insulation**, as defined in the **Enclosure Insulation Measures** section (**2.5.1**).
- **Low-Leakage Dampers**, as defined in the **Low-Leakage Dampers Measure** section (**2.5.3**).
- **Installation of an ERV**, as defined in the **ERV Measure** section (**2.5.5**).

2.5.8 Low Switchover Temperatures Measures

The Low Switchover Temperatures measure quantifies the impacts of adjusting ASHP RTUs' switchover temperatures (where heat pump compressors lockout and shift heating load to inefficient backup heating) at lower outdoor temperatures. This measure defines two switchover setpoint tiers:

- **Compressor Lockout #1:** A low compressor lockout of 15°F.
- **Compressor Lockout #2:** A very low compressor lockout of 5°F.

For all baseline systems, the team assumed a compressor lockout at a 30°F outside air temperature, aligning with the team's experience in reviewing commercial heat pump program data, default temperatures and control configurations for some ASHP manufacturers, and commercial heat pump installation contractor outreach.

The project team assumed emergency backup heating would be allowed to turn on at a 35°F outside air temperature as this is the most common backup allowance according to the DOE/PNNL commercial building prototypes. Most ASHP RTUs with gas backup currently on the market use a hard-switchover control,[43] meaning that the heat pump provides 100% of the heating load to a certain outside air temperature, and, at that temperature (i.e., the switchover temperature), the compressor will lockout, and 100% of the heating load will be met by the gas backup heating coil. Typically, ASHP RTUs with electric resistance backup can supplement heating loads as needed with the electric resistance heater (i.e., the heat

[43] Based on the project team's experience reviewing commercial heat pump program data, default temperature and control configurations for some ASHP RTU manufacturers, and commercial heat pump installation contractor outreach.

pump direct-expansion heating coil and backup electric resistance can operate simultaneously). **Table 24** displays the baseline switchover configuration for ASHP RTUs with gas backup.

Table 24: Baseline Switchover Configuration

Variable	Value	Reasoning	Source
Compressor Lockout	30°F	Most observed switchover temperature in several states.	Program data, default temperature for some ASHP RTU manufacturers, contractor outreach.
Gas Switchover Control	Hard-switchover	Most observed switchover control in several states.	Program data, default temperature for some ASHP RTU manufacturers, contractor outreach.
Electric Resistance Switchover Control	Backup allowed to provide supplemental heating when needed to meet load.	Typical control configuration for systems with electric resistance backup.	Engineering judgement.
Allowed Temperature for Backup Heating	35°F	To allow emergency backup heating to turn on if the heat pump alone cannot meet the load; the most representative allowance for backup heating.	DOE/PNNL prototype models.

For the **Compressor Lockout #1** and **Compressor Lockout #2** scenarios, the team assumed that emergency backup heating would be allowed to provide supplemental heating whenever the primary heat pump heating component could not sufficiently provide the load to reduce unmet load hours at very cold temperatures. As with the baseline scenario, ASHP RTUs with electric-resistance backup heating can provide emergency electric-resistance backup heating simultaneously with the heat pump direct-expansion heating coil; for the gas backup heating system, however, the backup heating component is not allowed to provide heating simultaneously as the heat pump direct-expansion heating coil (i.e., backup boosting).

Table 25 lists the **Compressor Lockout #1** tier switchover configuration, while **Table 26** lists the **Compressor Lockout #2** tier switchover configuration.

Table 25: Compressor Lockout #1 Switchover Configuration

Variable	Value	Reasoning	Source

Compressor Lockout	15°F	Measure definition.	Measure definition.
Switchover Control	Backup allowed to provide supplemental heating when needed to meet load.	Common for heat pump systems that lockout at this low of an outside air temperature (OAT) to provide emergency backup heating available as needed; reduce unmet load hours.	Engineering judgement, review of existing products.
Allowed Temperature for Backup Heating	35°F	Allows emergency backup heating to turn on if the heat pump cannot meet the load alone.	Engineering judgement to align with electric resistance backup specification.

Table 26: Compressor Lockout #2 Switchover Configuration

Variable	Value	Reasoning	Source
Compressor Lockout	5°F	Measure definition.	Measure definition.
Switchover Control	Backup allowed to provide supplemental heating when needed to meet load.	Common for heat pump systems that lockout at this low of an OAT to have an emergency backup heating available as needed; reduce unmet load hours.	Engineering judgement, review of existing products.
Allowed Temperature for Backup Heating	35°F	To allow emergency backup heating to turn on if the heat pump cannot meet the load alone.	Engineering judgement to align with electric resistance backup specification.

2.5.9 Cold Climate Heat Pump Measure

The Cold Climate Heat Pump measure estimates the combined impacts of the following:

- **Removing compressor lockout entirely.**
- **Improving performance of heat pump units at cold temperatures.**

Table 27 shows Cold Climate Heat Pump measure characteristics for both heat pump equipment types. For this measure, the team removed the compressor lockout temperature to allow the heat pump to operate at very low temperatures. The team also increased the performance of heat pump systems by increasing the capacity at low temperatures.

Based on a review of cold climate heat pump systems conducted by CEE, the team increased the capacity of heat pump systems at 0°F from 29%[44] of rated capacity to 40%. Moreover, the team used the rated COPs found in the same review by CEE to define the efficiency of cold climate heat pumps. **Figure 7** shows the adjustment to performance curves, along with rated capacities for various heat pump sizes from CEE's analysis.

Lastly, the team assumed CCHP systems with gas backup heating would be capable of dual-fuel operation (backup boosting) given these high-performance systems are likely capable of backup boosting controls.

Table 27: Cold Climate Heat Pump Measure Key Variables and Sources

Variable	Value	Reasoning	Source
Allowed Temperature for Backup Heating	35°F	To allow emergency backup heating to turn on if the heat pump cannot meet the load alone; most representative allowance for backup heating.	DOE/PNNL prototype models.
Gas Switchover Control	Dual-fuel operation or "backup boosting"	Assumption that heat pump systems that lockout at very low OAT have increased heating performance to provide backup boosting/simultaneous heating of primary and backup heating component.	Engineering judgement, review of existing products.
Electric Resistance Switchover Control	Backup allowed to provide supplemental heating when needed to meet load.	Typical control configuration for systems with electric resistance backup.	Engineering judgement.
Compressor Lockout Temperature	-100°F (no lockout)	Allowing the compressor to never lockout allows the heat pump to operate at very low temperatures.	Measure definition.
Heat Pump Performance Curves	Increased capacity at 0°F OA dry bulb to 40%.	Higher capacities and efficiencies at low temperatures result in increased compressor use and reduced backup heating.	CEE heat pump data for cold climate heat pumps.

[44] Based on DOE's Commercial Prototype Building Models, https://www.energycodes.gov/prototype-building-models.

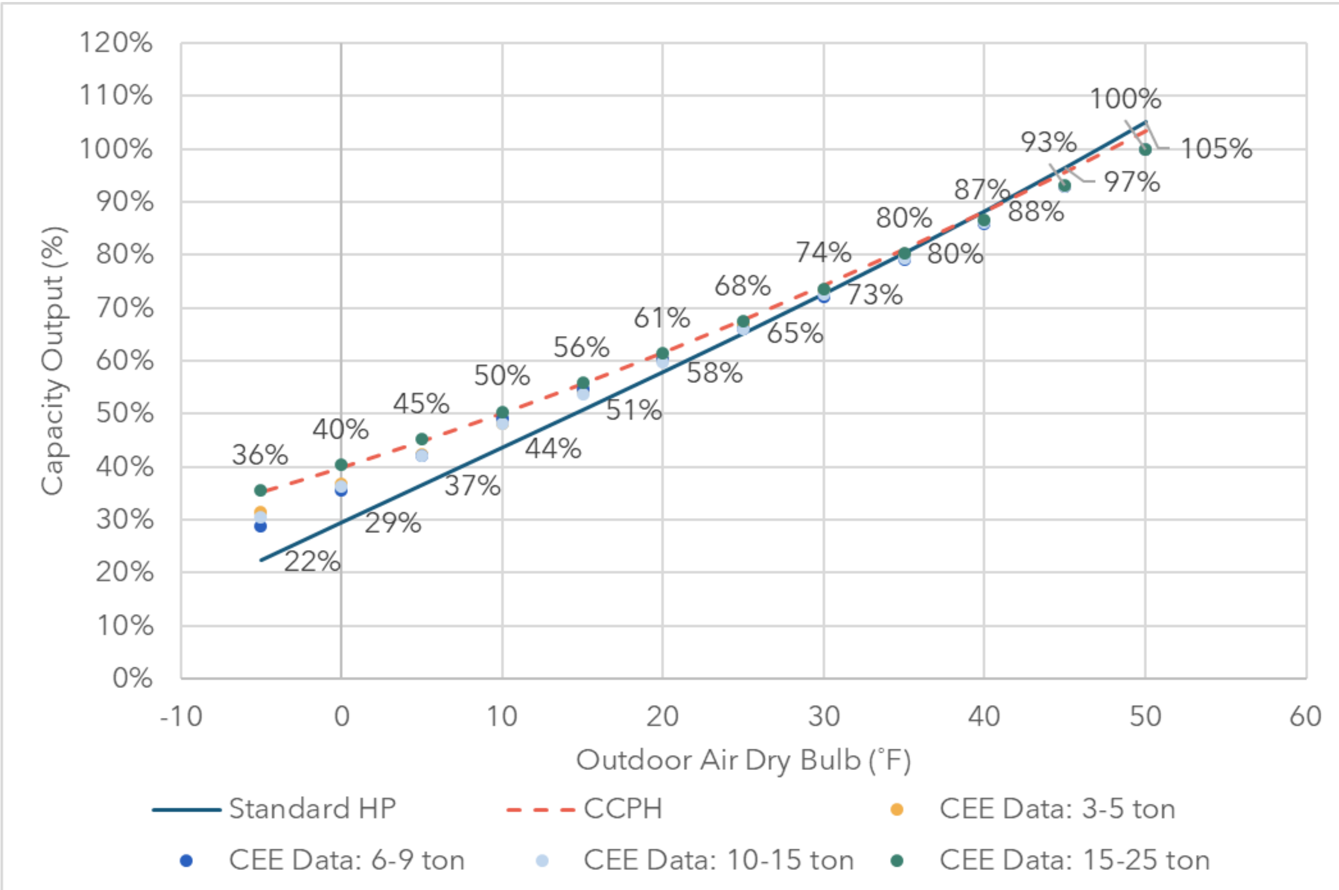

Figure 7: ASHP DOE/PNNL and CEE Performance Curves – Heat Pump Capacity as a Function of Outside Air Dry-Bulb Temperature (˚F)

2.5.10 Low Switchover Temperature 1 with NEEA Tiers Measure

The Low Switchover Temperature with NEEA Tiers measure estimates the combined impacts of the following measures for ASHP RTU units:

- **Low Switchover Temperature**, as defined in the **Low Switchover Temperatures Measures** section (**2.5.8**) using the Compressor Lockout #1 specification only (15˚F compressor lockout) for both heat pump systems.
- Both **NEEA Tier 1** and **NEEA Tier 2**, as defined in the **NEEA Tier 1 Measure** section (**2.5.6**) and **NEEA Tier 2 Measure** section (**2.5.7**).

2.5.11 Cold Climate Heat Pump with NEEA Tiers Measure

The Cold Climate Heat Pump with NEEA Tiers measure estimates the combined impacts of the following measures for ASHP RTU units:

- **Cold Climate Heat Pump**, as defined in the **Cold Climate Heat Pump Measure** section (**2.5.9**).
- Both **NEEA Tier 1** and **NEEA Tier 2**, as defined in the **NEEA Tier 1 Measure** section (**2.5.6**) and **NEEA Tier 2 Measure** section (**2.5.7**).

2.6 Quality Assurance and Quality Control

The team conducted QAQC checks using a structured three-step approach, as detailed in this section:

- **Custom Modelkit Version QAQC.** Verifying the functionality of the project team's custom Modelkit version.
- **Measure Sensitivity Testing QAQC.** Stress-testing measure inputs by setting extreme high and low values and validating that energy-use changes align with expectations.
- **Baseline Models Checklist QAQC.** Ensuring baseline models align with specifications and produce reasonable results.

2.6.1 Custom Modelkit QAQC

The project team developed a custom version of Big Ladder's Modelkit to generate, simulate, and collect results from EnergyPlus simulations. This initial QAQC step primarily sought to ensure that the team's custom Modelkit version operated correctly following the modifications.

As the DOE prototypes were built to run directly in EnergyPlus, "out-of-the-box" simulations performed in EnergyPlus directly served as "ground-truth" models. To verify the accuracy of this, the team compared results between the custom Modelkit version and EnergyPlus using the following process:

- Simulate a baseline gas RTU system in EnergyPlus v22.1 (ground-truth).
- Simulate the same baseline gas RTU system in the custom Modelkit version.
- Compare results between the custom Modelkit version and the EnergyPlus v22.1 ground-truth models.

Simulations were performed using both software programs for all building types under the following conditions:

- A baseline-configured gas RTU, as described in this report.
- Non-HVAC characteristics aligned with ASHRAE 90.1-2004 DOE Commercial Reference Prototypes.

- In a single climate zone: climate zone 4C (Seattle, WA).

The project team verified that annual/monthly consumption results did not differ significantly (+/-10%) between the custom Modelkit version and the ground-truth EnergyPlus v22.1 models. **Figure 8** shows annual net site energy-use intensity (EUI) comparisons and their respective percent changes, while **Figure 9** presents total energy consumption by fuel type.

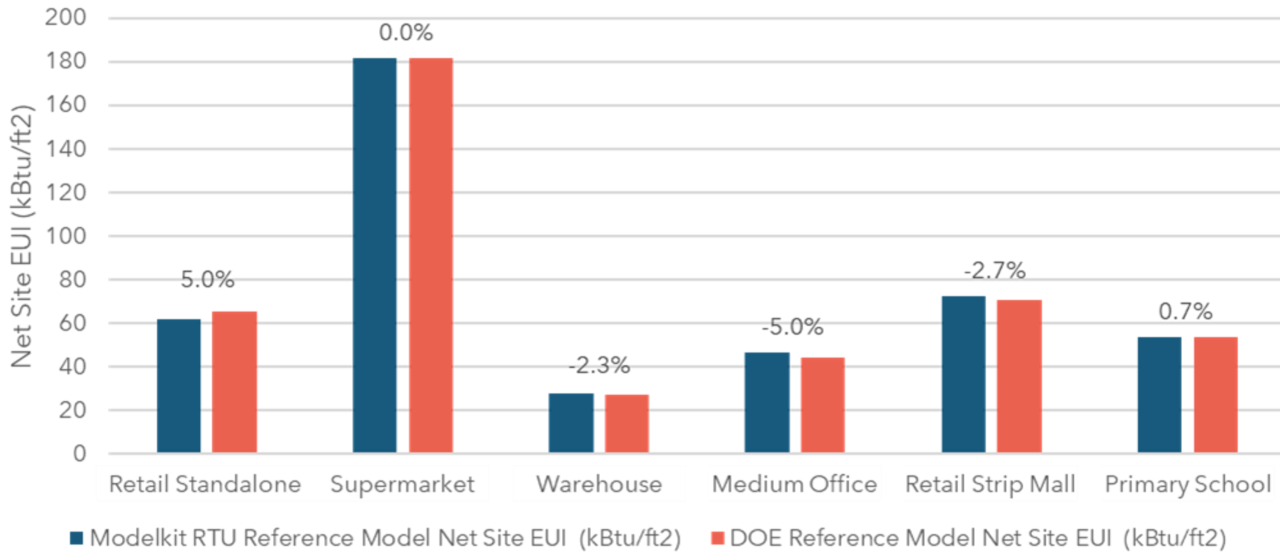

Figure 8: Annual Net Site EUI Energy Comparison by Building Type with Percent Change

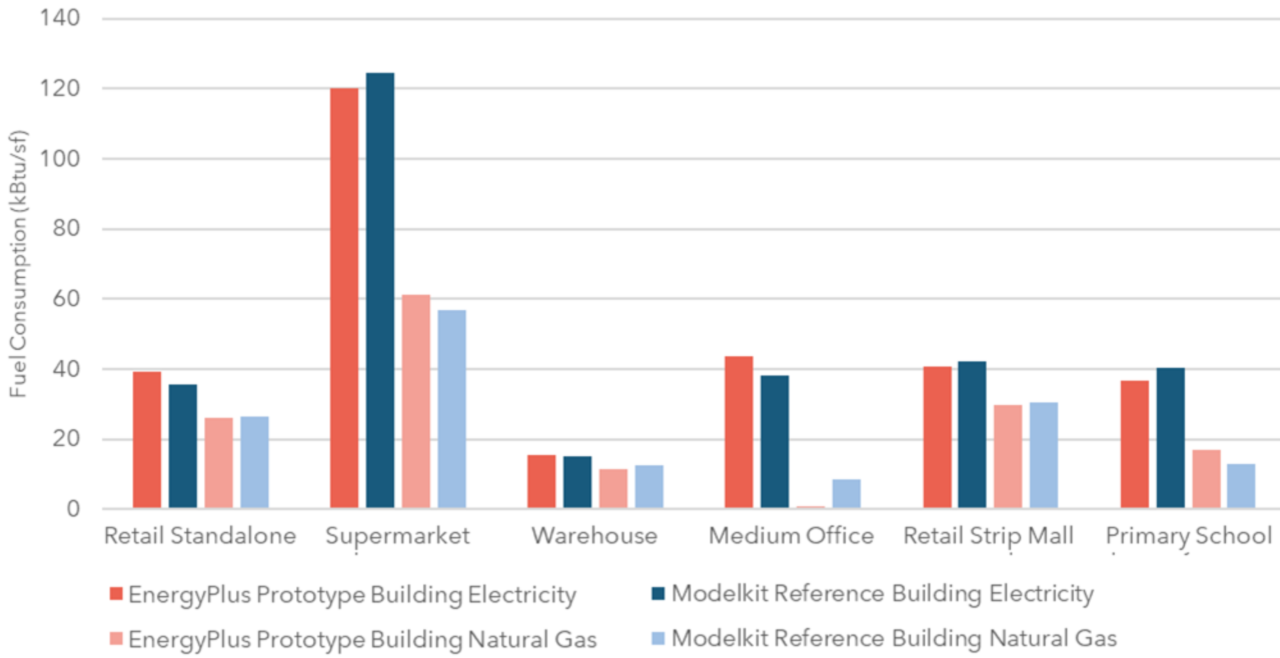

Figure 9: Total Consumption by Fuel and Building Type

In **Figure 9**, differences were anticipated for the Medium Office building type as DOE's Medium Office DOE prototype used a VAV electric reheat system, whereas this study specified a gas furnace RTU system. Consequently, electric consumption was higher and gas usage lower in the EnergyPlus v22.1 ground-truth models.

2.6.2 Measure Sensitivity Testing QAQC

The team conducted a second QC check by stress-testing key measure input parameters with extreme limits. This process ensured that custom Modelkit templates were robust and produced logical results. A total of 70 sensitivity simulations were performed using the following simulation segmentation:

- Three prototypes: Retail Strip Mall, Warehouse, and Single-Story Medium Office.[45]
- Two climate zones: 4C (Seattle, WA) and 6A (Minneapolis, MN).[46]
- Both gas RTU and ASHP RTU with electric resistance backup systems.

