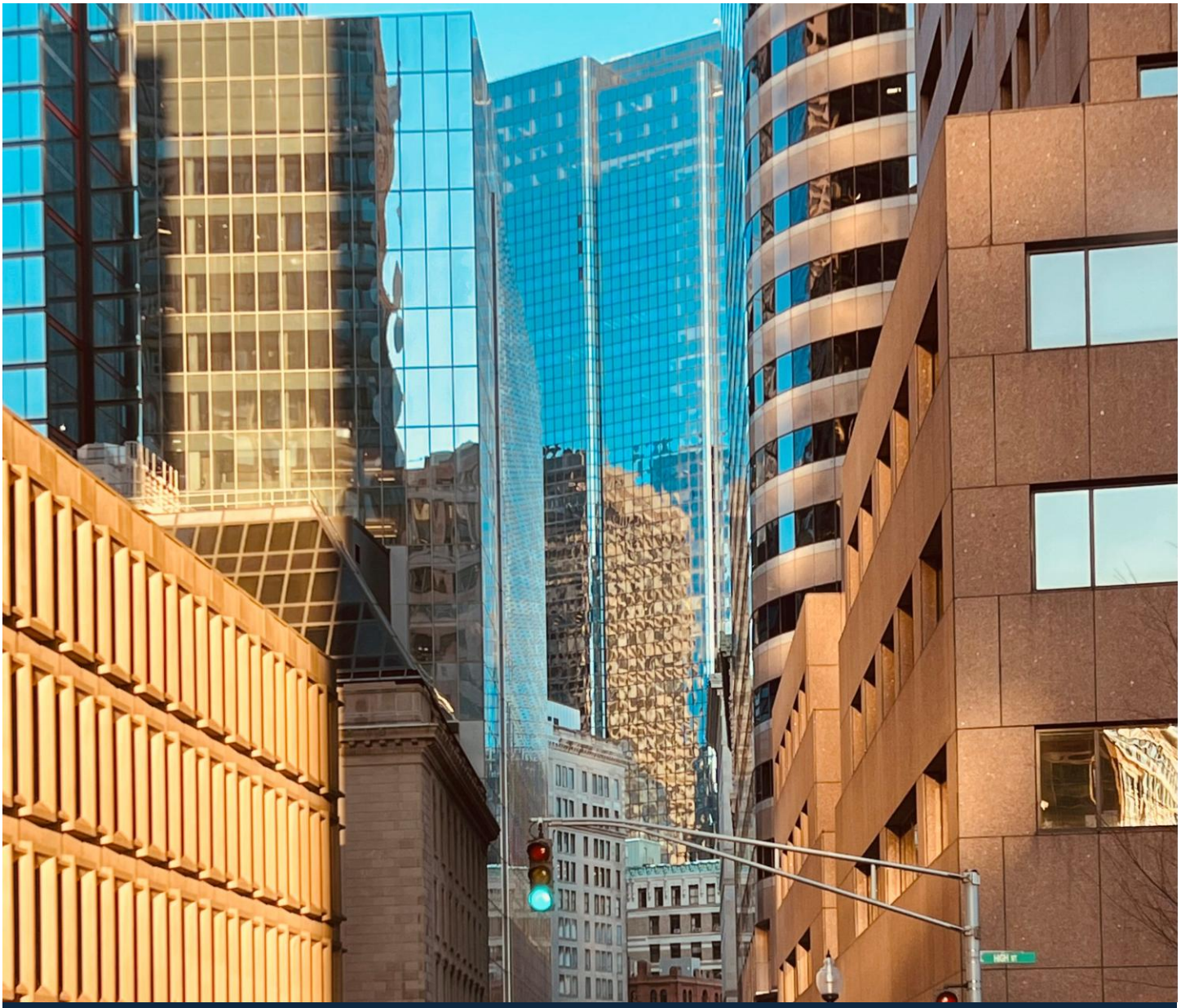


Commercial Building Electrification in the Northeast and Mid-Atlantic

Criteria Pollutant and Greenhouse Gas Reduction Potential

November 2026

Northeast States for Coordinated Air Use Management (NESCAUM) and the Ozone Transport Commission (OTC), with support from Synapse Energy Economics

Acknowledgements

This report was written by NESCAUM and the OTC, with support from Synapse Energy Economics. The report was developed by NESCAUM/OTC staff Riena Harker, Emily Levin, and Barbara Morin, with valuable support from Alexandra Karambelas and Alison Carney.