45 For RTU capacity-based properties (surface area and compressor speed), the project team only simulated the Retail Strip Mall prototype due to the complexity of integrating these tests within the Modelkit framework. To save time, the team chose the Retail Strip Mall building on which to focus these tests, given this building was the most responsive to RTU efficiency measures due to its high ratio of RTUs-to-floor area.

46 Performing this QAQC check in climate zone 6A allowed the team to test key measure inputs in an extreme weather environment to further validate the custom Modelkit's version.

The team tested the following key input parameters:

- Enclosure insulation R-Value.
- ERV sensible effectiveness.
- ERV latent effectiveness.
- OA temperature setpoint making the backup heat source available.
- OA temperature setpoint for compressor lockout.
- Area of the total RTU enclosure.
- Area of the RTU enclosure before the heat source.
- Area of the RTU enclosure after the heat source.
- Area of the RTU damper.
- Compressor speed.

All results from sensitivity testing met expectations. For details on this QAQC step, see Appendix C.

2.6.3 Baseline Model Checklist QAQC

After confirming the custom Modelkit version's accuracy and robustness, the team adjusted baseline model characteristics as specified in this report. To validate simulation results, the team conducted the QAQC checks shown in Table 28.

Table 28: Baseline Model QAQC Checklist

QAQC Check	Description
Daily Operation Variation	Verified that end-use operations aligned with hourly schedule specifications and environmental conditions (e.g., heating provided at varying setpoints during occupied and unoccupied hours).
Response to Outdoor Air Conditions	Ensured building loads aligned with outdoor air conditions (e.g., heating provided at cold outdoor air temperatures).
Seasonal Variation	Confirmed seasonal alignment of heating (winter) and cooling (summer) loads.
End and Fuel Use Variation	Validated end-use and fuel consumption aligned with model (e.g., fully-electric heating system not consuming gas heating).
Average Performance Metrics (COP) vs Outdoor Air Temperatures	Verified system performance aligned with model specifications (e.g., heating COP generally aligned with design conditions).
Occupant Thermal Comfort	Verified acceptable occupant thermal comfort levels within all zones (e.g., humidity within each zone only ranged from 60% to 75°F).
Warning Count	Ensured warnings did not indicate true model issues. Note that parametric analysis tools such as Modelkit produce hundreds or thousands of warnings, but most often these warnings are not an issue.
Error Count	Ensured errors did not indicate true model issues. Note that, generally, errors indicate true model issues; however, because the team developed custom

QAQC Check	Description
	measure templates to proxy-simulate certain measures, errors are present but do not represent true model issues.
Unmet Load Hours	Verified that unmet load hours fell within acceptable limits.[47]
Modeled Data Checks	Compared HVAC consumption to available modeled data sources, including DOE commercial prototypes,[48] 2022 RTU analysis,[49] and Comstock.[50]

[47] This unmet load hours' acceptance range was accordance with ASHRAE 90.1 Appendix G at 300 hours or less. For buildings with unmet load hours that exceeded this limit, the team performed additional QAQC analyses to confirm unmet load hours were not severe or problematic.

[48] "Prototype Building Models," DOE, https://www.energycodes.gov/prototype-building-models

[49] NEEA, "Energy Savings from Efficient Rooftop Units in Heating Dominated Climates," Cadeo Group, April 2022, https://neea.org/resources/energy-savings-from-efficient-rooftop-units-in-heating-dominated-climates

[50] ComStock, National Renewable Energy Laboratory, https://comstock.nrel.gov/

3 Model Results

This section details the results of over 3,300 unique energy models that the project team simulated for this analysis. Results are presented in terms of absolute EUI in kBtu/ft^2 per year. For brevity, results presented in this report, averaged across building types,[51] are shown for HVAC end-uses only (e.g., heating, cooling, fan energy). The project team delivered the full simulation results and analysis workbook to NEEA alongside this report for referencing detailed results, including results by building type.

This section breaks into three subsections, each presenting different results summaries, with the content and structure of each section tailored to the results presented:

- **Baseline Energy Consumption Results:** These baseline simulation EUI results aid in understanding how energy use varies between different climate zones and HVAC types. The EUI breakdown by HVAC end-uses defines the feasible scope of energy impacts from different measures when applied to these baseline models.
- **Measure Savings Results:** This section presents energy savings achieved from applying different measures to all models in this analysis. The report presents measure EUI results as relative impacts when compared to the corresponding baseline HVAC system. Using relative impact allowed the team to make direct comparisons of energy impacts across locations and HVAC types. Relative impacts also facilitate applications of simulation results to buildings not directly examined in the analysis, aiding in regional impact extrapolations based on building population data sets. Additionally, this section examines interactive effects by comparing the sum of impacts from individual measures to their equivalent package measures. The report examines this for the NEEA Tier 1, NEEA Tier 2, Low Switchover Temperature with NEEA Tiers, and the Cold Climate Heat Pump with NEEA Tiers measures. Lastly, this section presents potential HVAC energy impacts from a change in HVAC types. In this case, the gas RTU HVAC system used as a baseline has been compared to ASHP RTU HVAC systems and Cold Climate Heat Pump measure models.
- **Modeling Comparisons:** This section compares measure impacts with those found in the 2022 RTU analyses. While the team implemented a different modeling methodology than that used the 2022 RTU analysis, the results presented provide a helpful summary of what, if any, material differences can be seen in the findings from the two analysis efforts. Results are presented only for regions, building types, and measures where a direct overlap occurred.

[51] To present average energy savings results across building types, the team weighted EUI results by the conditioned square footage of RTUs nationally from CBECS (https://www.eia.gov/consumption/commercial/data/2018/).

3.1 Baseline Energy Consumption Results

This section provides HVAC end-use energy consumption for baseline models across all climate zones and HVAC systems. HVAC end uses include heating, cooling, and fan energy. The report breaks out baseline energy consumption results by HVAC type, presenting both in terms of (1) HVAC end uses as a percentage of total HVAC consumption; and (2) HVAC consumption as a percentage of total, whole-building energy consumption. The following figures are structured with bars that relate the percentage of HVAC EUI for each end use on the left axis; the green line relates to the axis on the right, indicating the percentage of HVAC consumption that is part of the whole-building EUI. **Figure 10** provides national average baseline consumption results by HVAC type and end use; in this figure, consumption results average across building types[52] and climate zones[53] to create singular consumption values for each HVAC type and end use.

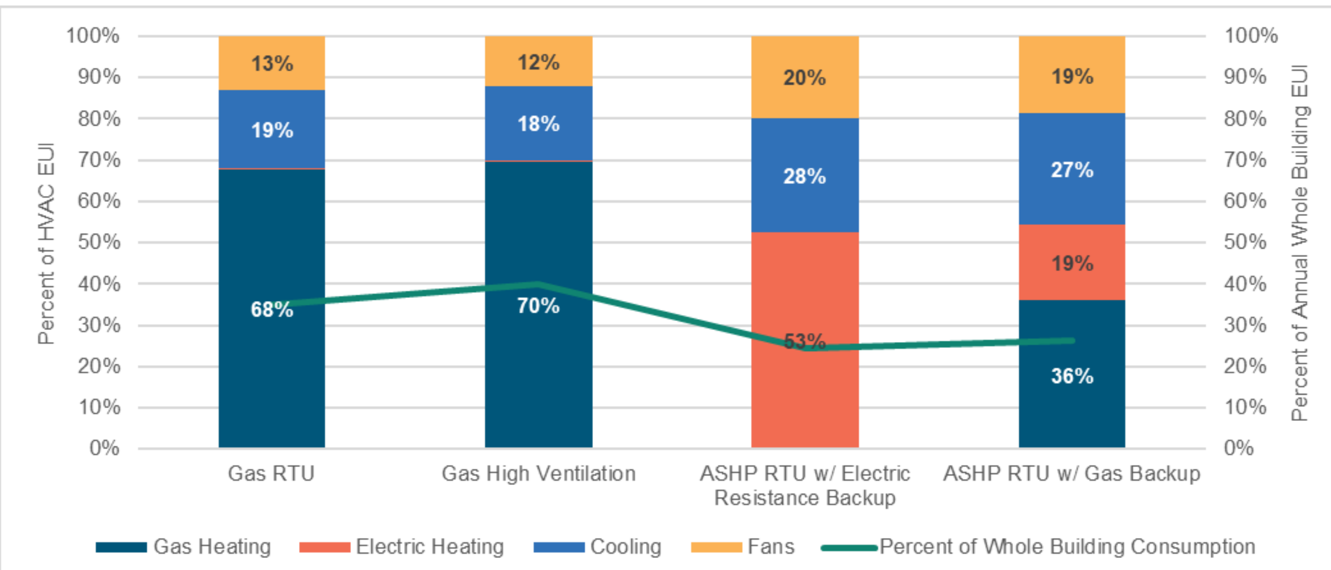

Figure 10: National Average Baseline Consumption by HVAC Type[54]

High-level findings derived from analyzing baseline consumption include the following:

- For gas RTUs, heating consumption makes up a large portion of HVAC and whole-building energy consumption, even in cooling-dominated climates. On a national average, heating consumption for gas RTUs makes up 68% of HVAC EUI.

[52] To present average energy savings results across building types, the team weighted EUI results by the conditioned square footage of RTUs nationally from CBECS (https://www.eia.gov/consumption/commercial/data/2018/).
[53] To present average energy savings results across climate zones, the team weighted EUI results by national RTU shipments from the DOE ASRAC Working Group: https://www.regulations.gov/document/EERE-2022-BT-STD-0015-0029.
[54] Some bars may not exactly equal 100% due to rounding errors.

- For gas RTUs with high ventilation rates, the team observed an increase in baseline energy consumption when increasing assumptions regarding outside air ventilation.
- Heat pump RTUs (either electric or gas backup) consume less heating than gas RTUs. In cold climates, heat pump systems observe a high heating load as they serve a significant portion of the heating load using inefficient gas or electric resistance backup heating.
- Heat pumps with gas backup offer an effective alternative to all-electric heat pumps for reducing gas consumption while balancing the increased cost of consuming electric heating. A consumer, however, will need to consider the costs to install a dual-fuel system as well as their climate to determine this hybrid system's effectiveness.

3.1.1 Gas RTU Baseline Consumption

Figure 11 provides baseline consumption results for gas RTU HVAC systems in each climate zone. Results for each climate zone derive from a weighted average of all building types. For these models, HVAC consumption makes up 20%-80% of whole-building EUI. In terms of total HVAC EUI and the percentage of whole-building EUI, models that consume the most energy are located in very cold climates, with high gas heating loads that include Great Falls, MT, Chicago, IL, and Minneapolis, MN. Models consuming the least energy are located in warm climates, where cooling energy makes up a large portion of the total HVAC EUI, such as Tucson, AZ, and Tampa, FL. This relationship aligns with the project team's expectations, given that cooling coils typically operate much more efficiently than heating coils.

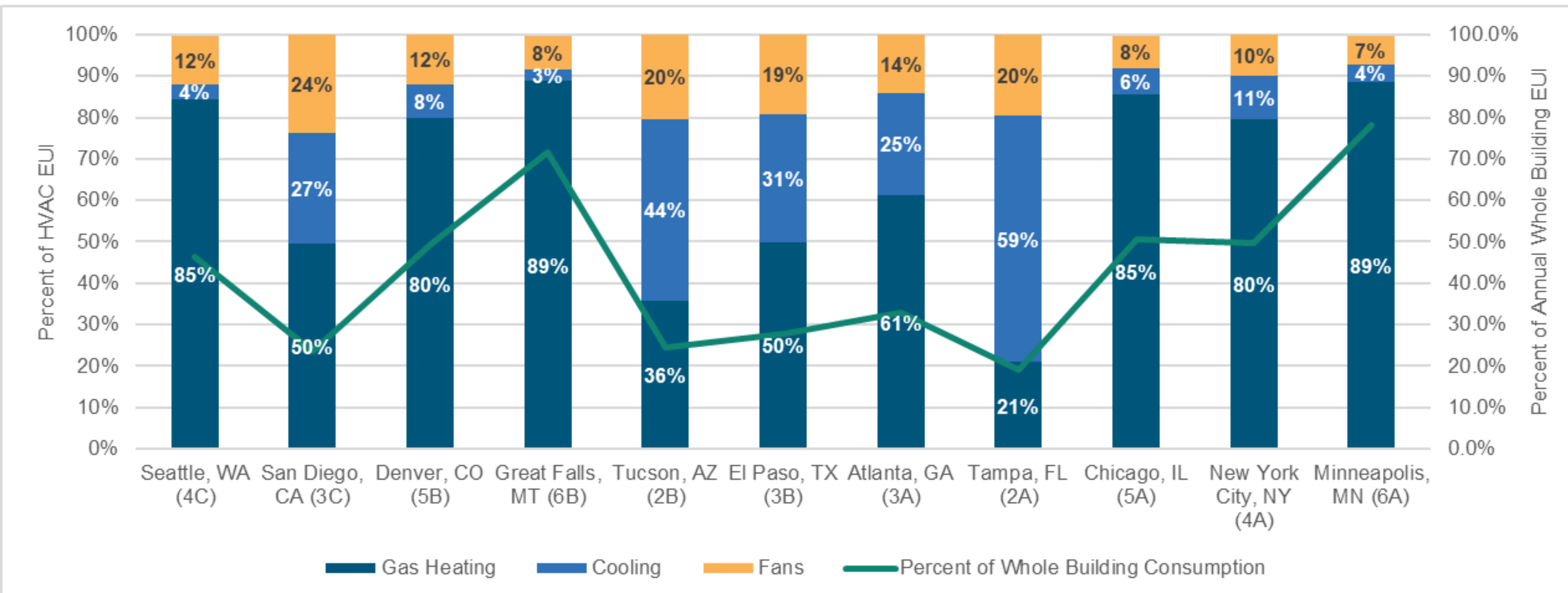

Figure 11: Gas RTU Baseline Consumption by Location[55]

3.1.2 Gas RTU with High Ventilation Baseline Consumption

Figure 12 provides baseline consumption results for gas RTU HVAC systems with ventilation rates equal to LEED v4.1 requirements, which equates to 30% higher outside air ventilation above ASHRAE 62.1-2016 requirements. Notably, this scenario is not a 100% outside air RTU (i.e., a dedicated outside air system (DOAS) system), though it remains a mixed air system. The primary research purpose for this HVAC type is to assess potential energy-savings increases for the ERV measure, given ventilation rates are typically higher than code minimum requirements, especially following the COVID-19 pandemic. As expected, HVAC energy consumption significantly increased due to increased ventilation compared to the code-minimum gas RTU system shown in **Figure 11**; HVAC consumption in this system ranges from 20%-90% of whole-building EUI. All HVAC consumption trends across locations remain the same between the two gas RTU HVAC systems.

[55] Some bars may not equal 100% exactly due to rounding errors.

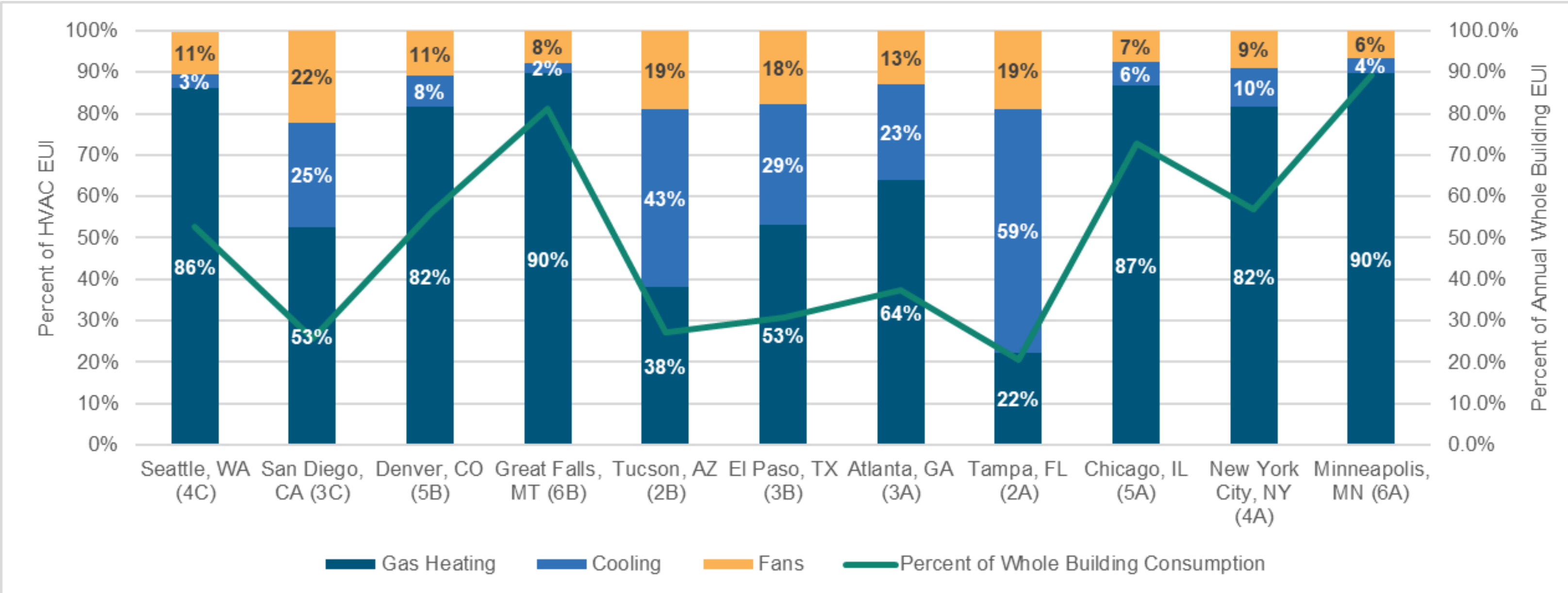

Figure 12: Gas RTU with High Ventilation Baseline Consumption by Location[56]

3.1.3 ASHP RTU with Electric Resistance Backup Baseline Consumption

Figure 13 provides baseline consumption results for ASHP RTUs, with electric resistance backup heating in each climate zone. In these all-electric systems, HVAC consumption makes up 8%-63% of whole building EUI. Gas heating can consume several times more energy than electric heating in meeting the same building load; so heating consumption is much less than the gas RTU system shown in **Figure 11**. In very cold climates (e.g., Minneapolis, MN and Great Falls, MT), outside air temperatures frequently drop below 35˚F. If backup heating is allowed to activate, it results in much higher electric heating consumption from inefficient electric resistance heating compared to mild climates (e.g., Seattle, WA). HVAC systems in warm climates, such as San Diego, CA,

[56] Some bars may not equal 100% exactly due to rounding errors.

and Tucson, AZ, consume the least amount of energy, aligning with the project team's expectations given mechanical cooling typically operates more efficiently than heating.

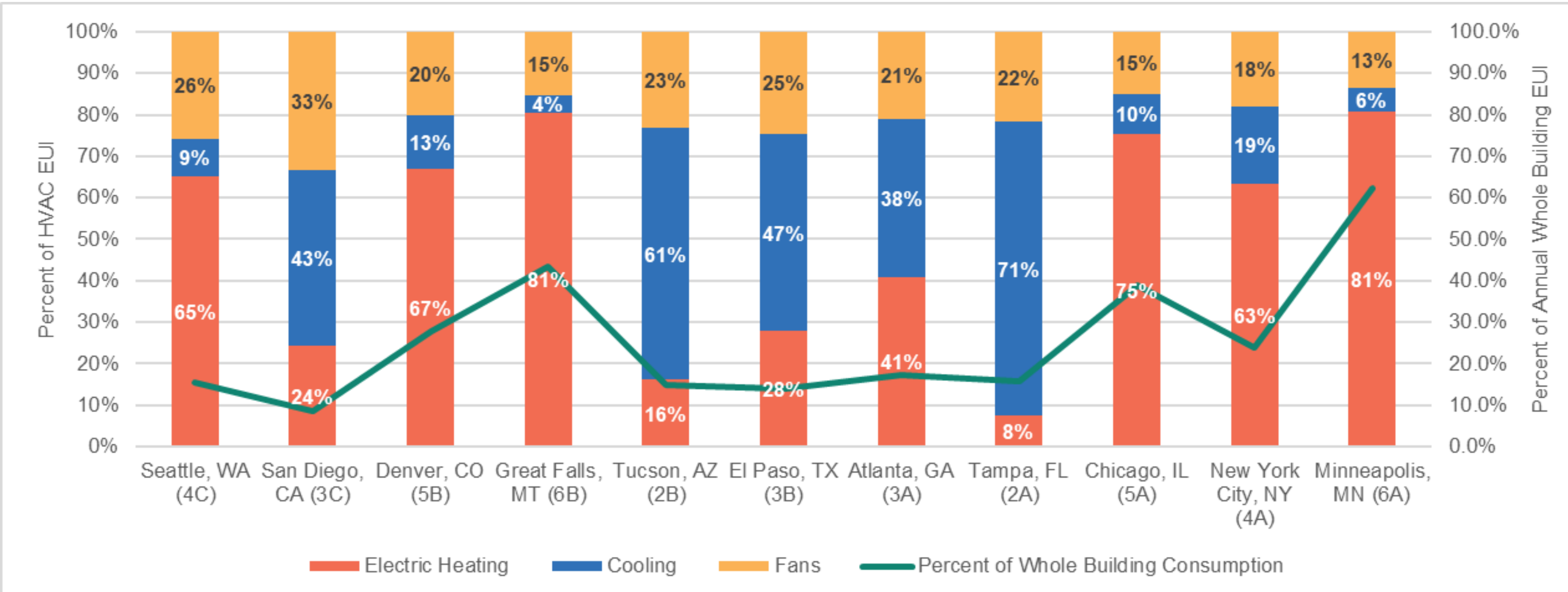

Figure 13: ASHP RTU with Electric Resistance Backup Baseline Consumption by Location[57]

3.1.4 ASHP RTU with Gas Backup Baseline Consumption

Figure 14 provides baseline consumption results for ASHP RTUs with gas backup heating in each climate zone. These results highlight that in mild or warm climates, the primary heat pump system can typically meet heating loads without use of gas backup. In very cold climates (e.g., Minneapolis, MN, and Great Falls, MT), however,

[57] Some bars may not equal 100% exactly due to rounding errors.

where outside air temperatures frequently drop below 35˚F and backup heating is allowed to turn on, backup heating provides much of the heating load and contributes the most to HVAC energy consumption.

For these dual-fuel systems, HVAC consumption makes up 8%-66% of whole-building EUI – a rate similar to an ASHP with electric backup, but lower than the gas RTU baseline. As with the all-electric ASHP RTUs, HVAC systems in warm climates (e.g., San Diego, CA, and Tucson, AZ) consume the least energy, aligning with the project team's expectations given mechanical cooling typically operates more efficiently than heating.

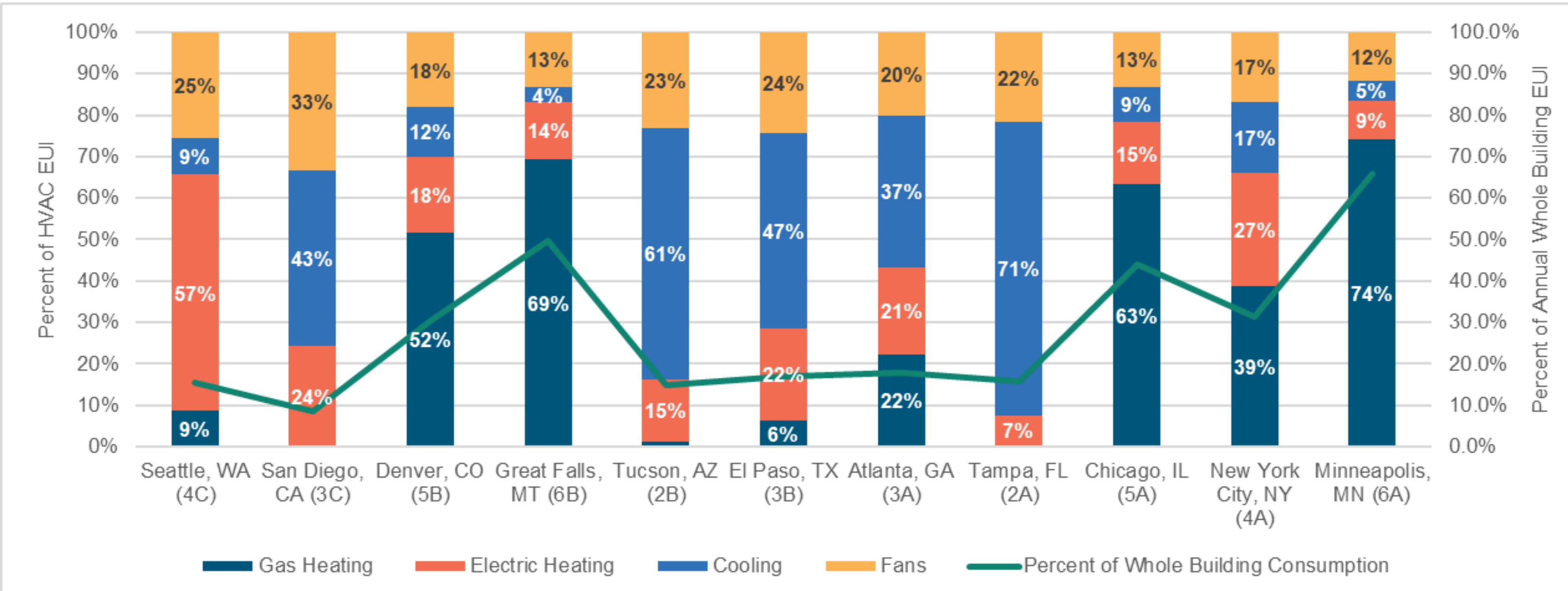

Figure 14: ASHP RTU with Gas Backup Baseline Consumption by Location[58]

[58] Some bars may not equal 100% exactly due to rounding errors.

3.2 Measure Savings Results

This section presents energy-saving outcomes derived from applying various measures to baseline models in this analysis, with the results broken into four sections:

- **National Savings Results by HVAC Type:** This section presents national average measure savings results by HVAC type. These results helped the team understand the impacts of these measures on RTU energy savings nationally for informing federal standards.
- **Results by Measure:** This section provides total HVAC measure energy savings results by HVAC type and climate zones, which provide a more detailed view of the ways measures impacts vary by region.
- **Interaction of Measures:** This section breaks down national HVAC energy savings potential by measure and summarizes any interactive effects these measures produce when combined with measure tiers.
- **Replacement of HVAC Types:** This section provides results for replacing a baseline gas RTU HVAC system with ASHP RTUs and CCHP HVAC systems. The project team summarized these results to better understand potential energy savings from changing HVAC types.

Some negative end-use savings impacts resulted from certain measure specifications (i.e., the ERV measure produced negative fan savings due to an increased total static pressure drop across the ERV, as noted in **Table 23**).

3.2.1 National Savings Results by HVAC Type

This section provides national average measure energy savings by HVAC type and measure. The team averaged savings results across building types[59] and climate zones[60] to create singular savings-potential figures for each HVAC type and measure combination nationally. Importantly, the team used national RTU shipment data to weight results across climate zones. RTU shipments are dominated by large cities in cold climates, such as New York City, NY (4A), Chicago, IL (5A), and Minneapolis (6A), creating bias in the national savings results

[59] To present average energy savings results across building types, the team weighted EUI results by the conditioned square footage of RTUs nationally from CBECS (https://www.eia.gov/consumption/commercial/data/2018/).
[60] To present average energy savings results across climate zones, the team weighted EUI results by national RTU shipments from the DOE ASRAC Working Group: https://www.regulations.gov/document/EERE-2022-BT-STD-0015-0029

toward colder climates. Regardless of this bias, national savings results provide a helpful snapshot of savings potential for informing national programs and standards.

As energy savings results vary significantly by HVAC type and because specific measures have only been assigned to certain HVAC types (shown in **Table 6**), the team broke out savings by HVAC type. To showcase measures with the greatest energy savings potential, the team organized tables in this section by measure, from highest to lowest average percent of HVAC energy savings.

For gas RTUs, NEEA Tier 2, and ERV measures produced the highest energy savings potential nationally. ERV installation proved to be the common attribute for savings between these measures.

For heat pump RTUs, combinations of Cold Climate Heat Pump and Low Switchover Temperature 1 measures produced the greatest energy savings potential nationally. The common attribute relating these measures is that the primary heat pump heating system's compressor locks out at a lower temperature, allowing the system to move heating loads from inefficient electric resistance or gas backup to the primary heat pump at outside air temperatures below 30˚F.

The NEEA Tier 2 measure also offers high energy savings potential, and the combination of heat pump upgrades and NEEA Tier 1 or 2, resulting in the largest savings potential for ASHP RTU, as shown in the Cold Climate Heat Pump + NEEA Tier 1 and Cold Climate Heat Pump + NEEA Tier 2 measure results.

HIGHEST ENERGY SAVINGS POTENTIALS NATIONALLY

For **gas RTUs**, the installation of an ERV produced the highest energy savings potential nationally, as shown in the NEEA Tier 2 and ERV measure results.

For **heat pump RTUs**, combinations of the Cold Climate Heat Pump and Low Switchover Temperature 1 measures produced the highest energy savings potential nationally. NEEA Tier 2 measure also had high energy savings potential, and the combination of the NEEA Tier 2 and Cold Climate Heat Pump produced the highest energy savings potential nationally of any measure.

On a national average, the Efficient Cooling and ERV measures offered the lowest energy savings potential for ASHP RTUs, though they achieved higher savings in certain climate zones (detailed further in section **3.2.2**). While the ERV measure offered significant heating savings potential, the fan consumption penalty from the increased total static pressure drop heavily reduced total HVAC energy savings potential. Comparatively, Efficient Cooling saved less as opportunities for heating savings were higher in most climates (i.e., more baseline consumption to reduce) and because cooling systems in the baseline were already very efficient.

Though Low Switchover Temperature 1 and 2 provide control improvements, they do not change the heat pump's capacity performance curves. ASHP RTU results show how control methods can impact heat pumps' energy savings potential. The Cold Climate Heat Pump measure serves both as a controls measure and a capacity curve improvement for the heat pump, resulting in about 1%-3% more HVAC energy savings compared to switchover temperature measures for both heat pump systems. For the all-electric heat pump, the NEEA Tier 2 measure resulted in HVAC energy savings (12%), similarly to the Cold Climate Heat Pump (13%) and Low Switchover Temperature 1 and 2 measures (11%-12%). NEEA Tier 2 measures are not heat pump improvements; so they could be added to a system regardless of HVAC type.

3.2.1.1 Gas RTU National Measure Savings

Table 29 provides national average energy savings by measure for the gas RTU HVAC type. As shown, the NEEA Tier 2 measure offered the greatest savings potential, followed by the ERV measure. This finding highlights the significant energy savings potential for installing ERVs in addition to other RTU upgrades for gas-fueled systems.

Table 29: Gas RTU National Average Energy Savings by Measure

Measure	Gas Heating Savings (kBTU/ft²)	Cooling Savings (kBTU/ft²)	Fan Savings (kBTU/ft²)	Percent HVAC Savings
NEEA Tier 2	6.8	0.28	0.38	20%
ERV	3.9	0.24	-0.60	11%
NEEA Tier 1	2.9	0.03	0.18	9.4%
Enclosure Leakage	1.9	0.06	0.07	6.0%
Enclosure Insulation R12	1.5	0.05	0.08	5.2%
Enclosure Insulation R8	1.4	0.04	0.07	4.7%
Low-Leakage Dampers	1.4	-0.01	0.10	4.2%
Efficient Cooling	0.0	0.35	0.0	1.8%

3.2.1.2 Gas RTU with High Ventilation National Measure Savings

The team simulated gas RTUs with a high ventilation HVAC type only using the ERV measure to assess how the ERV measure's energy savings potential changes, given ventilation rates are typically higher than code minimum requirements, especially after the COVID-19 pandemic. Most modeling efforts (including this one) assume code-minimum ventilation rates, which could mean they underestimate the savings potential from ERVs in the real world. **Table 30** provides ERV measure savings for the gas RTU system and the gas RTU with high ventilation, also graphed in **Figure 15**. On a national average, HVAC energy savings are 3% higher for RTUs with high ventilation.

Table 30: Gas RTU and Gas RTU with High Ventilation National Average Energy Savings for ERV Measure

HVAC Type	Measure	Gas Heating Savings (kBTU/ft^2)	Cooling Savings (kBTU/ft^2)	Fan Savings (kBTU/ft^2)	Percent HVAC Savings
Gas RTU with High Ventilation	ERV	5.3	0.34	-0.56	14%
Gas RTU	ERV	3.9	0.24	-0.60	11%

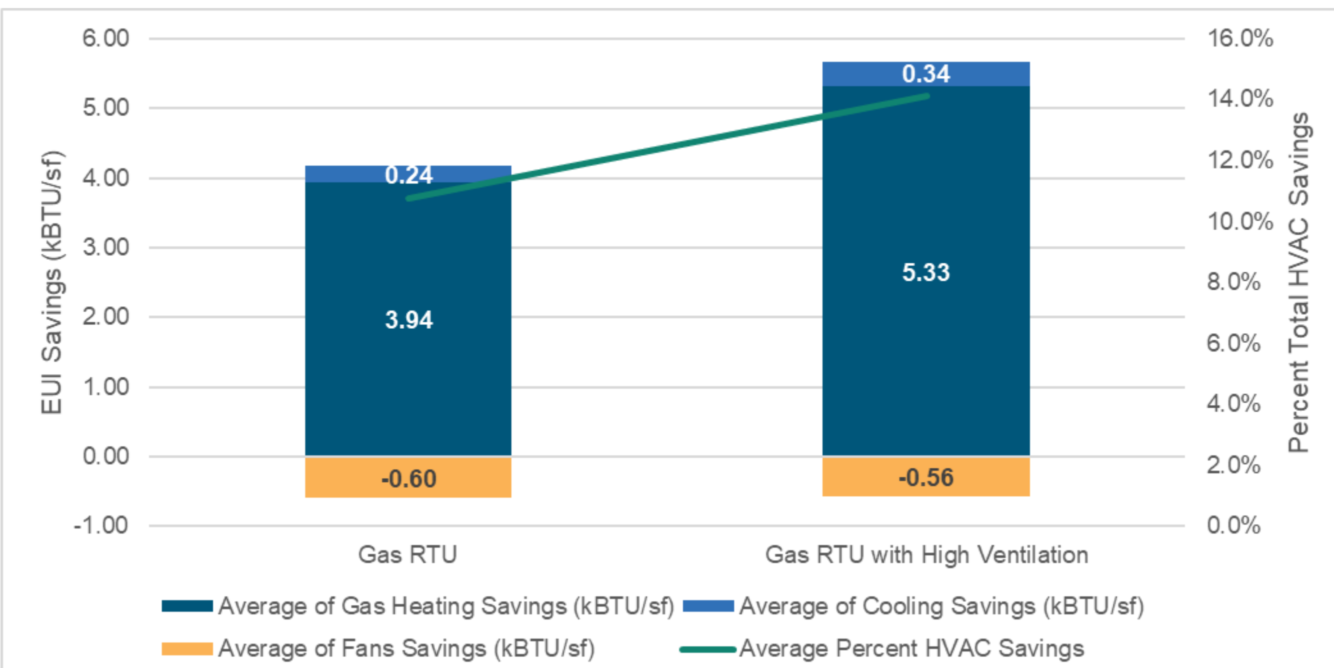

Figure 15: Gas RTU and Gas RTU with High Ventilation National Average Energy Savings for ERV Measure

3.2.1.3 ASHP RTU with Electric Resistance Backup National Measure Savings

Table 31 provides national average energy savings by measure for the ASHP RTU with an electric resistance backup HVAC type. More measures exist for this HVAC type as several measures serve as heat pump upgrades not applicable to gas RTUs.

Table 31: ASHP RTU with Electric Resistance Backup Heating National Energy Average Savings by Measure

Measure	Electric Heating Savings ($kBTU/ft^2$)	Cooling Savings ($kBTU/ft^2$)	Fan Savings ($kBTU/ft^2$)	Percent HVAC Savings
Cold Climate Heat Pump + NEEA Tier 2	5.7	0.3	-0.06	23%
Low Switchover Temperature 1 + NEEA Tier 2	5.1	0.3	-0.13	21%
Cold Climate Heat Pump + NEEA Tier 1	4.6	0.03	0.56	20%
Low Switchover Temperature 1 + NEEA Tier 1	4.0	0.03	0.51	18%
Cold Climate Heat Pump	3.3	0.0	0.35	13%
Low Switchover Temperature 2	3.0	0.0	0.32	12%
NEEA Tier 2	3.0	0.3	-0.45	12%
Low Switchover Temperature 1	2.6	0.0	0.30	11%
NEEA Tier 1	1.8	0.03	0.26	8.4%
Enclosure Leakage	1.0	0.06	0.07	4.8%
Enclosure Insulation R12	0.87	0.05	0.10	4.3%
Low-Leakage Dampers	0.92	-0.01	0.15	4.0%
Enclosure Insulation R8	0.78	0.04	0.09	3.9%
Efficient Cooling	0.0	0.50	0.0	3.5%
ERV	1.22	0.27	-0.76	3.4%

3.2.1.4 ASHP RTU with Gas Backup National Measure Savings

Table 32 provides national average energy savings by measure for the ASHP RTU with a gas backup HVAC type. More measures are available for this HVAC type as several measure serve as heat pump upgrades not applicable to gas RTUs. In general, savings trends for this HVAC type match the all-electric ASHP RTU.