From Synapse Energy Economics, Kenji Takahashi and Tenzin Gyalmo conducted the refrigerant analysis, and Shelley Kwok drafted background information on commercial HVAC technologies and barriers, with contributions from Philip Eash-Gates and Kenji Takahashi.

We would also like to acknowledge expert input from the following organizations:

- California Air Resources Board
- Massachusetts Department of Environmental Protection
- New York State Department of Environmental Conservation
- Refrigerant Emissions Elimination Forum

We utilized expert input in tandem with market research to develop some of the assumptions used in the refrigerants section of report. All refrigerant emissions analysis reflects final work by Synapse Energy Economics, and does not represent official views of any of the organizations listed above or their affiliates.

The cover image was obtained royalty-free from Pexels.com.

NESCAUM
NORTHEAST STATES FOR COORDINATED AIR USE MANAGEMENT

OZONE TRANSPORT COMMISSION

Synapse
Energy Economics, Inc.

Contents

Acknowledgements **1**

1. Introduction **1**

2. Background **2**

Air Pollution from Combustion in Commercial Buildings *2*

Commercial Building Electrification Technologies *3*

Barriers to Commercial Building Electrification *5*

Policy Landscape *8*

3. Overview of the Study Method **11**

NLR ComStock Tool *11*

Methods Summary *16*

Step 1: Assess Changes in Commercial Building Energy Consumption *17*

Step 2: Collect and Calculate Emissions Factors for Fossil Fuel Combustion and Electricity Generation *17*

Step 3: Estimate Total Emissions Changes for ComStock Scenarios *23*

Step 4: Screen for Health Benefits Associated with Emissions Reductions *23*

Step 5: Estimate the GHG Impacts of Refrigerant Emissions *24*

4. Results **29**

Baseline Energy Consumption *29*

Changes in Energy Consumption *30*

Changes in Emissions *32*

Health Impacts Screening *40*

Refrigerant Leakage and Associated GHG Emissions *41*

5. Discussion **47**

Summary of Findings *47*

Comparison with Residential Building Electrification Report *48*

Refrigerant Leakage and Emissions Key Findings *50*

Looking Ahead *51*

6. Appendices **52**

1. Introduction

This report summarizes findings from an analysis of the changes in air emissions that could occur due to electrification of commercial buildings – primarily by upgrading commercial space heating equipment to zero-emission heat pumps – in states that are members of the Ozone Transport Commission.[1] Specifically, we examine the emissions reduction potential for carbon dioxide-equivalent (CO_2e – also referred to as greenhouse gases or GHGs), nitrogen oxides (NO_x), fine particulate matter ($PM_{2.5}$), volatile organic compounds (VOCs), and sulfur dioxide (SO_2).

This analysis was conducted by the Northeast States for Coordinated Air Use Management (NESCAUM)[2] and the Ozone Transport Commission (OTC)[3] for states that are members of NESCAUM and the OTC: Connecticut, Delaware, the District of Columbia, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and Virginia. Synapse Energy Economics provided supporting research and analysis on commercial building technologies and refrigerant impacts.

This report builds on the 2024 NESCAUM and OTC report, Residential Building Electrification in the Northeast and Mid-Atlantic: Criteria Pollutant and Greenhouse Gas Reduction Potential ("Residential Building Electrification Report"). In the 2024 Residential Building Electrification Report, we used the National Laboratory of the Rockies (NLR, formerly known as the National Renewable Energy Lab or NREL) ResStock tool to evaluate the emissions reduction potential of various electrification scenarios in residential buildings. Likewise, for the present Commercial Building Electrification report, we use NLR's ComStock tool to assess changes in air emissions expected from electrification scenarios in commercial buildings. Since neither ResStock nor Comstock evaluates the GHG emissions impacts of refrigerants used in heat pumps and air conditioners (ACs), we conducted an additional analysis to understand the impact of refrigerant leaks on GHG emissions from these equipment types.

This analysis does not evaluate emissions changes from electrifying coal or biomass-burning appliances, which are not included in ComStock. It also does not assess the impacts of a changing climate on heating or cooling demand.

Section 2 of this report provides background information on commercial building emissions, the need to reduce criteria pollutant and GHG emissions, barriers to

[1] States in the Ozone Transport Commission include Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Washington, D.C., Vermont, and Virginia. .