Table 32: ASHP RTU with Gas Backup National Average Energy Savings by Measure

Measure	Gas Heating Savings (kBTU/ft²)	Electric Heating Savings (kBTU/ft²)	Cooling Savings (kBTU/ft²)	Fan Savings (kBTU/ft²)	Percent HVAC Savings
Cold Climate Heat Pump + NEEA Tier 2	9.3	-1.9	0.31	-0.06	27%
Low Switchover Temperature 1 + NEEA Tier 2	7.1	-0.7	0.31	-0.13	24%
Cold Climate Heat Pump + NEEA Tier 1	9.2	-2.8	0.03	0.56	23%
Low Switchover Temperature 1 + NEEA Tier 1	6.9	-1.6	0.03	0.51	20%
Cold Climate Heat Pump	8.75	-3.8	0.0	0.35	17%
Low Switchover Temperature 2	7.5	-3.0	0.0	0.32	16%
Low Switchover Temperature 1	6.1	-2.4	0.0	0.30	14%
NEEA Tier 2	2.1	1.3	0.31	-0.45	12%
NEEA Tier 1	1.8	0.4	0.31	0.26	8.7%
Enclosure Leakage	0.91	0.28	0.06	0.07	4.9%
Enclosure Insulation R12	0.78	0.24	0.05	0.10	4.5%
Low-Leakage Dampers	0.94	0.16	-0.01	0.15	4.1%
Enclosure Insulation R8	0.70	0.22	0.04	0.09	4.0%
ERV	0.36	0.93	0.27	-0.76	3.4%
Efficient Cooling	0.0	0.0	0.50	0.0	3.4%

3.2.2 Results by Measure

This section provides total HVAC percent energy savings results by measure for all climate zones and HVAC types.

Table 33 summarizes these results by ranking the measures by energy savings impact for each climate zone. To compare and rank impacts across all measures, the table is specific only to the all-electric ASHP RTU; measure rankings for gas RTUs results may differ.[61] This table also provides a heat map that shows the relative proprortion of average HVAC energy savings across climate zones, with the darker coloring relating to the greatest energy savings.

Lastly, the table provides energy savings per square foot estimates for measures with the highest and lowest energy savings potential for each climate zone, illustrating maximum and mininimum savings potential ranges. As shown, this analysis found the measure combinations of Low Switchover Temperature and Cold Climate Heat Pump with NEEA Tier 1 and NEEA Tier 2 specifications consistently produced the highest total HVAC energy savings in all climate zones.

For heating-dominated climates, simulated in **red**, individual measures with the highest total HVAC energy savings potential included Cold Climate Heat Pump, Low Switchover Temperature, and NEEA Tier 2. Measures for heating-dominated climates typically include the greatest energy savings potential, as shown by darker green coloring. For cooling-dominated climates, simulated in **blue**, individual measures with the highest total HVAC energy savings potential often included NEEA Tier 2, ERV, and Efficient Cooling.

Notably, the absolute magnitude of energy savings varies across each climate zone and building type, which may impact cost-effectiveness for some measures. For more detailed measure energy savings

MEASURE IMPACTS BY CLIMATE ZONE

Across all climates, combinations of Cold Climate Heat Pump and Low Switchover Temperature with NEEA Tier 1 and NEEA Tier 2 specifications consistently had the highest total HVAC energy savings potential.

For individual measures in **heating-dominated climates**, Cold Climate Heat Pump, Low Switchover Temperature, and NEEA Tier 2 measures often had the highest energy savings potential.

For individual measures **cooling-dominated climates**, NEEA Tier 2, ERV, and Efficient Cooling often had the highest energy savings potential.

[61] As an example, the ERV measure has a much higher impact and ranking in San Diego (3C) for gas RTUs. See the accompanying Savings Workbook for final measure-results comparisons for each climate zone.

results, including those by HVAC end use (e.g., gas heating, electric heating, cooling, and fans), refer to the accompanying savings results workbook.

Table 33: ASHP RTU with Electric Resistance Backup Relative Measure Performance by Location

Most Impactful -> Least Impactful	Seattle, WA (4C)	Denver, CO (5B)	Great Falls, MT (6B)	Chicago, IL (5A)	New York City, NY (4A)	Minneapolis, MN (6A)	San Diego, CA (3C)	Tucson, AZ (2B)	El Paso, TX (3B)	Atlanta, GA (3A)	Tampa, FL (2A)
	CCHP + NEEA T2 (2.3 kBTU/ft^2)	CCHP + NEEA T2 (7.3 kBTU/ft^2)	CCHP + NEEA T2 (10.5 kBTU/ft^2)	CCHP + NEEA T2 (10.2 kBTU/ft^2)	CCHP + NEEA T2 (5.2 kBTU/ft^2)	CCHP + NEEA T2 (14.6 kBTU/ft^2)	CCHP + NEEA T1 (0.3 kBTU/ft^2)	CCHP + NEEA T2 (1.1 kBTU/ft^2)	CCHP + NEEA T2 (1.1 kBTU/ft^2)	CCHP + NEEA T2 (2.7 kBTU/ft^2)	CCHP + NEEA T2 (1.2 kBTU/ft^2)
	LST 1 + NEEA T2	CCHP + NEEA T1	CCHP + NEEA T1	CCHP + NEEA T1	LST 1 + NEEA T2	CCHP + NEEA T1	LST 1 + NEEA T1	LST 1 + NEEA T2	LST 1 + NEEA T2	LST 1 + NEEA T2	LST 1 + NEEA T2
	NEEA T2	LST 1 + NEEA T2	LST 1 + NEEA T2	LST 1 + NEEA T2	CCHP + NEEA T1	LST 1 + NEEA T2	CCHP + NEEA T2	NEEA T2	NEEA T2	CCHP + NEEA T1	NEEA T2
	ERV	LST 1 + NEEA T1	LST 1 + NEEA T1	LST 1 + NEEA T1	LST 1 + NEEA T1	LST 1 + NEEA T1	LST 1 + NEEA T2	ERV	CCHP + NEEA T1	LST 1 + NEEA T1	ERV
	CCHP + NEEA T1	CCHP	CCHP	CCHP	NEEA T2	CCHP	NEEA T2	EC	LST 1 + NEEA T1	NEEA T2	EC
	LST 1 + NEEA T1	LST 2	NEEA T2	LST 2	CCHP	LST 2	EC	CCHP + NEEA T1	NEEA T1	ERV	EL
	NEEA T1	LST 1	LST 2	LST 1	LST 2	LST 1	NEEA T1	LST 1 + NEEA T1	ERV	CCHP	CCHP + NEEA T1
	EL	NEEA T2	LST 1	NEEA T2	LST 1	NEEA T2	EL	NEEA T1	EC	LST 2	LST 1 + NEEA T1
	EI R12	NEEA T1	NEEA T1	NEEA T1	ERV	NEEA T1	EI R12	EL	CCHP	LST 1	NEEA T1
	EI R8	ERV	ERV	ERV	NEEA T1	EL	EI R8	EI R12	LST 2	NEEA T1	EI R12
	LLD	EI R12	EL	EL	EL	LLD	LLD	EI R8	LST 1	EL	EI R8
	CCHP	EL	LLD	LLD	EI R12	EI R12	CCHP	LLD	EI R12	EC	LLD
	LST 2	EI R8	EI R12	EI R12	EI R8	EI R8	LST 2	CCHP	EL	EI R12	CCHP
	LST1	LLD	EI R8	EI R8	LLD	ERV	LST 1	LST 2	EI R8	EI R8	LST 2
	EC (0.1 kBTU/ft^2)	EC (0.3 kBTU/ft^2)	EC (0.2 kBTU/ft^2)	EC (0.4 kBTU/ft^2)	EC (0.4 kBTU/ft^2)	EC (0.3 kBTU/ft^2)	ERV (0.0 kBTU/ft^2)	LST 1 (0.1 kBTU/ft^2)	LLD (0.1 kBTU/ft^2)	LLD (0.4 kBTU/ft^2)	LST 1 (0.0 kBTU/ft^2)

3.2.2.1 Enclosure Insulation Energy Savings Results

Table 34 and **Table 35** provide measure energy savings results for increasing RTU enclosure insulation to R8 and R12, respectively. Percent HVAC energy savings for increasing RTU enclosure insulation range from 1.3%-7.2% for R8 insulation and 1.4%-7.9% for R12 insulation, depending on the HVAC type and location. Colder climate zones offer the highest savings potential, with the highest savings potential located in Denver, CO (5B) and the lowest savings potential located in San Diego, CA (3C) and Tampa, FL (2A).

Table 34: Enclosure Insulation R8 Measure Energy Savings

Climate Zones	Gas RTU Percent HVAC Savings	ASHP RTU with Electric Resistance Backup Percent HVAC Savings	ASHP RTU with Gas Backup Percent HVAC Savings
Seattle, WA (4C)	5.5%	4.4%	4.5%
San Diego, CA (3C)	2.9%	1.3%	1.3%
Denver, CO (5B)	7.2%	6.5%	6.8%
Great Falls, MT (6B)	6.4%	5.7%	5.8%
Tucson, AZ (2B)	3.8%	2.8%	2.8%
El Paso, TX (3B)	4.5%	3.1%	3.2%
Atlanta, GA (3A)	4.3%	3.4%	3.6%
Tampa, FL (2A)	1.9%	1.4%	1.4%
Chicago, IL (5A)	5.5%	5.0%	5.1%
New York City, NY (4A)	4.9%	4.3%	4.5%
Minneapolis, MN (6A)	5.5%	5.1%	5.2%

Table 35: Enclosure Insulation R12 Measure Energy Savings

Climate Zones	Gas RTU Percent HVAC Savings	ASHP RTU with Electric Resistance Backup Percent HVAC Savings	ASHP RTU with Gas Backup Percent HVAC Savings
Seattle, WA (4C)	6.1%	4.9%	5.0%
San Diego, CA (3C)	3.3%	1.4%	1.4%
Denver, CO (5B)	7.9%	7.3%	7.5%
Great Falls, MT (6B)	7.1%	6.3%	6.4%
Tucson, AZ (2B)	4.2%	3.1%	3.1%

Climate Zones	Gas RTU Percent HVAC Savings	ASHP RTU with Electric Resistance Backup Percent HVAC Savings	ASHP RTU with Gas Backup Percent HVAC Savings
El Paso, TX (3B)	5.0%	3.4%	3.5%
Atlanta, GA (3A)	4.8%	3.8%	3.9%
Tampa, FL (2A)	2.1%	1.6%	1.6%
Chicago, IL (5A)	6.1%	5.6%	5.7%
New York City, NY (4A)	5.5%	4.8%	4.9%
Minneapolis, MN (6A)	6.1%	5.6%	5.8%

Simulating two insulation levels allowed team to assess potential savings-impact differences. The simulations indicated that about 90% of potential energy savings from simulating R12 already have been achieved by increasing enclosure insulation levels to R8. This finding suggests that diminishing savings returns occur when increasing enclosure insulation past R8 due to additional costs from a manufacturer's perspective.

3.2.2.2 Enclosure Leakage Energy Savings Results

Table 36 provides measure energy savings results for decreasing RTU enclosure leakage. Percent HVAC energy savings for this measure range from 1.3%-7.7%, depending on HVAC types and locations. Colder climate zones offer the greatest savings potential, with the highest savings potential located in Great Falls, MT (6B), and the lowest savings potential located in San Diego, CA (3C), and Tampa, FL (2A). As increased enclosure leakage can act as additional economizing, cooling savings can be penalized, and results are negative in mild climates such as Seattle, WA (4C) and San Diego, CA (3C).

This was the first time that the team modeled enclosure leakage as a measure; so the magnitude of energy savings potential was unknown. The resulting key finding is that the Enclosure Leakage measure, like the Low-Leakage Dampers or Enclosure Insulation measures, is a moderate savings measure nationally (as detailed in section **3.2.1**).

New Measure: This is the first time energy savings from reducing enclosure leakage have been estimated. As such, the magnitude of savings was unknown. This analysis shows that the Enclosure Leakage measure produces modest savings nationally, akin to Low-Leakage Dampers and Enclosure Insulation.

Table 36: Enclosure Leakage Measure Energy Savings

Climate Zones	Gas RTU Percent HVAC Savings	ASHP RTU with Electric Resistance Backup Percent HVAC Savings	ASHP with Gas Backup Percent HVAC Savings
Seattle, WA (4C)	7.0%	5.1%	5.2%
San Diego, CA (3C)	3.4%	1.3%	1.3%
Denver, CO (5B)	7.3%	6.1%	6.3%
Great Falls, MT (6B)	7.7%	6.5%	6.7%
Tucson, AZ (2B)	4.2%	3.1%	3.1%
El Paso, TX (3B)	4.7%	3.1%	3.1%
Atlanta, GA (3A)	5.5%	4.2%	4.3%
Tampa, FL (2A)	3.1%	2.6%	2.6%
Chicago, IL (5A)	7.4%	6.5%	6.7%
New York City, NY (4A)	6.7%	5.5%	5.7%
Minneapolis, MN (6A)	7.6%	6.7%	6.9%

3.2.2.3 Low-Leakage Dampers Energy Savings Results

Low-Leak Dampers have modest energy savings potential and are an easily accessible upgrade.

Table 37 provides measure energy savings results for decreasing damper leakage. Percent HVAC energy savings for this measure range from 0.2%-8.0%, depending on HVAC types and locations. Colder climate zones offer the greatest savings potential, with the highest savings potential located in Minneapolis, MN (6A), and Great Falls, MT (6B), and with the lowest savings potential located in Tampa, FL (2A). As increased damper leakage can act as additional economizing, cooling savings can be penalized and are negative in most climates.

The Low-Leakage Dampers measure is well-known by the RTU industry, and low leak dampers are available from all major manufacturers. Additionally, low-leak dampers have been required by national building codes for many years. Heating or cooling test procedures for RTU efficiency ratings (e.g., IEER, IVEC, IVHE) do not account for damper leakage as the test method prescribes blocking off outside air dampers before testing.

Based on interviews with manufacturers, the research team understands that many RTUs (as much as one-half) remain installed with dampers that do not meet leakage ratings prescribed in energy codes. Manual Dampers (which would have a much higher leakage rate than the baseline leakage rate used in this modeling study) may still be selected for some smaller RTUs, meaning the savings potential from a low leakage upgrade could be much higher than the results shown below. Low-Leak Dampers installed as an upgrade may not be applicable for every RTU installed (e.g., a new build that triggers commercial code requirements), but for replacement units that may not have selected Low-Leak Dampers, this measure offers moderate savings potential and an easily accessible upgrade.

Table 37: Low-Leakage Dampers Measure Energy Savings

Climate Zone	Gas RTU Percent HVAC Savings	ASHP RTU with Electric Resistance Backup Percent HVAC Savings	ASHP RTU with Gas Backup Percent HVAC Savings
Seattle, WA (4C)	3.7%	3.4%	3.4%
San Diego, CA (3C)	1.5%	0.3%	0.3%
Denver, CO (5B)	5.8%	6.1%	6.4%
Great Falls, MT (6B)	7.5%	7.9%	8.0%
Tucson, AZ (2B)	1.6%	0.8%	0.8%
El Paso, TX (3B)	2.4%	1.6%	1.7%
Atlanta, GA (3A)	3.1%	2.6%	2.9%
Tampa, FL (2A)	0.5%	0.2%	0.2%
Chicago, IL (5A)	6.6%	6.7%	6.9%
New York City, NY (4A)	4.0%	3.9%	4.1%
Minneapolis, MN (6A)	7.1%	7.4%	7.5%

3.2.2.4 Efficient Cooling Energy Savings Results

Table 38 provides measure energy savings results for increasing RTU Cooling Efficiency. This measure only impacts cooling consumption. Percent HVAC energy savings for this measure range from 0.3%-9.0%, depending on HVAC types and locations. Warmer climate zones offer the highest savings potential, with the highest potential located in Tampa, FL (2A), and the lowest potential located in Great Falls, MT (6B).

While efficient cooling is a focus of some specifications for commercial RTUs, the Efficient Cooling measure has small-to-moderate energy savings nationally, largely due to baseline systems already achieving high cooling efficiency.

Efficient Cooling is another historically well-considered and adopted efficiency measure for RTUs. Many RTU programs offer incentives for increased efficiency ratings, and Efficient Cooling is the primary focus of ENERGY STAR's specification for light commercial RTUs. Over time, minimum cooling efficiencies required at the federal level have increased, and RTUs sold today are much more efficient than previous units. This modeling effort found that, on a national level, the Efficient Cooling measure saved small-to-moderate amounts. The baseline system for cooling is already very efficient, and the baseline cooling load is much smaller than for heating, resulting in lower savings potential from the Efficient Cooling measure.

Table 38: Efficient Cooling Measure Energy Savings

Climate Zones	Gas RTU Percent HVAC Savings	ASHP RTU with Electric Resistance Backup Percent HVAC Savings	ASHP RTU with Gas Backup Percent HVAC Savings
Seattle, WA (4C)	0.3%	1.1%	1.1%
San Diego, CA (3C)	2.5%	5.3%	5.3%
Denver, CO (5B)	0.8%	1.7%	1.5%
Great Falls, MT (6B)	0.3%	0.5%	0.5%
Tucson, AZ (2B)	4.1%	7.7%	7.7%
El Paso, TX (3B)	2.9%	6.0%	6.0%
Atlanta, GA (3A)	2.4%	4.9%	4.7%
Tampa, FL (2A)	5.6%	9.0%	9.0%
Chicago, IL (5A)	0.6%	1.2%	1.1%
New York City, NY (4A)	1.0%	2.4%	2.2%
Minneapolis, MN (6A)	0.4%	0.8%	0.6%

3.2.2.5 ERV Energy Savings Results

Table 39 provides measure energy savings results for installing ERVs. Fan savings for the ERV measure are negative due to increased total static pressure drops across the ERV, as noted in **Table 23**.

Energy savings potential varies widely across climate zones and HVAC systems. Percent HVAC energy savings for this measure range from 0.1%-31.8%, depending on HVAC types and locations. For gas RTUs, savings potential is consistently high for all climate zones, ranging from 5.5%-31.8%. Mild heating-dominated climates such as Seattle, WA (4C), offer the highest savings potential. Warm and cold climates also offer significant savings potential by reducing the amount of heat and moister air entering the building and by recovering heat and moisture from the RTU's exhaust air stream. For ASHP systems, San Diego, CA (3C), poses a net-negative savings potential, given the fan penalty. It should be noted that in very cold climates, such as Minneapolis, MN (6A), the benefit of the ERV is dependent on the frost control strategy utilized to avoid the heat recovery device from freezing. As a default control in all climate zones, this modeling was based on an exhaust-only freeze protection strategy, where the building would maintain ventilation and bypass the energy recovery device to mitigate frost formation.

Unlike other measures, the project team assessed measure energy savings impacts when installing an ERV in a gas RTU with ventilation levels greater than code minimum requirements, given ventilation rates are typically higher than code minimum requirements, especially following the COVID-19 pandemic. Energy savings impacts increase from 1%-5% for gas RTUs when simulating units with high ventilation rates.

Table 39: ERV Measure Energy Savings

Climate Zones	Gas RTU Percent HVAC Savings	Gas RTU with High Ventilation Percent HVAC Savings	ASHP RTU with Electric Resistance Backup Percent HVAC Savings	ASHP RTU with Gas Backup Percent HVAC Savings
Seattle, WA (4C)	26.9%	31.8%	13.1%	13.0%
San Diego, CA (3C)	11.0%	15.8%	-0.1%	-0.1%
Denver, CO (5B)	9.9%	13.1%	2.7%	2.9%
Great Falls, MT (6B)	8.2%	10.2%	2.2%	2.3%
Tucson, AZ (2B)	9.6%	14.3%	4.1%	4.1%
El Paso, TX (3B)	11.6%	17.0%	3.5%	3.5%
Atlanta, GA (3A)	14.0%	18.3%	5.1%	5.0%

Climate Zones	Gas RTU Percent HVAC Savings	Gas RTU with High Ventilation Percent HVAC Savings	ASHP RTU with Electric Resistance Backup Percent HVAC Savings	ASHP RTU with Gas Backup Percent HVAC Savings
Tampa, FL (2A)	7.7%	11.4%	4.2%	4.2%
Chicago, IL (5A)	8.6%	10.6%	2.4%	2.5%
New York City, NY (4A)	16.0%	19.7%	5.8%	5.6%
Minneapolis, MN (6A)	5.5%	6.9%	1.3%	1.5%

3.2.2.6 NEEA Tier 1 Energy Savings Results

Table 40 provides measure energy savings results for the NEEA Tier 1 measure package. Percent HVAC energy savings for this measure range from 1.7%-14.4%, depending on HVAC types and locations. Colder climate zones offer the greatest savings potential, with the highest savings potential located in Great Falls, MT (6B), and the lowest savings potential located in Tampa, FL (2A). The **Interaction of Measures** (**3.2.3**) section explores the interactive effects of each measure for NEEA Tier 1

Table 40: NEEA Tier 1 Measure Energy Savings

Climate Zones	Gas RTU Percent HVAC Savings	ASHP RTU with Electric Resistance Backup Percent HVAC Savings	ASHP RTU with Gas Backup Percent HVAC Savings
Seattle, WA (4C)	9.6%	8.1%	8.3%
San Diego, CA (3C)	4.7%	1.7%	1.7%
Denver, CO (5B)	13.6%	13.4%	14.0%
Great Falls, MT (6B)	14.4%	14.2%	14.4%
Tucson, AZ (2B)	5.7%	3.8%	3.8%
El Paso, TX (3B)	7.2%	4.9%	5.0%
Atlanta, GA (3A)	7.8%	6.4%	6.9%
Tampa, FL (2A)	2.6%	1.7%	1.7%
Chicago, IL (5A)	12.7%	12.5%	12.9%
New York City, NY (4A)	9.4%	8.7%	9.1%
Minneapolis, MN (6A)	13.3%	13.3%	13.5%

3.2.2.7 NEEA Tier 2 Energy Savings Results

Table 41 provides measure energy savings results for the NEEA Tier 2 measure package. Percent HVAC energy savings for this measure range from 1.6%-36.1%, depending on HVAC types and locations. Colder climate zones offer the greatest savings potential, with the highest savings potential located in Seattle, WA (4C), and the lowest savings potential located in San Diego, CA (3C). The **Interaction of Measures** (**3.2.3**) section explores interactive effects of each measure for NEEA Tier 2.

Table 41: NEEA Tier 2 Measure Energy Savings

Climate Zones	Gas RTU Percent HVAC Savings	ASHP RTU with Electric Resistance Backup Percent HVAC Savings	ASHP RTU with Gas Backup Percent HVAC Savings
Seattle, WA (4C)	36.1%	21.4%	21.5%
San Diego, CA (3C)	15.3%	1.6%	1.6%
Denver, CO (5B)	23.3%	16.3%	16.9%
Great Falls, MT (6B)	22.5%	16.4%	16.7%
Tucson, AZ (2B)	15.3%	8.3%	8.3%
El Paso, TX (3B)	18.6%	8.5%	8.7%
Atlanta, GA (3A)	21.7%	11.7%	12.1%
Tampa, FL (2A)	10.5%	6.3%	6.3%
Chicago, IL (5A)	21.2%	15.0%	15.4%
New York City, NY (4A)	25.4%	14.6%	14.8%
Minneapolis, MN (6A)	18.7%	14.6%	15.0%

3.2.2.8 Low Switchover Temperatures Energy Savings Results

Table 42 provides measure energy savings results for the Low Switchover Temperature 1 measure (i.e., the compressor set to lock out at an outside air temperature of 15˚F), and **Table 43** provides measure energy savings results for the Low Switchover Temperature 2 measure (i.e., the compressor set to lock out at an outside air temperature of 5˚F).

Energy savings impacts vary widely for these measures due to temperature differences in each climate zone. In San Diego, CA (3C), the measure does not achieve savings as outside air temperatures do not drop below 30˚F in the TMY3 weather data. Percent HVAC savings range from 0.0%-26.2% for Low Switchover Temperature 1 and 0.0%-29.3% for Low

Switchover Temperature 2, depending on HVAC types and locations. Colder climate zones offer the highest energy savings potential, with the highest potential located in Denver, CO (5B), and the lowest savings potential located in San Diego, CA (3C). For dual-fuel ASHP systems, lowering the compressor lockout allows the heat pump to provide a greater portion of the heating load at cold outside air temperatures, reducing the gas backup heating load; this results in negative electric savings for this system type, but with high gas savings.

Table 42: Low Switchover Temperature 1 Measure Energy Savings

Climate Zones	ASHP RTU with Electric Resistance Backup Percent HVAC Savings	ASHP RTU with Gas Backup Percent HVAC Savings
Seattle, WA (4C)	2.6%	3.6%
San Diego, CA (3C)	0.0%	0.0%
Denver, CO (5B)	20.9%	26.2%
Great Falls, MT (6B)	12.3%	14.9%
Tucson, AZ (2B)	0.5%	0.6%
El Paso, TX (3B)	2.8%	3.8%
Atlanta, GA (3A)	9.0%	12.0%
Tampa, FL (2A)	0.2%	0.2%
Chicago, IL (5A)	17.1%	21.3%
New York City, NY (4A)	15.5%	19.9%
Minneapolis, MN (6A)	18.9%	22.9%

Table 43: Low Switchover Temperature 2 Measure Energy Savings

Climate Zones	ASHP RTU with Electric Resistance Backup Percent HVAC Savings	ASHP RTU with Gas Backup Percent HVAC Savings
Seattle, WA (4C)	2.6%	3.6%
San Diego, CA (3C)	0.0%	0.0%
Denver, CO (5B)	23.1%	29.4%
Great Falls, MT (6B)	15.3%	19.0%
Tucson, AZ (2B)	0.5%	0.6%
El Paso, TX (3B)	2.8%	3.8%
Atlanta, GA (3A)	9.3%	12.4%

Climate Zones	ASHP RTU with Electric Resistance Backup Percent HVAC Savings	ASHP RTU with Gas Backup Percent HVAC Savings
Tampa, FL (2A)	0.2%	0.2%
Chicago, IL (5A)	20.6%	26.0%
New York City, NY (4A)	16.2%	20.8%
Minneapolis, MN (6A)	22.6%	27.8%

A goal of simulating two compressor lockout points was to assess potential savings impact differences. **Figure 16** shows energy savings differences from changing the lockout temperature from 15˚F to 5˚F. Only six climate zones experienced savings differences from the two lockout points, which were the only weather files where outside air temperatures dropped below 15˚F. Total energy savings increase as the frequency of sub-15˚F outside air temperatures increase, with Minneapolis, MN (6A) offering the highest additional savings potential of up to 2.3 kBTU/ft^2 of additional total HVAC savings. However, the electric penalty also increases.

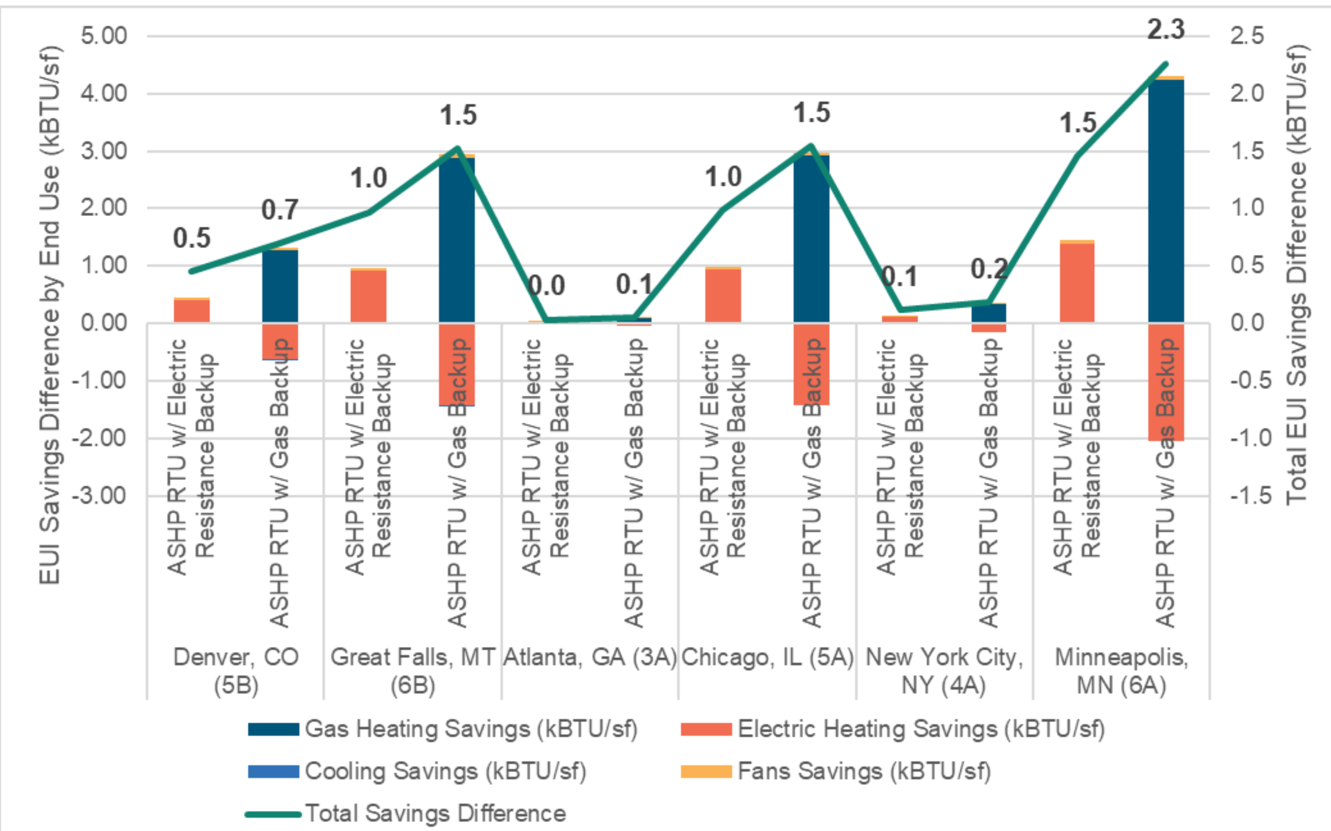

Figure 16: Low Switchover Temperature Measure Differences

The Low Switchover Temperature measures are not an additional heat pump feature or an improved performance (capacity) curve. They are a control difference rather than a baseline heat pump measure. The large energy savings potential that this measure offers in colder climates shows how important control and commissioning of a heat pump can be in maximizing its savings potential. The research team also found that this measure resulted in increased unmet load hours, particularly during mornings when buildings became occupied (i.e., thermostat setpoints moving from setback to setpoint temperatures) – a caveat to these savings. Conducting a field study of this measure would be valuable in validating the savings potential and verifying that occupant comfort is not impacted by slower warm-up times.

3.2.2.9 Cold Climate Heat Pump Energy Savings Results

Table 44 provides measure energy savings results for replacing industry standard ASHP RTUs with CCHP RTUs. Energy savings impacts vary widely for these measures due to temperature differences in each climate zone. In San Diego, CA (3C), no measure savings accrue as outside air temperatures do not drop below 30˚F in the TMY3 weather data. Percent HVAC savings range from 0.0%-32.0%, depending on HVAC types and locations. Colder climate zones present the greatest savings potential, with the highest potential located in Minneapolis, MN (6B), and the lowest potential located in San Diego, CA (3C). For dual-fuel ASHP systems, lowering the compressor lockout allows the heat pump to provide a greater portion of the heating load at cold outside air temperatures, reducing the gas backup heating load; this system type results in negative electric savings but high gas savings.

Table 44: Cold Climate Heat Pump Measure Energy Savings

Climate Zones	ASHP RTU with Electric Resistance Backup Percent HVAC Savings	ASHP RTU with Gas Backup Percent HVAC Savings
Seattle, WA (4C)	2.7%	3.7%
San Diego, CA (3C)	0.0%	0.0%
Denver, CO (5B)	24.0%	30.6%
Great Falls, MT (6B)	18.9%	25.4%
Tucson, AZ (2B)	0.5%	0.7%
El Paso, TX (3B)	2.8%	3.9%
Atlanta, GA (3A)	9.5%	12.6%
Tampa, FL (2A)	0.2%	0.2%

Climate Zones	ASHP RTU with Electric Resistance Backup Percent HVAC Savings	ASHP RTU with Gas Backup Percent HVAC Savings
Chicago, IL (5A)	22.6%	29.1%
New York City, NY (4A)	16.6%	21.4%
Minneapolis, MN (6A)	25.1%	32.0%

The team's simulation findings indicate very high savings potential for this measure in very cold climates, especially for dual-fuel systems where heat pump primary heating contributes a greater share of the heating load than gas supplemental heating. Recent CEE research for dual-fuel RTU units in New York City[62] display characteristics similar to the Cold Climate Heat Pump measure, with gas supplemental heating turned on only 1% of the time. This indicates that the heat pump's primary heating component can meet heating loads at very cold temperatures, corroborating the measure's results. Metered and billing data analyses could further validate or improve this measure's results.

3.2.2.10 Low Switchover Temperature 1 with NEEA Tiers Energy Savings Results

Table 45 and **Table 46** provides measure energy savings results for running the Low Switchover Temperature measure with a 15˚F compressor lockout with the NEEA Tier 1 and NEEA Tier 2 measure packages, respectively. As with the Low Switchover Temperature measure, this measure's savings impacts vary widely due to temperature differences in each climate zone. Percent HVAC savings range from 1.7%-35.4% for NEEA Tier 1 and 1.6%-37.8% for NEEA Tier 2, depending on HVAC types and locations. Colder climate zones present the greatest savings potential, with the highest savings located in Denver, CO (5B), and the lowest savings located in San Diego, CA (3C). Each measure's interactive effects are explored in the **Interaction of Measures** (**3.2.3**) section.

Table 45: Low Switchover Temperature 1 with NEEA Tier 1 Measure Energy Savings

Climate Zones	ASHP RTU with Electric Resistance Backup Percent HVAC Savings	ASHP RTU with Gas Backup Percent HVAC Savings
Seattle, WA (4C)	10.2%	11.1%
San Diego, CA (3C)	1.7%	1.7%
Denver, CO (5B)	30.5%	35.4%

[62] CEE, "Final Performance Report: Dual Fuel RTU Monitoring", CEE Final Performance Report Dual Fuel RTU Monitoring V4 - Adobe cloud storage

Climate Zones	ASHP RTU with Electric Resistance Backup Percent HVAC Savings	ASHP RTU with Gas Backup Percent HVAC Savings
Great Falls, MT (6B)	24.3%	26.7%
Tucson, AZ (2B)	4.2%	4.4%
El Paso, TX (3B)	7.0%	8.0%
Atlanta, GA (3A)	13.9%	16.8%
Tampa, FL (2A)	1.9%	1.9%
Chicago, IL (5A)	27.1%	30.9%
New York City, NY (4A)	22.2%	26.3%
Minneapolis, MN (6A)	29.3%	32.9%

Table 46: Low Switchover Temperature 1 with NEEA Tier 2 Measure Energy Savings

Climate Zones	ASHP RTU with Electric Resistance Backup Percent HVAC Savings	ASHP RTU with Gas Backup Percent HVAC Savings
Seattle, WA (4C)	23.4%	24.1%
San Diego, CA (3C)	1.6%	1.6%
Denver, CO (5B)	33.1%	37.8%
Great Falls, MT (6B)	26.4%	28.7%
Tucson, AZ (2B)	8.6%	8.8%
El Paso, TX (3B)	10.7%	11.6%
Atlanta, GA (3A)	19.1%	21.8%
Tampa, FL (2A)	6.4%	6.5%
Chicago, IL (5A)	29.5%	33.2%
New York City, NY (4A)	28.0%	31.8%
Minneapolis, MN (6A)	30.5%	34.0%

3.2.2.11 Cold Climate Heat Pump with NEEA Tier Energy Savings Results

Table 47 and **Table 48** provides measure energy savings results for running the Cold Climate Heat Pump measure with the NEEA Tier 1 and NEEA Tier 2 measure packages, respectively. As with the Cold Climate Heat Pump measure, energy savings impacts vary widely for these measures due to temperature differences in each climate zone. Percent HVAC savings range from 1.7%-40.8% for NEEA Tier 1 and 1.6%-41.9% for NEEA Tier 2, depending on HVAC types and locations. This measure package resulted in the greatest savings result determined through this study, boosting additional NEEA Tier 2 savings by over 20% in Seattle, WA (4C), compared to the Cold Climate Heat Pump alone. Colder climate zones have the greatest savings potential, with the highest savings potential located in Minneapolis, MN (6B) and the lowest savings potential located in San Diego, CA (3C). Each measure's interactive effects are explored in the **Interaction of Measures** (**3.2.3**) section.

Table 47: Cold Climate Heat Pump with NEEA Tier 1 Measure Energy Savings

Climate Zones	ASHP RTU with Electric Resistance Backup Percent HVAC Savings	ASHP RTU with Gas Backup Percent HVAC Savings
Seattle, WA (4C)	10.3%	11.2%
San Diego, CA (3C)	1.7%	1.7%
Denver, CO (5B)	33.2%	39.0%
Great Falls, MT (6B)	30.2%	36.0%
Tucson, AZ (2B)	4.2%	4.4%
El Paso, TX (3B)	7.1%	8.1%
Atlanta, GA (3A)	14.3%	17.3%
Tampa, FL (2A)	1.9%	1.9%
Chicago, IL (5A)	32.0%	37.8%
New York City, NY (4A)	23.2%	27.7%
Minneapolis, MN (6A)	34.8%	40.8%

Table 48: Cold Climate Heat Pump with NEEA Tier 2 Measure Energy Savings

Climate Zones	ASHP RTU with Electric Resistance Backup Percent HVAC Savings	ASHP RTU with Gas Backup Percent HVAC Savings
Seattle, WA (4C)	23.4%	24.3%
San Diego, CA (3C)	1.6%	1.6%
Denver, CO (5B)	35.7%	41.3%
Great Falls, MT (6B)	32.3%	37.9%

Climate Zones	ASHP RTU with Electric Resistance Backup Percent HVAC Savings	ASHP RTU with Gas Backup Percent HVAC Savings
Tucson, AZ (2B)	8.7%	8.8%
El Paso, TX (3B)	10.7%	11.7%
Atlanta, GA (3A)	19.5%	22.4%
Tampa, FL (2A)	6.4%	6.5%
Chicago, IL (5A)	34.3%	40.0%
New York City, NY (4A)	29.0%	33.1%
Minneapolis, MN (6A)	35.9%	41.9%

3.2.3 Interaction of Measures

Combining measures produces few interactive effects.