[2] NESCAUM is the regional nonprofit association of state air quality agencies in Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont.

[3] The OTC was established by Congress in the 1990 Clean Air Act Amendments to address regional ozone pollution affecting the OTC member jurisdictions. In addressing their collective regional ozone problem, the OTC members are responsible for developing and implementing initiatives to reduce NOx and VOCs, the emitted precursor air pollutants that contribute to ground-level ozone formation.

commercial building decarbonization, and policy drivers for reducing emissions from commercial buildings. Section 3 reviews the methods used in the study. Section 4 summarizes the results of the analysis, and Section 5 provides conclusions and areas for further research.

2. Background

Air Pollution from Combustion in Commercial Buildings

Fossil fuel combustion in buildings, mostly for heating, contributes to ambient air pollution that causes health harms. Air pollutants include GHGs such as CO_2, methane, and nitrous oxide (N_2O); criteria air pollutants such as NO_x, SO_2, and $PM_{2.5}$; and VOCs such as formaldehyde and acetaldehyde.[4,5] These emissions adversely affect local and regional air quality and contribute to climate change. While direct fuel combustion in commercial buildings is responsible for around 3% of NO_x and 7% of GHG emissions nationally, it is of significantly greater concern in OTC states, which have a higher density of buildings than other regions due to higher population density. Commercial buildings produce approximately 7% of NO_x and 12% of GHG emissions among OTC states (Figure 1).[6]

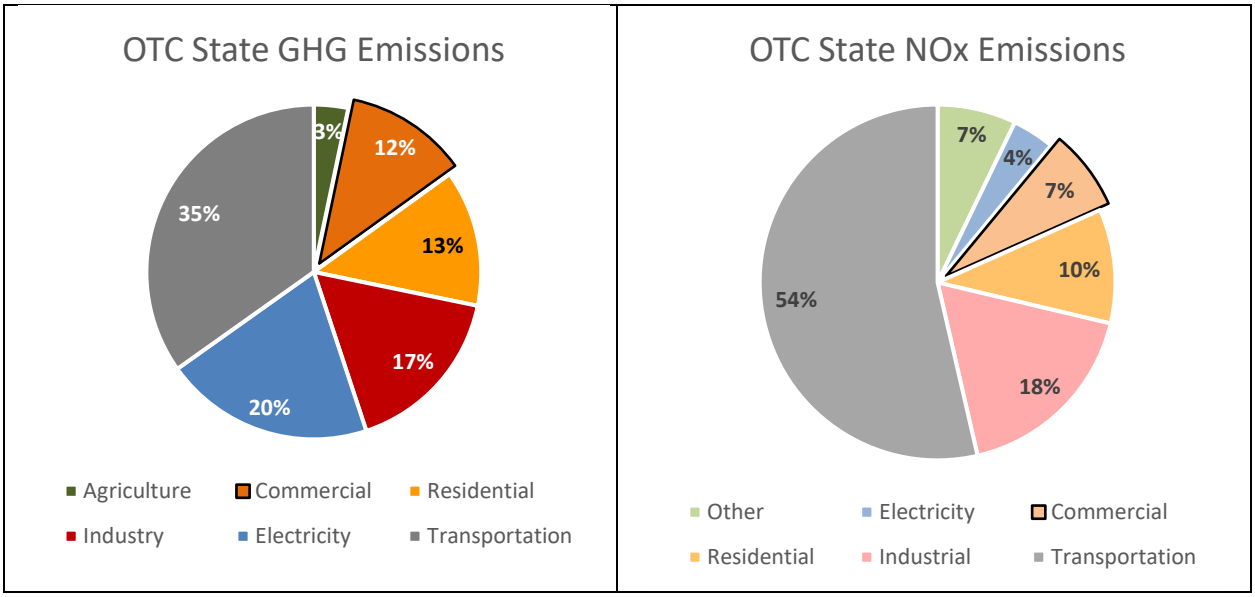


Figure 1. Sources of Annual GHG and NO_x Emissions in OTC States (Source: 2023 NEI)

As detailed in the Residential Building Electrification Report, NO_x contributes to secondary $PM_{2.5}$, ground-level ozone, and smog formation. Ozone is primarily a concern in the

[4] Gaffney, J., and Marley, N. (2009), "The impacts of combustion emissions on air quality and climate – From coal to biofuels and beyond," *Atmospheric Environment* 43(1): 23-36.

[5] Mullen, N., et al., "Impact of natural gas appliances on pollutants levels in California homes," Lawrence Berkeley National Laboratory, December 2012.

[6] NESCAUM analysis of the 2023 National Emissions Inventory and 2022 National Greenhouse Gas Inventory from U.S. EPA.

summer when heat and sunlight accelerate the chemical reactions of NO_X and VOCs that create it,[7] and is less likely to be influenced by air emissions from heating in commercial buildings. However, NO_x poses a year-round environmental and health concern due to its contributions to:[8]

- Direct respiratory harm including lung irritation, coughing, and shortness of breath;[9] as well as long-term increased mortality risk – particularly for populations with comorbidities.[10]
- Secondary $PM_{2.5}$, which contributes to a variety of respiratory and other health harms.
- Eutrophication, which is an oversaturation of nutrients in aquatic ecosystems that accelerates aquatic plant growth, causes oxygen depletion when the plant overgrowth decomposes, and suffocates fish and other aquatic animals.
- Regional haze, which states are currently required to address under EPA's Regional Haze Rule, to bring visibility to "natural conditions" by 2064.[11]

In addition to NO_x, this report assesses the impacts of commercial building electrification on SO_2 and VOC emissions (both of which can aerosolize to form secondary $PM_{2.5}$), and primary $PM_{2.5}$ to allow for analysis of health effects; and on CO_2-equivalent (CO_2e) to compare GHG emissions under different upgrade scenarios.

Commercial Building Electrification Technologies

This report evaluates the emissions impacts of replacing "baseline" commercial heating equipment with zero-emission and energy-efficient heating technologies, referred to as "upgrade" equipment in this report. Table 1 reviews the equipment types examined in this report, and Table 3 in Section 3 provides details on upgrade equipment specifications from the ComStock model.

This report focuses on heat pumps as the best-practice electrification technology to eliminate emissions from onsite combustion for commercial building heating. Because heat pumps move heat rather than create it, they are the most energy-efficient heating equipment available, with ENERGY STAR-rated light commercial heat pumps having a minimum coefficient of performance of 2.1 to 2.4 at 17°F.[12] We focused this analysis on space heating and cooling because those end uses consume the greatest share of

[7] U.S. EPA, "Ground-level Ozone Basics," last updated March 11, 2025.

[8] *See* NESCAUM & OTC, "Residential Building Electrification in the Northeast and Mid-Atlantic: Criteria Air Pollutant and Greenhouse Gas Reduction Potential," updated March 2025.

[9] Agency for Toxic Substances and Disease Registry, "ToxFAQs for Nitrogen Oxides," March 25, 2014.

[10] Yang, et al. (2025), "Associations of Long-Term Exposure to Nitrogen Oxides with All-Cause and Cause-Specific Mortality," *Nature Communications* 16: 1730.

[11] MANE-VU, "Timeline for Regional Haze Implementation Plan Preparation," updated March 2004.

[12] ENERGY STAR, "Light Commercial HVAC Key Product Criteria," accessed May 15, 2026.

commercial building energy, at over 45% of commercial energy use in the Northeast.[13] Water heating and cooking are excluded from this analysis, as they each comprise less than 6% of Northeast commercial building energy consumption,[14] and, in the case of water heating, are not included as upgrades in ComStock.[15]

Table 1: Baseline and Upgrade Heating Equipment in Commercial Buildings[16]

Baseline Equipment	**Gas Rooftop Units (RTUs)**	Rooftop or "packaged" units contain multiple components in a single outdoor apparatus that is located either on the roof or to the side of a building. RTUs can be configured to provide either heating (via gas combustion) or cooling (via a central air conditioner) through air ducts.
	Furnaces	Commercial furnaces are standalone pieces of equipment that provide hot air only, blown through ducts. These are typically installed indoors in a mechanical room or basement, and can be powered by fossil fuel combustion or electric resistance.
	Multizone Variable Air Volume (VAV) Systems	VAV systems use ductwork to provide conditioned air from a central air handler to multiple independently controlled zones. This system allows different parts of the building to be heated or cooled at different temperatures.[17]
	Boilers	Commercial boilers provide heat through hot water or steam circulated by radiators, baseboard units, or fan coils. They are more commonly used in older and larger buildings, and can also be configured to provide domestic hot water. Boilers can be powered by fossil fuel combustion or electric resistance.[18]
Upgrade Equipment	**Heat Pump RTUs (HP RTUs)**	HP RTUs operate similarly to gas RTUs, except they use zero-emission air source heat pumps (ASHPs) to supply hot air rather than gas combustion. HP RTUs can be technically feasible and cost-competitive replacements for gas RTUs, and provide cooling.