The following tables outline national average total HVAC percent energy savings for the measures composing each tier. This report breaks out tables by HVAC type. The "Measure Total" row is the sum of modeled outcomes for measures simulated individually, and the "Tier Result" row is the outcome achieved when measures are simulated together in that specific tier. In all cases, small interactive effects occur between different measures, ranging from -2.6% to +0.2%. This limited interaction between measures can make impact accounting easier and could possibly preclude additional tier simulations in the future.

Table 49: Impacts by Tier and Constituent Measure for Gas RTUs

	NEEA T1	NEEA T2
Enclosure Insulation R12	5.2%	5.2%
Low Leakage Dampers	4.2%	4.2%
ERV	-	10.8%
Measure Total	**9.4%**	**20.2%**
Tier Result	**9.4%**	**20.0%**

Table 50: Impacts by Tier and Constituent Measure for ASHP RTUs with Electric Resistance Backup

	NEEA T1	NEEA T2	LST 1 + NEEA T1	LST 1 + NEEA T2	CCHP + NEEA T1	CCHP + NEEA T2
Enclosure Insulation R12	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%
Low-Leakage Dampers	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%
ERV	-	3.4%	-	3.4%	-	3.4%
Low Switchover Temperature 1	-	-	10.9%	10.9%	-	-
Cold Climate Heat Pump	-	-	-	-	13.4%	13.4%
Measure Total	**8.3%**	**11.7%**	**19.2%**	**22.6%**	**21.7%**	**25.1%**
Tier Result	**8.4%**	**11.9%**	**17.7%**	**21.1%**	**19.9%**	**23.3%**

Table 51: Impacts by Tier and Constituent Measure for ASHP RTUs with Gas Backup

	NEEA T1	NEEA T2	LST 1 + NEEA T1	LST 1 + NEEA T2	CCHP + NEEA T1	CCHP + NEEA T2
Enclosure Insulation R12	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%
Low-Leakage Dampers	4.1%	4.1%	4.1%	4.1%	4.1%	4.1%
ERV	-	3.4%	-	3.4%	-	3.4%
Low Switchover Temperature 1	-	-	13.7%	13.7%	-	-
Cold Climate Heat Pump	-	-	-	-	17.3%	17.3%
Measure Total	**8.6%**	**12.0%**	**22.3%**	**25.7%**	**25.9%**	**29.3%**
Tier Result	**8.7%**	**12.2%**	**20.3%**	**23.6%**	**23.4%**	**26.7%**

3.2.4 Replacement of HVAC Types

In addition to the impacts of energy-efficiency measures, the project team investigated the impact results from replacing gas RTUs with various all-electric and dual-fuel ASHP RTUs. In this case, the gas RTU served as the baseline, and the different HVAC type served as the measure. These "measure" scenarios investigated include the following HVAC types:

- ASHP RTU with electric resistance backup heating and gas backup heating.
- Cold climate heat pump RTU with electric resistance backup heating and gas backup heating.

- Cold climate heat pump RTU employing NEEA Tier 1 specifications, with electric resistance backup heating and gas backup heating.
- Cold climate heat pump RTU employing NEEA Tier 2 specifications, with electric resistance backup heating and gas backup heating.

The following tables provide annual energy savings results by HVAC end use achieved by replacing gas RTUs with each heat pump RTU scenario. All tables are organized by locations with the highest percent savings potential. Findings include the following:

- All scenarios indicate high gas savings potential, particularly in mild and cold climates.
- Due to an electric primary heating component in all replacement scenarios, an electric penalty (negative electric savings) always occurs when switching fuel-types.
- Even after accounting for the electric penalty, total HVAC percent energy savings are high, reaching as much as 67.8% for CCHP RTUs with NEEA Tier 2 specifications in Seattle, WA (4C).
- Additional energy savings captured between an industry-standard ASHP and a CCHP vary widely, ranging from 0.0%-27.6%, depending on the HVAC type and location, with very cold locations such as Minneapolis, MN (6B) exhibiting the greatest bump in additional savings. On average, savings increase from 33.2% for an ASHP RTU replacement to 42.2% for a CCHP replacement.
- Relative to installing a CCHP RTU, average energy savings increase from 42.2% to 46.3% when using additional NEEA Tier 1 measure specifications and 48.2% for NEEA Tier 2 measure specifications.

Notably, given the increase in electric energy consumption, energy bills may increase for consumers due to electric energy's higher costs than gas. Dual-fuel heat pumps may provide a preferred option for consumers in very cold climates, where significant gas savings potential exists without consuming more expensive electric backup heating at very cold temperatures.

Table 52: ASHP RTU Replacement Energy Savings Results

Location	ASHP RTU with Electric Resistance Backup					ASHP RTU with Gas Backup				
	Gas Heating Savings (kBTU/sf)	Electric Heating Savings (kBTU/sf)	Cooling Savings (kBTU/sf)	Fans Savings (kBTU/sf)	Perc. HVAC Savings	Gas Heating Savings (kBTU/sf)	Electric Heating Savings (kBTU/sf)	Cooling Savings (kBTU/sf)	Fans Savings (kBTU/sf)	Perc. HVAC Savings
Seattle, WA (4C)	20.4	-6.1	-0.08	0.12	58.2%	19.6	-5.5	-0.08	0.12	57.5%
New York City, NY (4A)	25.8	-11.3	-0.17	-0.27	42.3%	18.5	-5.3	-0.17	-0.27	37.7%
San Diego, CA (3C)	5.9	-1.5	-0.23	0.22	36.7%	5.9	-1.5	-0.23	0.22	36.7%
Atlanta, GA (3A)	13.3	-5.3	-0.27	0.01	34.3%	10.3	-2.9	-0.27	0.01	31.5%
El Paso, TX (3B)	8.9	-2.9	-0.32	0.44	33.8%	8.2	-2.4	-0.32	0.44	33.1%
Denver, CO (5B)	25.6	-13.7	-0.17	-0.51	33.7%	14.0	-4.2	-0.17	-0.51	26.5%
Chicago, IL (5A)	38.3	-22.4	-0.15	-0.99	31.7%	16.9	-5.1	-0.15	-0.99	22.3%
Great Falls, MT (6B)	43.7	-26.4	-0.10	-1.06	31.5%	17.5	-5.2	-0.10	-1.06	21.1%
Minneapolis, MN (6A)	50.3	-33.1	-0.14	-1.6	26.2%	14.9	-4.4	-0.14	-1.6	14.1%
Tucson, AZ (2B)	6.2	-1.8	-0.34	0.54	26.0%	6.1	-1.7	-0.34	0.54	25.9%
Tampa, FL (2A)	2.9	-0.78	-0.42	0.14	13.4%	2.8	-0.74	-0.42	0.14	13.3%

Table 53: CCHP RTU Replacement Energy Savings Results

Location	CCHP RTU with Electric Resistance Backup					CCHP RTU with Gas Backup				
	Gas Heating Savings (kBTU/sf)	Electric Heating Savings (kBTU/sf)	Cooling Savings (kBTU/sf)	Fans Savings (kBTU/sf)	Perc. HVAC Savings	Gas Heating Savings (kBTU/sf)	Electric Heating Savings (kBTU/sf)	Cooling Savings (kBTU/sf)	Fans Savings (kBTU/sf)	Perc. HVAC Savings
Seattle, WA (4C)	20.4	-5.9	-0.08	0.15	59.3%	20.0	-5.7	-0.08	0.15	59.1%

Location	CCHP RTU with Electric Resistance Backup					CCHP RTU with Gas Backup				
	Gas Heating Savings (kBTU/sf)	Electric Heating Savings (kBTU/sf)	Cooling Savings (kBTU/sf)	Fans Savings (kBTU/sf)	Perc. HVAC Savings	Gas Heating Savings (kBTU/sf)	Electric Heating Savings (kBTU/sf)	Cooling Savings (kBTU/sf)	Fans Savings (kBTU/sf)	Perc. HVAC Savings
New York City, NY (4A)	25.8	-8.6	-0.17	-0.01	51.9%	24.5	-7.5	-0.17	-0.01	51.1%
Denver, CO (5B)	25.6	-9.5	-0.17	0.19	49.7%	24.5	-8.6	-0.17	0.19	49.1%
Chicago, IL (5A)	38.3	-16.4	-0.15	-0.41	47.2%	33.0	-12.1	-0.15	-0.41	45.1%
Minneapolis, MN (6A)	50.3	-23.8	-0.14	-0.72	44.9%	40.5	-15.9	-0.14	-0.72	41.7%
Great Falls, MT (6B)	43.7	-21.0	-0.10	-0.37	44.6%	35.3	-14.1	-0.10	-0.37	41.4%
Atlanta, GA (3A)	13.3	-4.2	-0.27	0.14	40.5%	12.8	-3.9	-0.27	0.14	40.1%
San Diego, CA (3C)	5.9	-1.5	-0.23	0.22	36.7%	5.9	-1.5	-0.23	0.22	36.7%
El Paso, TX (3B)	8.9	-2.6	-0.32	0.47	35.7%	8.8	-2.6	-0.32	0.47	35.6%
Tucson, AZ (2B)	6.2	-1.8	-0.34	0.54	26.4%	6.2	-1.8	-0.34	0.54	26.4%
Tampa, FL (2A)	2.9	-0.76	-0.42	0.14	13.5%	2.9	-0.75	-0.42	0.14	13.5%

Table 54: CCHP RTU + NEEA Tier 1 Replacement Energy Savings Results

Location	CCHP RTU + NEEA Tier 1 with Electric Resistance Backup					CCHP RTU + NEEA Tier 1 with Gas Backup				
	Gas Heating Savings (kBTU/sf)	Electric Heating Savings (kBTU/sf)	Cooling Savings (kBTU/sf)	Fans Savings (kBTU/sf)	Perc. HVAC Savings	Gas Heating Savings (kBTU/sf)	Electric Heating Savings (kBTU/sf)	Cooling Savings (kBTU/sf)	Fans Savings (kBTU/sf)	Perc. HVAC Savings
Seattle, WA (4C)	20.4	-5.4	-0.09	0.24	62.7%	20.1	-5.1	-0.09	0.24	62.5%
Denver, CO (5B)	25.6	-8.0	-0.15	0.48	56.0%	24.7	-7.2	-0.15	0.48	55.5%
New York City, NY (4A)	25.8	-7.7	-0.16	0.16	55.9%	24.7	-6.7	-0.16	0.16	55.2%

Location	CCHP RTU + NEEA Tier 1 with Electric Resistance Backup					CCHP RTU + NEEA Tier 1 with Gas Backup				
	Gas Heating Savings (kBTU/sf)	Electric Heating Savings (kBTU/sf)	Cooling Savings (kBTU/sf)	Fans Savings (kBTU/sf)	Perc. HVAC Savings	Gas Heating Savings (kBTU/sf)	Electric Heating Savings (kBTU/sf)	Cooling Savings (kBTU/sf)	Fans Savings (kBTU/sf)	Perc. HVAC Savings
Chicago, IL (5A)	38.3	-14.0	-0.14	-0.04	53.8%	33.9	-10.4	-0.14	-0.04	52.0%
Great Falls, MT (6B)	43.7	-17.8	-0.10	0.09	52.6%	36.7	-12.2	-0.10	0.09	50.0%
Minneapolis, MN (6A)	50.3	-20.5	-0.13	-0.21	52.2%	41.9	-13.7	-0.13	-0.21	49.5%
Atlanta, GA (3A)	13.3	-3.8	-0.22	0.24	43.7%	12.9	-3.4	-0.22	0.24	43.4%
El Paso, TX (3B)	8.9	-2.3	-0.22	0.53	38.6%	8.8	-2.3	-0.22	0.53	38.5%
San Diego, CA (3C)	5.9	-1.36	-0.25	0.22	37.7%	5.9	-1.4	-0.25	0.22	37.7%
Tucson, AZ (2B)	6.2	-1.6	-0.15	0.61	29.2%	6.2	-1.6	-0.15	0.61	29.1%
Tampa, FL (2A)	2.3	-0.70	-0.31	0.17	14.9%	2.9	-0.69	-0.31	0.17	14.9%

Table 55: CCHP + NEEA Tier 2 Replacement Energy Savings Results

Location	CCHP RTU + NEEA Tier 2 with Electric Resistance Backup					CCHP RTU + NEEA Tier 2 with Gas Backup				
	Gas Heating Savings (kBTU/sf)	Electric Heating Savings (kBTU/sf)	Cooling Savings (kBTU/sf)	Fans Savings (kBTU/sf)	Perc. HVAC Savings	Gas Heating Savings (kBTU/sf)	Electric Heating Savings (kBTU/sf)	Cooling Savings (kBTU/sf)	Fans Savings (kBTU/sf)	Perc. HVAC Savings
Seattle, WA (4C)	20.4	-3.5	-0.10	-0.17	67.8%	20.1	-3.3	-0.10	-0.17	67.6%
New York City, NY (4A)	25.8	-6.2	0.03	-0.37	59.0%	24.7	-5.3	0.03	-0.37	58.3%
Denver, CO (5B)	25.6	-6.8	-0.01	-0.21	57.4%	24.8	-6.1	-0.01	-0.21	56.9%
Chicago, IL (5A)	38.3	-12.6	0.02	-0.76	55.3%	34.1	-9.2	0.02	-0.76	53.6%
Great Falls, MT (6B)	43.7	-16.3	-0.03	-0.77	53.9%	37.0	-10.8	-0.03	-0.77	51.4%

Location	CCHP RTU + NEEA Tier 2 with Electric Resistance Backup					CCHP RTU + NEEA Tier 2 with Gas Backup				
	Gas Heating Savings (kBTU/sf)	Electric Heating Savings (kBTU/sf)	Cooling Savings (kBTU/sf)	Fans Savings (kBTU/sf)	Perc. HVAC Savings	Gas Heating Savings (kBTU/sf)	Electric Heating Savings (kBTU/sf)	Cooling Savings (kBTU/sf)	Fans Savings (kBTU/sf)	Perc. HVAC Savings
Minneapolis, MN (6A)	50.3	-19.1	-0.01	-1.10	52.9%	42.3	-12.7	-0.01	-1.10	50.4%
Atlanta, GA (3A)	13.3	-2.8	0.17	-0.26	46.8%	12.9	-2.5	0.17	-0.26	46.5%
El Paso, TX (3B)	8.9	-1.6	0.12	-0.04	40.5%	8.8	-1.6	0.12	-0.04	40.4%
San Diego, CA (3C)	5.9	-0.88	-0.20	-0.25	36.8%	5.9	-0.88	-0.20	-0.25	36.8%
Tucson, AZ (2B)	6.2	-1.1	0.57	0.05	32.1%	6.2	-1.1	0.57	0.05	32.1%
Tampa, FL (2A)	2.9	-0.47	0.61	-0.29	18.8%	2.9	-0.46	0.61	-0.29	18.8%

3.3 Modeling Comparisons

Analyses described in this report parallel those performed by Cadeo Group through a modeling effort conducted for NEEA in 2020 and in the P.8 test procedure development. While analyses significantly align, key differences include the purposes for the two analyses, what specifically was modeled, and how the modeling was performed.

The original P.8 modeling's primary goal was to develop a set of weights that represented the amount of time an RTU spends in different heating operating modes (i.e., high fire, low fire, ventilation only, and standby) throughout the heating season. The CSA P.8 standard used these operating mode weights to calculate a whole-system heating season performance metric, accounting for RTU operational behaviors in average Canadian climate conditions; the standard included performance impacts from different RTU characteristics. While the standard did not reference measure savings values, the P.8 energy models provided an initial look at heating season performance impacts for reduced damper leakage, increased enclosure insulation, and ERV installation. These measures' favorable results on heating season energy use in the P.8 models led to their inclusion in NEEA's Efficient RTU Specification.

The current modeling and the 2020 modeling effort has focused more on informing development of the Efficient RTU Specifications for NEEA and Nicor Gas. This focus shift affected the analysis approach in five critical ways:

- Regions included in the analysis.
- Building types included in the analysis.
- Simulated outdoor air flow rates.
- Measures simulated and simulation approach used.
- Period over which measure impacts were modeled.

As NEEA's and Nicor's territories are situated in the Northwest and Midwest regions, respectively, climates used in the latest analysis differ from climate zones 5A, 6A, and 7 used in the P.8 effort. Though some overlap occurred between climate zones used in all analyses, it was limited to climate zone 5A and not in the same location. The 2020 model also included climate zones 4C, 5A, and 6B, all of which overlap with this analysis.

The P.8 analysis examined two building types: retail and warehouse. The 2020 model analysis shifted the building types by excluding warehouse and including retail strip malls, groceries, and medium office building types. As with climate locations, the building types used in all of the analyses contained one overlap point (retail).

For each building type, the P.8 analysis examined three different outdoor air flow rates (i.e., 0%, 30%, and 100% OA) as they needed to account for all configurations possible when developing the standard's calculation methodology. This also provided an opportunity to understand how different measures would be affected by varying outside air percentages. Given the current analysis focuses on the most common and most representative applications, OA% did not vary for each building type, holding constant at the ASHRAE 62.1-2004 criteria. Dropping this dimension reduced the analysis dimensionality and allowed the simulation of more building types and locations.

Only three measures overlap between the P.8 analysis and the more recent analyses: ERVs, Low-Leakage Dampers, and Enclosure Insulation (R8). Beyond the addition of new measures, the project team changed the modeling approach for all measures. **Table 56** summarizes these changes.

Table 56: Model Approach Changes

Measure	Changes in Approach
ERV	Updated the fan energy impact modeling approach in the 2020 model, then increased the total static pressure drops throughout the RTU via this analysis, from 1.25" w.c. to 3.2" w.c. in the baseline and 4.0" w.c. in the measure simulation. Further, the project team accounted for leakage in the RTU enclosure, which directly impacts the ERV measure's effectiveness as heat cannot always be recovered.
Low-Leakage Dampers	Modeled directly in the EnergyPlus 2020 model. No changes occurred from the 2020 model in this analysis.
Enclosure Insulation	Modeled directly in the EnergyPlus 2020 model. No changes occurred from the 2020 model in this analysis.
Efficient Cooling	Not modeled in the P.8 analysis. No changes from the 2020 model in this analysis.

Lastly, the P.8 analysis only examined measure impacts during the heating season, defined as October 1 to April 30, whereas the more recent analyses determined measure impacts for the entire year. In general, this change diminished the impact of simulated heating-focused measures for part of both analyses.

As shown in **Figure 17**, results are in general agreement where overlap occurs in terms of building types, locations, and measures.