[13] U.S. EIA, "2018 Commercial Building Energy Consumption Survey: Consumption and Expenditures Highlights," December 2022.

[14] U.S. EIA, "Table E1. Major Fuels Consumption by End Use, 2018," December 2022.

[15] NLR, "ComStock Reference Documentation: 2025 Release 3," pp. 76, November 2025.

[16] Synapse Energy Economics, "ComStock Analysis Recommendations," internal research conducted for NESCAUM, October 2025.

[17] Pacific Northwest National Laboratory, "Variable Air Volume (VAV) Systems Operations and Maintenance," April 2021.

[18] Note: The ComStock model, and therefore our analysis, only includes gas-fired boilers.

Upgrade Equipment	**HP Boilers**[19]	HP boilers draw heat from the air, ground, or water and use it to produce hot water for space heating. They can replace gas and electric resistance boilers, although HP boilers may have lower temperature setpoints (e.g., 140°F compared to 180°F for gas units) that may not be compatible with high-temperature distribution systems.[20] The ComStock upgrade for HP boilers only includes ASHPs.
	Variable Refrigerant Flow (VRF)	VRF systems consist of an outdoor compressor unit connected via refrigerant lines to many indoor air handlers that provide heat and cooling to various indoor zones. Unlike HP RTUs, which can only provide either heating or cooling at one time, VRF systems can provide heating and cooling simultaneously to different indoor zones. Unlike VAV systems, which distribute air via ductwork, VRF systems use refrigerant to transfer heat to individual indoor units.

Barriers to Commercial Building Electrification

This section describes barriers to electrifying heating systems in commercial buildings, including barriers specific to heating, ventilation, and air conditioning (HVAC) technologies.

Lack of access to capital and disincentives to invest

While heat pumps provide all-in-one heating and cooling, upfront costs and associated upgrades can be higher than for like-for-like fossil fuel equipment replacements, especially if building owners do not replace their existing cooling systems at the same time. Even when lifecycle economics are favorable, limited access to capital, especially for smaller building owners, can delay or prevent projects. In particular, the rapid turnover of commercial real estate, with buildings changing owners every 5 to 10 years on average, presents a major barrier to energy efficiency investments.[21] Although the economic returns on energy efficiency can be substantial over a building's lifespan, the financial benefits are likely to accrue to future owners rather than the original investor, disincentivizing upgrades. Building owners typically prefer retrofit projects with payback periods of 3-5 years, which is difficult for most energy upgrades to meet.

[19] Heat pumps that capture thermal energy from the outside air, ground, or water to heat water go by many different names: heat pump boilers, hydronic boilers, and air-to-water heat pumps (AWHPs). Heat pump water heaters also pull heat from the air to heat water, but produce potable drinking water rather than hot water for space heating.

[20] Woldekidan, K., "End-Use Savings Shapes Measure Documentation: Boiler Replacement with Air-Source Heat Pump Boiler and Electric Boiler Backup," NLR, May 2024.

[21] American Council for an Energy-Efficient Economy (ACEEE), "Financial and Systemic Barriers and Solutions to Implementing Commercial Retrofits at Scale," December 4, 2023.

Perceived risk and performance concerns

Cold-climate heat pumps for commercial buildings are relatively new in the United States. Given limited familiarity with the technology, owners may be cautious about comfort at low outdoor temperatures, integration with existing heating distribution systems (e.g., air handlers and ducts or water circulation systems), and potential disruption during installation.[22] Perceived risks can outweigh potential energy savings benefits.

Electrical service restrictions

Commercial building electrification can require multiple types of building upgrades. First, a building's electrical panel may lack sufficient capacity or breaker space to accommodate new electric equipment and appliances. Upgrading electrical panels and wiring to accommodate electrification adds cost and complexity to retrofit projects. Second, local distribution systems, particularly in dense urban areas with older infrastructure, may be constrained by capacity at substations, feeders, and distribution lines.[23] Due to their larger sizes and higher electricity demands, commercial and multifamily buildings are more likely to trigger electric capacity upgrades at the distribution feeder level than single-family homes.