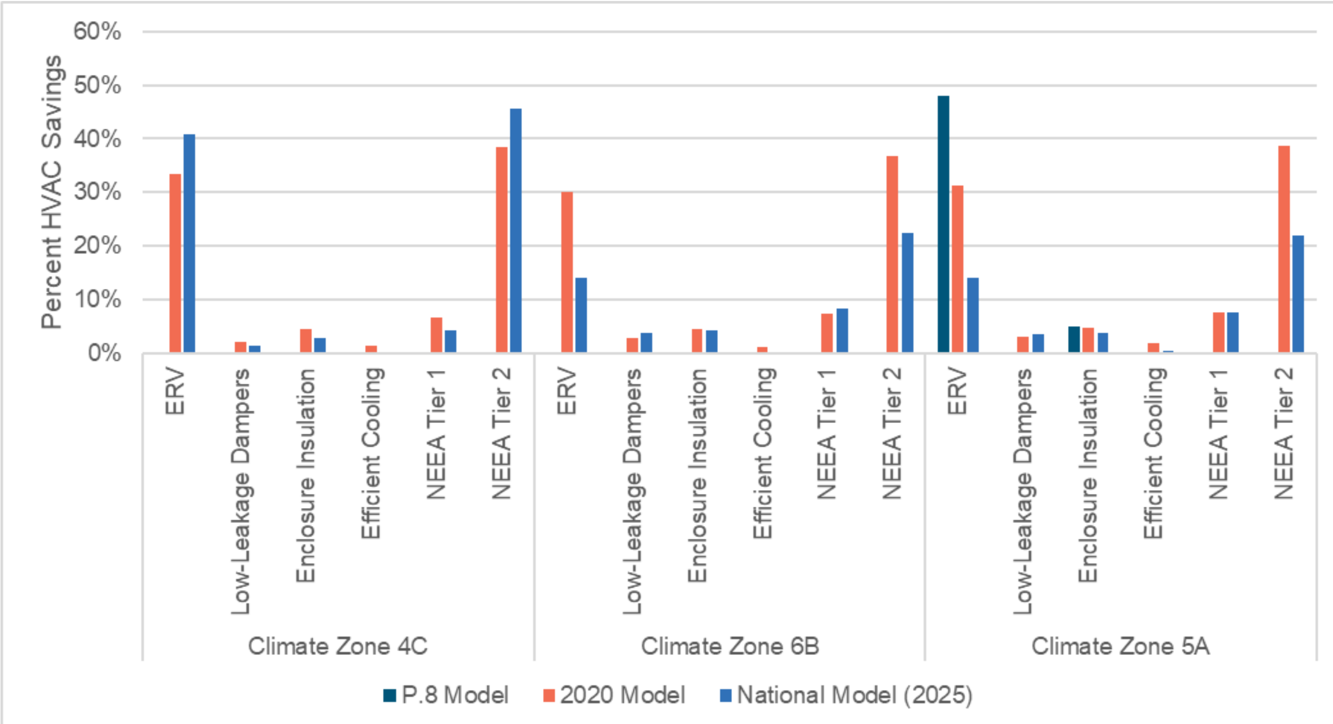

Figure 17: Energy Savings Comparisons Between P.8, 2020 Model, and Current Analysis by Climate Zone and Measure

Of overlapping measures, the ERV measure produces the most divergent outcomes. In climate zone 4C, ERV energy savings are slightly higher in this analysis than in the 2020 model. However, savings decrease substantially in climate zones 6B and 5A. P.8 savings results differed from the more recent analyses due to the change in fan energy and the period over which the impacts were calculated. Between the 2020 model and this analysis, ERV savings differed partially due to increased pressure drops throughout the RTU, from 1.25" w.c. in all scenarios in the 2020 model to 3.2" w.c. in the baseline and 4.0" w.c. in the current measure simulation.

This change produces high impacts in cold climates, where RTUs operate at higher full-load hours for a greater percent of the time, exacerbating fan consumption. Moreover, in this analysis, the project team accounted for leakage in the RTU enclosure, which was not considered in the 2020 model. As the ERV is downstream of the RTU enclosure, this modification decreases ERV savings in very cold climates due to heat lost through the RTU enclosure before it can be recovered. The project team, however, believes this modification more closely aligns RTU performance with real-world behaviors.

4 Findings, Recommendations, and Next Steps

This section summarizes key analysis findings and their implications for national program development, market transformation, and influence codes and standards. This section also summarizes key findings discussed elsewhere in the report and includes recommendations for program development and future research. Findings and recommendations fall into the following categories:

- **General Notes and Observations**
- **Findings for Notable Measures**
- **Recommendations for National Engagement, Programmatic Structure, and Future Research**

General Notes and Observations

- **Measure energy savings and total HVAC percent savings vary widely by location.** The most impactful measures varied by climate zone, though similar trends and results occurred when grouping measures by cold or hot climates. This research produced national average savings, but, as those national averages masked variations by climate zones, it may be more appropriate to consider impacts by climate regions. For example, cooling performance produces considerable RTU energy savings opportunities in hot climates, but efficient cooling exhibits low energy savings potential in cold climates.
- **For gas RTUs, heating consumption produces a significant portion of the HVAC load, even in warm climates.** On average, the heating load as a percentage of total HVAC EUI for gas RTUs ranges from 19%-89% across the climate zones. Even if systems are cooling-dominated from a building load perspective, large heating consumption occurs in the baseline as heating systems in gas RTUs run less efficiently than cooling systems. Heating-focused measures offer more savings opportunities due to higher heating consumption. Heat pump RTUs reduce heating consumption, but it remains dominant in most climates.
- **In general, combined measure packages produce very minor interactive effects in relation to savings potential.** Incremental (or decremental) savings resulting from interactive effects between different measures range from -2.6% to +0.2%. Each measure also has its own challenges in installation or implementation and should be considered individually given short-term goals, long-term goals, and costs. For example, installing new dampers is relatively easy and inexpensive, whereas ERVs are expensive and heavy, and increased enclosure insulation is a manufacturer improvement.

Findings for Notable Measures

- **For gas RTUs, adding ERVs (and therefore the NEEA Tier 2 measure) offers high energy savings potential.** On average, ERVs have an HVAC energy savings potential of 6%-27% for gas RTUs, depending on climate zones, with potential energy savings up to 32% when accounting for increased ventilation. ERV measure energy savings are lower when installed in all-electric or dual-fuel heat pump RTUs. Despite ERVs high energy savings potential, they are not currently valued in RTU test procedures or federal standards. The team recommends that NEEA consider how ERVs can be incorporated into codes, standards, and/or market transformation initiatives. Some energy codes, such as the Washington State Energy Code, already require heat recovery for certain outside air percentages; so code requirements involving ERVs are not novel. For customers and installation contractors, it's important to consider the additional cost, size, and weight of ERVs, though the units may be easier for customers to implement in comparison to RTU upgrades that require manufacturer interventions (e.g., increased RTU enclosure insulation and decreased enclosure leakage).
- **The greatest energy savings potential comes from replacing gas RTUs with standard heat pumps, dual-fuel heat pumps, or CCHPs.** Depending on the climate zone and backup fuel type, converting a pre-existing gas RTU to a standard-practice heat pump RTU or CCHP can save 13%-59% of total HVAC energy usage on average. Total HVAC energy savings can be even higher, up to 68% when incorporating NEEA Tier 1 and NEEA Tier 2 measure packages. Although this study did not examine carbon savings, these measures also have a drastic (or even complete) reduction in emissions, depending on the electricity source. In areas such as the Northwest, with low electricity costs and a clean grid, this could provide a compelling case for business owners. Dual-fuel heat pumps can save a similar amount of energy with a less expensive backup source and without requiring electrical upgrades. The additional energy savings captured between an industry-standard ASHPs and CCHPs vary widely, with very cold locations experiencing the greatest increase in additional savings.
- **Low Switchover Temperature and Cold Climate Heat Pump measures offer high energy savings potential in very cold climates.** On average, the Low Switchover Temperature measure's energy savings potential ranges from 0%-29% of total HVAC energy usage, with the measure's impact potential heavily favoring cold climates. With similar control enhancements, the Cold Climate Heat Pump measure's energy savings potential ranges from 0%-32%. Installing controls that allow the heat pump to condition at low temperatures provides a low-cost upgrade, though it is important to

note the additional costs for operating heat pump systems where heat pump loads replace gas backup heating. Moreover, additional costs result from installing a heat pump with CCHP performance.

- **Nationally, the Efficient Cooling measure produces the lowest total HVAC average percent energy savings.** Measure specifications are based on the Advanced Tier from the Consortium of Energy Efficiency 2024 Unitary AC Specs – among the highest cooling efficiency specifications. While the Efficient Cooling measure poses substantial energy savings potential in hot climates, very little energy savings potential exists in mild and cold climates. When weighting results to create national energy savings estimates, average HVAC potential energy savings are the lowest among all measures, ranging from 2%-3% of total HVAC energy savings. Currently, many efficiency specifications focus on cooling efficiency. This report's simulation results demonstrate that cooling efficiency alone is not as beneficial as other measures and will continue to produce diminishing savings potential in all but the hottest climates as RTUs continually increase their cooling efficiency.
- **Enclosure Insulation and Low-Leakage Dampers measures offer moderate energy savings potential individually, but packaged together (NEEA Tier 1) these measures offer more substantial energy savings for all HVAC types.** Depending on the climate zone and HVAC type, average HVAC potential energy savings for Enclosure Insulation and Low-Leakage Dampers range from 0%-8%. When these measures are combined through the NEEA Tier 1 measure package, the energy savings potential increases, ranging from 2%-14% of total average HVAC savings. In general, the average energy savings potential for Enclosure Insulation, Low-Leakage Dampers, and NEEA Tier 1 measures are also consistent across HVAC types for any given climate zone. Additional energy savings are experienced in the NEEA Tier 2 measure through the addition of an ERV, ranging from 2%-36% of total HVAC energy savings.
- **The Enclosure Leakage measure, which has never been modeled before, could be used to inform future RTU specifications.** When weighting results to create national energy savings estimates, Enclosure Leakage offers considerable energy savings potential – similar to other enclosure measures such as Enclosure Insulation and Low-Leakage Dampers – ranging from 1%-8% of total HVAC energy use on average. As with all other measures, this study's results can be used to promote enclosure leakage as an efficiency feature. Currently, test procedures do not exist for enclosure leakage, but, once a test procedure is developed, enclosure leakage can be considered in future specifications.

Recommendations for National Engagement, Programmatic Structure, and Future Research

- **Use information from this research effort to support standards efforts.** Some measures demonstrating significant energy savings through this research are not currently valued in RTU test procedures and federal regulations. Previously, NEEA has researched how RTU test procedures (e.g., ANSI Z21.47 and AHRI 340/360) account for various measures, determining that the ERV, Low-Leakage Dampers, and Low Switchover Temperatures (1 and 2) measures would not improve RTU ratings. Additionally, while test procedures partially account for the value of the Cold Climate Heat Pumps, Enclosure Insulation, and Enclosure Leakage measures, impacts on the ratings from these measures are not proportional to their energy savings potential. This research can be used to support NEEA's efforts to improve RTU regulations through adoption of whole-box test procedures and performance metrics by quantifying the measures' value in climates across the U.S.
- **Support addition or expansion of code requirements for efficient RTU features.** In addition to federal standards, this research can support efforts to require efficient RTU features in energy codes. For some installations, code already requires Low-Leak Dampers and ERVs. These requirements could be increased or expanded to include other measures, such as Enclosure Insulation or advanced heat pump controls. As the research indicates that energy savings for some measures vary significantly by climate zones, energy codes present an opportunity to account for regional variability in a way that federal standards typically cannot.
- **Prioritize heating performance in RTU program specifications.** Historically, the priority for RTU programs has been to achieve cooling efficiency. Rebates are offered for RTUs with cooling efficiencies (e.g., SEER, IEER) that exceed the current practice baseline. These research findings suggest that cooling efficiency may have reached a point of diminishing returns for all but the hottest climates, while features that reduce heating consumption (e.g., ERVs, heat pumps, heat pump controls) offer large energy-savings opportunities. Consequently, RTU specifications and programs should focus on more than heating *ratings* (e.g., furnace efficiency, such as AFUE), but should examine heating performance holistically, which may mean combining multiple energy-saving measures.
- **Consider combining multiple measures into a package to maximize energy savings.** While the interactive effects of combining measures often does not produce additional energy savings, combining measures maximizes potential energy savings in all climate zones, particularly for the Cold Climate Heat Pump measure and all measures included in NEEA Tier 2 specifications. Considering barriers will also be important in installing each measure. For example, Low Leak Dampers offer relatively inexpensive and easy installations, while ERVs are expensive, heavy, and can be

difficult to install. The team recommends that programs advocate for combined multiple measures while considering installation barriers.

- **Analyze RTU operating modes.** This study's simulation results could be used to analyze how often RTUs operate in various modes, including full-load heating/cooling, part-load heating/cooling, economizing, and stand-by. Analyzing how often RTUs operate in each mode could inform future test procedures and standards. The team recommends using currently available simulation data to investigate this through a follow-up study:
    - An example use case is that current RTU furnace test procedures weight results for part-loads at full-load operations evenly in the final rating due to a lack of information on how often units run in each mode. Modeling might show that units spend a high percentage of operating time in part-load heating, which could be used to recommend improved weighting.
    - This analysis could be used to show *when* each measure saves energy. For example, learning which operating mode (e.g., active cooling, standby, active heating) proves most important for the Enclosure Insulation measure.
- **Collect data on RTU shipments by climate zone.** Data that this study used to weight national energy savings results by climate zone were the same as those used for development of upcoming federal standards. These were based on one manufacturer's shipments data from the early 2000s. As we found measure energy savings vary so much by climate, these shipment data are critical to understanding the weighted average national potential. The team recommends conducting research to understand RTU shipments nationally and to potentially update the weighting used in this analysis to better understand national energy savings potential.
- **Field metering studies to validate energy savings.** Field studies would prove particularly helpful in validating energy savings for the Cold Climate Heat Pump and Low Switchover Temperature measures in cold climates, where significant energy savings have been observed from improving heat pump controls. Field studies could validate impacts for combining measures or for HVAC replacements. For individual measures with small energy savings potential (<5%), difficulties may arise in validating savings, but pseudo lab and/or field studies could be considered that include increased monitoring and measurement to "catch" small differences in energy consumption.

5 Conclusion

This study provides a comprehensive analysis of commercial HVAC efficiency measures for various commercial RTU equipment, including their energy savings potential, broader implications for market transformation, and influencing codes and standards. The findings highlight significant energy savings potential for various measures and measure combinations.

One key takeaway from this analysis is the variation in measure energy savings by climate zone. While national average energy savings estimates provide a broad perspective, breaking down impacts by climate region offers a more precise understanding of where specific measures have the greatest impact.

Across all climate zones and HVAC system types, the highest measure energy savings potential comes from combining multiple measures. Combinations of the Cold Climate Heat Pump and Low Switchover Temperature measures paired with the NEEA Tier 2 measure achieve the most substantial HVAC energy savings nationally. The NEEA Tier 2 measure itself includes a measure package of improved Enclosure Insulation, Low-Leakage Dampers, and ERV installation. This finding supports the recommendation to advocate for bundled measures in efficiency programs rather than focusing solely on individual upgrades.

Among individual efficiency measure performance nationally, gas RTUs can benefit the most from the ERV measure and/or upgrading to a heat pump. The Cold Climate Heat Pump measure had the highest potential energy savings for heat pump RTUs.

One critical insight from this research is that cooling efficiency improvements face diminishing returns in most climates. This study suggests a need for a shift in regulatory focus from cooling efficiency toward incorporating features such as ERVs, heat pump controls, and combinations of enclosure measures, which provide more substantial energy savings.

Many measures studied are not considered in current RTU test procedures and federal standards. While some measures may not be appropriate or may face hurdles for federal standards, codes provide another opportunity for widespread awareness and adoption.

In addition to these technical findings, the study provides several recommendations for future research and programmatic improvements. The key recommendations include advocating for inclusion of high-impact measures in codes and standards, conducting field metering studies to validate simulated energy savings, performing additional analyses on existing simulation results (such as an RTU operating mode analysis), and collecting updated RTU shipment data by climate zones to refine national energy savings estimates.

Overall, this study contributes valuable insights to inform efficiency programs, policy development, and market transformation efforts. Using data from this effort, programs can drive meaningful advancements in HVAC efficiency, leading to substantial energy and cost savings nationwide.

Appendix A Code-Regulated Inputs

This appendix includes final input values for parameters regulated by code requirements, as summarized in Table 57. These inputs, along with envelope constructions not included in Table 57, align with the DOE Commercial Reference Buildings[63] based on ASHRAE 90.1-2004. This table excludes code-regulated inputs specific to baseline or measure HVAC system definitions, such as cooling coil COP, which are defined elsewhere in this report.

Table 57: Code-Regulated Inputs

Input	Units	Medium Office	Single-Story Medium Office	Primary School	Retail Standalone	Retail Strip Mall	Grocery	Warehouse
Cooling sizing factor	None	1.15	1.15	1.75[64]	1.15	1.15	1.15	1.15
Heating sizing factor	None	1.25	1.25	1.75[65]	1.25	1.25	1.25	1.25
District hot water heater efficiency	None	80%	80%	80%			80%	
Fan motor efficiency	None	91%	91%	91%	87.5%	82.5%	87.5% | 91%	
Outside air ventilation per person	M^3/s-person	0.0125	0.0125	0.008 | 0.025			0.0015 | 0.01	0.01
Outside air ventilation per area	$M^3/s\text{-}m^2$			0.0005	0.0 | 0.0015	0.00152	0.00075 | .0015	0.00025
Pump motor efficiency	None	85%	85%	85%			100%	
Window SHGC	None	0.39	0.39	0.39	0.39	0.39	0.39	0.7
Window U-value	W/m^2-K	3.23646	3.23646	3.23646	3.23646	3.23646	3.23646	6.92716

63 "Commercial Reference Buildings", United States Department of Energy https://www.energy.gov/eere/buildings/commercial-reference-buildings

64 The team increased the cooling sizing factor to reduce unmet load hours.

65 The team increased the heating sizing factor to reduce unmet load hours.

Appendix B Non-Code-Regulated Inputs

This appendix includes final input values for parameters not regulated by code requirements, as defined by the DOE Commercial Reference buildings.[66] These values, shown below in **Table 58**, do not include schedule assumptions (also defined by the DOE Commercial Reference Buildings) or non-code-regulated inputs related to baseline or measure HVAC system definitions, such as backup heating setpoints. HVAC-related inputs specific to baseline or measure HVAC system definitions are defined elsewhere in this report.