Historic building designations

If a building has any historic designations, it may be subject to limitations that prevent the installation of certain energy efficiency measures or electrification equipment. Building owners affected by these restrictions may need to be creative with HVAC design to comply with all requirements.

Space limitations

Heat pumps require adequate space and airflow for efficient operation, and most systems include outdoor components for heat exchange. Limited space in urban areas, in combination with equipment clearance and property setback requirements, may limit installation options.[24]

Building-type considerations

Economic and technical feasibility varies significantly by commercial building type and size. Simple paybacks are shorter for energy-intensive facilities (e.g., inpatient medical, laboratory, and food service) and for buildings with long operating hours (e.g., retail, offices, and nursing facilities). Larger buildings also experience shorter payback periods

---

[22] Amarnath, N., "Heat Pumps are Hot, but Commercial Retrofits Face Cold Realities," Utility Dive, November 1, 2023.

[23] U.S. Department of Energy, "Guidance Document on Space Heating Electrification for Large Commercial Buildings with Boilers," pp. 18, April 2024.

[24] New Jersey Department of Environmental Protection, "Strategic Roadmap for Building Decarbonization," November 2025.

than smaller ones due to economies of scale and higher total energy use.[25] In contrast, education buildings may be more challenging to electrify – technically and economically – due to reliance on high-temperature centralized boilers, particularly in the Northeast.

Conversion to HP Boiler

Buildings that currently rely on boilers can be challenging to electrify. HP Boilers are one of the few efficient electric heating technologies that can provide hot water for radiator or fan-coil heating loops and are compatible with existing hydronic distribution systems. However, they are generally more complex and costly to install than other types of heat pumps and present technological challenges.

First, HP Boilers provide lower-temperature water than gas-fired boilers and may need a temperature "booster" from a different heating source to meet heating loads. Second, the U.S. HP Boiler market is less developed, with limited examples of retrofits – particularly in multifamily buildings. Third, HP Boilers are most economical when they can use a building's existing distribution system (such as hot water pipes and fan-coil units); retrofit costs can increase substantially if a building's piping is degraded and needs to be modified or replaced. In these cases, building owners may opt to install ducts and use an RTU or VRF system instead. Finally, HP Boilers generally require more boiler room and outdoor space than other technologies, and can be further space-constrained by the number of hot-water storage tanks needed.[26]

Conversion to VRF

VRF systems are highly versatile, capable of serving multiple zones within a building and of varying heating or cooling output to meet individual load requirements. They also have compact indoor and outdoor components that require less space than other heat pump systems, making them more compatible with older and historic buildings.[27] Challenges for VRF systems include long refrigerant piping runs and larger refrigerant charges, which can reduce system performance and elevate refrigerant leak risk if not properly managed,[28] as well as the need for a separate dedicated outdoor-air system (DOAS) to provide ventilation.[29] Additionally, VRF systems are typically more expensive to install than RTUs or furnaces. One modeling study found that payback periods for VRF retrofits without incentives are around 50 years compared to 12-18 years for HP RTUs, although VRF

[25] ACEEE, "Electrifying Space Heating in Existing Commercial Buildings: Opportunities and Challenges," October 28, 2020.

[26] ACEEE, "Decarbonizing Space Heating in Existing Centrally Heated Multifamily Buildings," July 13, 2025.

[27] ACEEE, "Electrifying Space Heating in Existing Commercial Buildings: Opportunities and Challenges," October 28, 2020.

[28] Taitem, NYSERDA, and New York City Department of Housing Preservation and Development, "Large Split VRF Systems in Multifamily Buildings," December 9, 2024.

[29] ACEEE, "Electrifying Space Heating in Existing Commercial Buildings: Opportunities and Challenges," October 28, 2020.

systems can be more cost-effective when replacing high-cost equipment such as boiler systems.[30]

Conversion to HP RTU

Buildings with existing fossil fuel RTUs represent one of the best opportunities for commercial building decarbonization, as upgrading to an all-electric HP RTU is typically a straightforward one-for-one replacement. These retrofits do not require distribution system modifications, and HP RTUs are widely available on the market.[31]

One key consideration is that HP RTUs may require backup heat on the coldest days, which can decrease efficiency and increase emissions. Key factors when evaluating HP RTUs for a commercial building upgrade include:[32]