Table 58: Non-Code-Regulated Inputs

Input	Units	Medium Office	Single-Story Medium Office	Primary School	Retail Standalone	Retail Strip Mall	Grocery	Warehouse
Cooling setpoint	˚C	24.0	24.0	24.0	24.0	24.0	24.0	24.0
Cooling setup	˚C	26.7	26.7	27.0	30.0	30.0	30.0	30.0
Design pump head	Pa	179352	179352	1			0.1	
District hot water design peak flow rate	M^3/s	0.0000104	0.0000104	0.0000594			0.00000525	
District hot water design loop exit temperature	˚C	60.0	60.0	60.0			60.0	
District hot water heater fuel type	None	Natural gas	Natural gas	Natural gas			Natural gas	
Exterior lighting consumption	W	14804	14804	8575	8266	11485	13577	8923
Exterior wall type	None	Mass	Mass	Mass	Mass	Steel frame	Mass	Metal
Fan mode	None	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous
Fan speed	None	Variable	Variable	Variable	Variable	Variable	Variable	Variable

[66] "Commercial Reference Buildings", United States Department of Energy https://www.energy.gov/eere/buildings/commercial-reference-buildings

Input	Units	Medium Office	Single-Story Medium Office	Primary School	Retail Standalone	Retail Strip Mall	Grocery	Warehouse
Floor area per person	M^2 per person	18.58	18.58	0.3 | 20	6.19 | 27.87	6.19	11.61 | 27.87	
Foundation type	None	Slab on grade	Slab on grade	Slab on grade	Slab on grade	Slab on grade	Slab on grade	Slab on grade
Heating setpoint	˚C	21.0	21.0	21.0	21.0	21.0	21.0	21.0
Heating setback	˚C	15.6	15.6	16.0	15.6	15.6	15.6	15.5
Interior electrical equipment power density	W/m^2	10.76	10.76	4.0 | 25.39	3.23 | 21.52	4.3	5.38 | 8.07	2.56 | 8.07
Interior electrical equipment consumption	W			576 | 31996			524 | 12105	
Interior gas equipment consumption	W			160284			6053	
Interior lighting power density	W/m^2	10.76	10.76	5.38 | 16.14	8.61 | 18.29	13.77 | 23.99	8.61 | 18.29	9.68 | 15.06
Interior wall type	None	Gypsum	Gypsum	Gypsum	Gypsum	Gypsum	Gypsum	Gypsum
Number of people	People							5
Outside air infiltration rate	$M^3/s\text{-}m^2$	0.000302	0.000302	0.000302	0.000302	0.000302	0.000302	0.000302
Pump speed	None	Constant	Constant	Constant			Variable	
Roof type	None	Insulation entirely above deck	Insulation entirely above deck	Insulation entirely above deck	Insulation entirely above deck	Insulation entirely above deck	Insulation entirely above deck	Metal

Appendix C Measure Sensitivity Testing QAQC

This appendix documents the QAQC process undertaken to evaluate the robustness of key measure input parameters in the custom-built Modelkit version. The project team performed stress tests on a set of critical inputs to confirm the templates produced logical, consistent, and intuitive results across difference scenarios. Key parameters tested include:

- Enclosure insulation R-Value
- ERV sensible effectiveness.
- ERV latent effectiveness.
- OA temperature setpoint the backup heat source is available.
- OA temperature setpoint the compressor is locked out.
- Area of the RTU enclosure.
- Area of the RTU enclosure before the heat source.
- Area of the RTU enclosure after the heat source.
- Area of the RTU damper.
- Compressor speed.

Each parameter was tested by setting it to extreme high and low values to assess its impact on model performance. A total of 70 sensitivity simulations were performed using the following simulation segmentation:

- Three prototypes: Strip-mall Retail, Warehouse, and Single-Story Medium Office.[67]
- Two climate zones: 4C (Seattle, WA) and 6A (Minneapolis, MN).[68]
- Both gas RTU and ASHP RTU with electric resistance backup systems.

For RTU capacity-based properties (surface area and compressor speed), the project team only simulated the Strip-mall Retail prototype due to the complexity of integrate these tests within the Modelkit framework. To save time, the team chose the Strip-mall Retail building to focus these tests due to this building being the most responsive to RTU efficiency measures caused by its high ratio of RTUs to floor area.

The following metrics were analyzed to ensure the integrity of sensitivity testing results:

- Unmet hours
- Annual energy

[67] For the RTU area sensitivity parameters and compressor speed parameter (the RTU properties that are based on capacity), the project team only simulated the Retail Strip-mall prototype. This choice was made because these sensitivity tests were the most complicated to integrate into the Modelkit framework. To save time, the Retail Strip-mall building was chosen as it previously displayed the most responsiveness to RTU efficiency measures due to the high ratio of RTUs to floor area.

[68] Performing this QAQC check in climate zone 6A allowed the team to test key measure inputs in an extreme weather environment to further validate our custom Modelkit version.

- Annual heating energy
- Annual cooling energy
- Annual fan energy

Table 59 documents the prototype buildings and climate zones simulated for each parameter. Also included in Table 59 are the extreme values tested as part of this sensitivity analysis, indicated as "A" and "B."

Table 59: Measure Input Parameters and Simulation Prototypes

Parameter	Sensitivity Cases		Simulated Prototype (Climate Zone)		
	A	B			
Enclosure insulation R-Value	0.1	20	Strip-mall Retail (CZ4C, CZ6A)	Warehouse (CZ4C, CZ6A)	Single-Story Medium Office (CZ4C, CZ6A)
ERV sensible effectiveness	0	0.9	Strip-mall Retail (CZ4C, CZ6A)	Warehouse (CZ4C, CZ6A)	Single-Story Medium Office (CZ4C, CZ6A)
ERV latent effectiveness	0	0.7	Strip-mall Retail (CZ4C, CZ6A)	Warehouse (CZ4C, CZ6A)	Single-Story Medium Office (CZ4C, CZ6A)
OA temperature setpoint the backup heat source is available	45F	5F	Strip-mall Retail (CZ4C, CZ6A)	Warehouse (CZ4C, CZ6A)	Single-Story Medium Office (CZ4C, CZ6A)
OA temperature setpoint the compressor is locked out	40F	0F	Strip-mall Retail (CZ4C, CZ6A)	Warehouse (CZ4C, CZ6A)	Single-Story Medium Office (CZ4C, CZ6A)
Total area of the RTU enclosure	10%	300%	Strip-mall Retail (CZ4C, CZ6A)	-	-
Area of the RTU enclosure before the heat source	10%	300%	Strip-mall Retail (CZ4C, CZ6A)	-	-
Area of the RTU enclosure after the heat source	10%	300%	Strip-mall Retail (CZ4C, CZ6A)	-	-
Area of the RTU damper	10%	300%	Strip-mall Retail (CZ4C, CZ6A)	-	-
Compressor speed	1	3	Strip-mall Retail (CZ4C, CZ6A)	-	-

Overall, the measure sensitivity analysis confirmed that the custom Modelkit templates behave as expected across a wide range of parameter inputs, reinforcing confidence in their accuracy and reliability. **Figure 18** through **Figure 21** provide graphical representations of annual energy consumption results by HVAC type, climate zone, and building type. The baseline results are shown in gray, with sensitivity results higher than baseline in orange and lower than baseline in green. Test results for RTU area properties and compressor speeds (measure inputs only tested in the Strip-mall Retail building type) are shown in **Figure 20** and **Figure 21**, respectively.

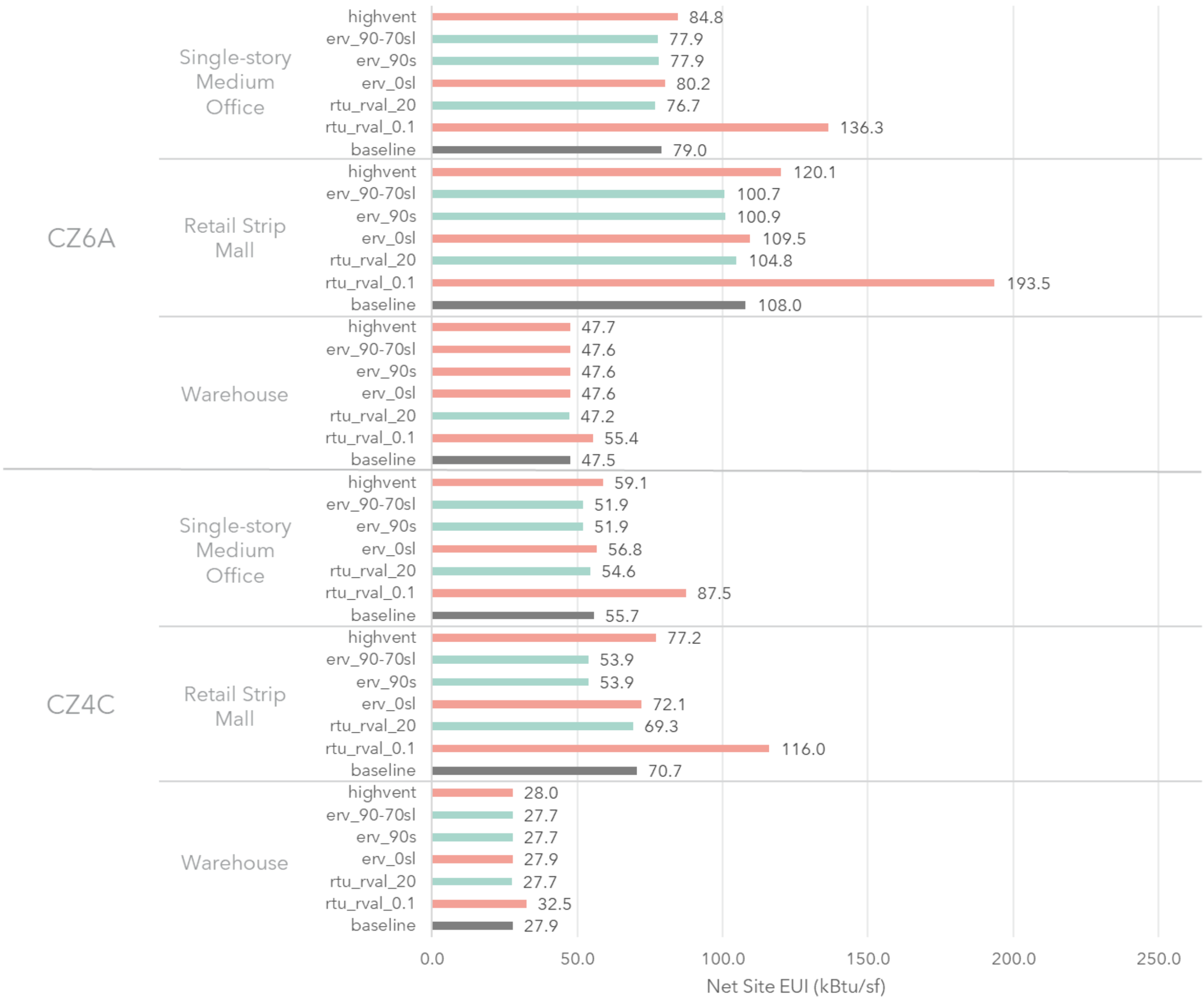

Figure 18: Gas RTU Net Site EUI by Measure Input Sensitivity Test, Building Type, and Climate Zone

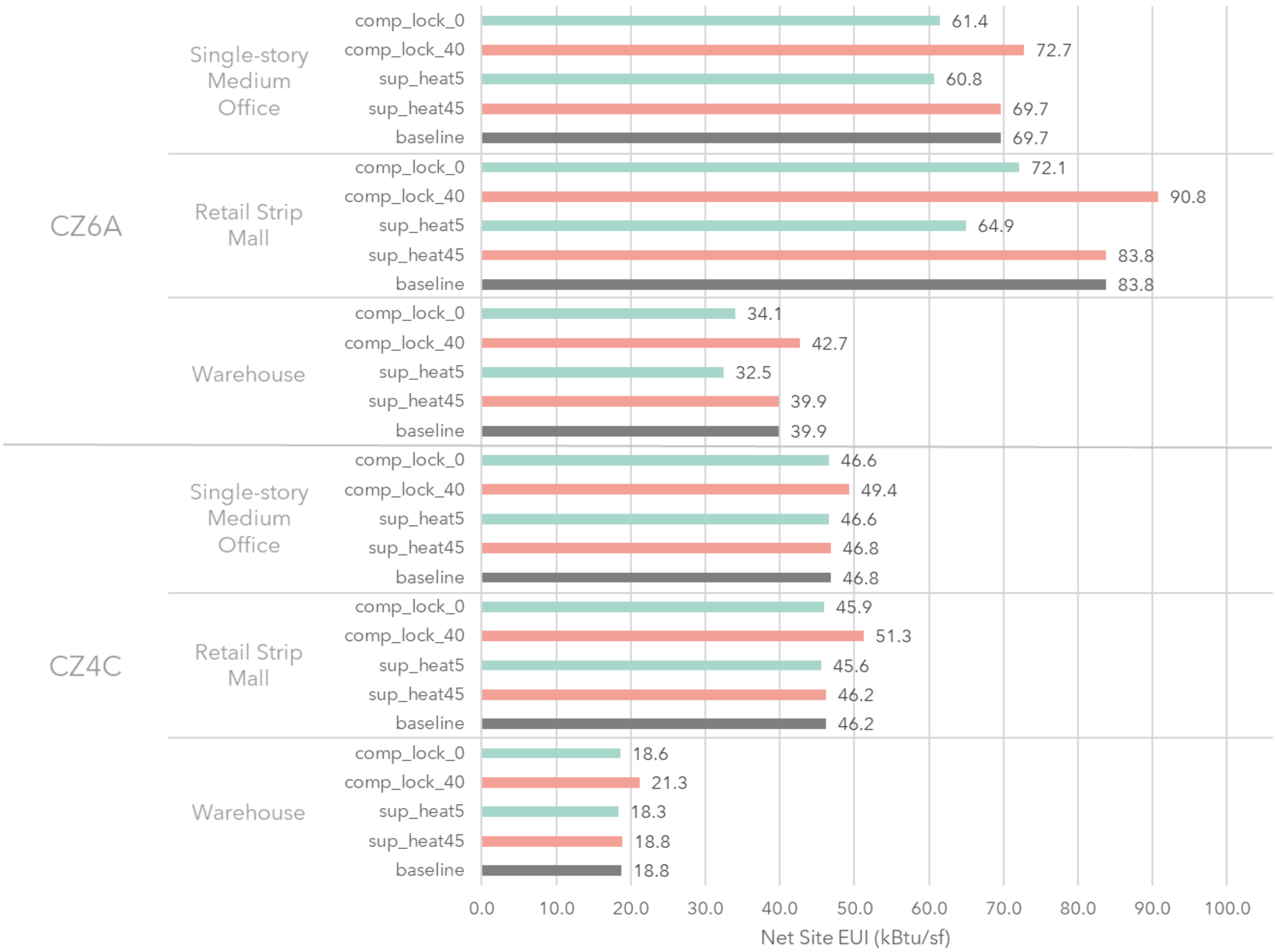

Figure 19: ASHP RTU w/ Electric Resistance Backup by Measure Input Sensitivity Test, Building Type, and Climate Zone

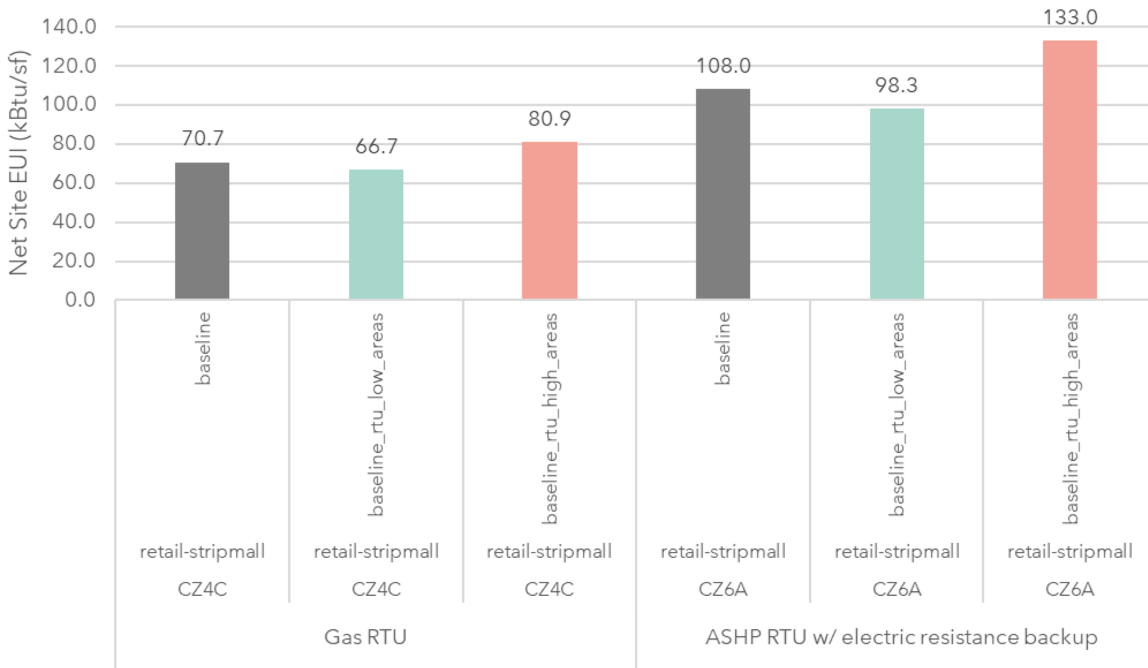

Figure 20: RTU Area Properties Test Results

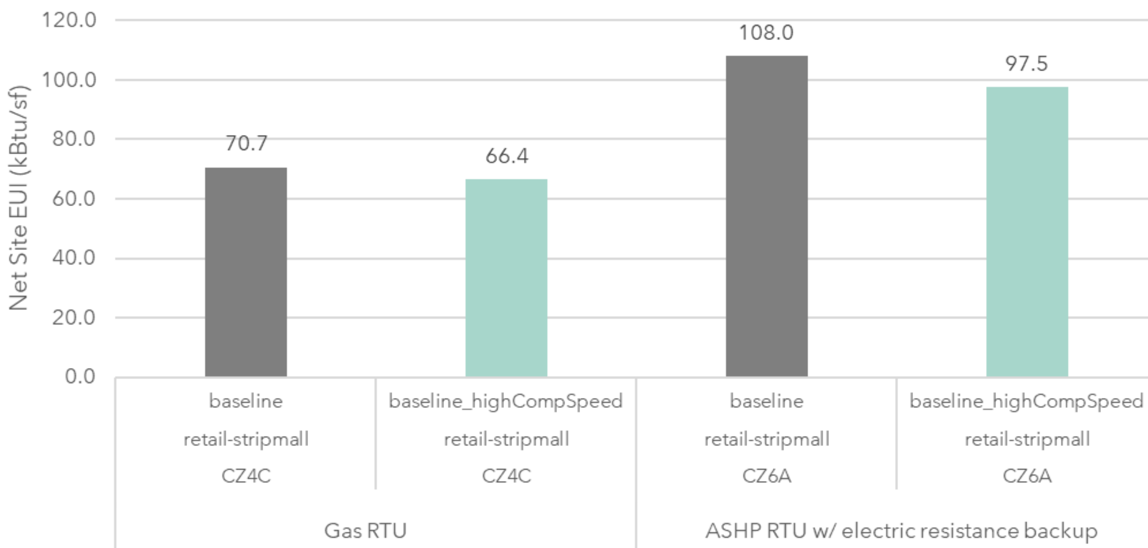

Figure 21: Compressor Speed Test Results (1-speed vs 3-speed)