- **Cost and efficiency:** HP RTUs often come with a slight price premium relative to gas RTUs due to their higher efficiency. Depending on utility rates and climate, not all buildings may realize operational savings.
- **Climate suitability:** Although they have higher capital costs than standard HP RTUs, cold-climate HP RTUs should be considered in locations with winters consistently below 20°F to reduce or eliminate the need for backup heat.
- **Space requirements**: HP RTUs can have larger footprints than older, fossil fuel RTUs, so building owners need to provide adequate roof space and structural support for larger and heavier equipment.
- **Building type suitability**: DOE notes that HP RTUs deliver the greatest operating cost benefits for buildings with consistent space conditioning needs and schedules – such as offices and small retail. Buildings that require increased ventilation (e.g., schools) or have limited heating needs (e.g., warehouses) may see fewer savings.[33]

Policy Landscape

Regulations to address criteria air pollutant and GHG emissions from residential and commercial buildings have lagged behind controls for other sectors (e.g., transportation) at the federal and state levels. Consequently, the buildings sector constitutes a growing share of total air pollutant emissions,[34] and many states and local jurisdictions have developed targets and policies to address them.

---

[30] Ibid.

[31] Redwood Energy, "Pocket Guide to All-Electric Retrofits of Commercial Buildings," pp. 12-13, June 2022; CaraDonna, C., et al., "End-Use Savings Shapes Measure Documentation: Heat Pump Rooftop Units With Exhaust Air Energy Recovery," NLR, April 2024.

[32] U.S. Department of Energy (DOE), "Key Considerations for Adopting Commercial Heat Pump Rooftop Units," Better Buildings, n.d.

[33] Ibid.

[34] US Department of Energy (DOE), "Decarbonizing the U.S. Economy by 2050," April 2024.

State Targets

Table 2 highlights select emissions reduction targets for commercial buildings established by four OTC states. It provides a sample of relevant targets and is not a comprehensive listing of all state goals applicable to commercial buildings.

Table 2. Building Emission Reduction Targets in the Northeast and Mid-Atlantic

State	Near-Term Targets	Long-Term Targets
Maryland	20% reduction in net GHGs (compared to 2025 levels) by 2030 for large buildings covered by a statewide Building Performance Standard.[35]	Net-zero economy-wide direct GHG emissions by 2040.[36]
Massachusetts	49% reduction in GHG emissions (compared to 1990 levels) by 2030 for commercial and industrial heating and cooling.[37]	92% reduction in GHG emissions (compared to 1990 levels) by 2050 for commercial and industrial heating and cooling.[38]
New Jersey	20,000 additional electrified commercial buildings between 2023 and 2030.[39]	89% reduction in building sector emissions (compared to 2018 levels) down to 2.7 MMT CO_2e by 2050.[40]
New York	10-20% of commercial space served by heat pumps by 2030.[41]	85% of homes and commercial building space electrified by 2050.[42]

State Policies

In addition to setting targets, states and local jurisdictions are adopting policies and programs designed to reduce emissions from the commercial building sector. Key policies being explored and implemented include:

Building Performance Standards (BPS)

BPS (otherwise known as Building Energy Performance Standards, or BEPS) set benchmarking requirements and energy performance or emissions standards for

[35] Maryland General Assembly, "SB0528: Climate Solutions Now Act of 2022," effective June 1, 2022.

[36] Ibid.

[37] Massachusetts Executive Office of Energy and Environmental Affairs, "Determination of Statewide GHG Emissions Limits and Sector-Specific Sublimits for 2025 and 2030," June 30, 2022.

[38] Massachusetts Executive Office of Energy and Environmental Affairs, "Determination of Statewide GHG Emissions Limit and Sector-Specific Sublimits for 2050," December 21, 2022.

[39] New Jersey Governor's Office, "Executive Order No. 316," signed February 15, 2022.

[40] New Jersey Department of Environmental Protection, "Strategic Roadmap for Building Decarbonization," November 2025.

[41] New York State Climate Action Council, "Scoping Plan," December 2022.

[42] Ibid.

large commercial and multifamily buildings. Performance standards are set in advance and can increase in stringency over time, providing building owners with a runway to plan building energy efficiency and electrification upgrades.[43] BPS are currently being implemented in several states, including Colorado, Maryland, Oregon, Washington state, and Washington, D.C.[44]

Zero-Emission Standards for Space and Water Heating Equipment (ZEHES)

ZEHES set a future date after which space and water heating equipment sold in the implementing jurisdiction cannot emit specific air pollutants (e.g., NO_x or GHGs). South Coast Air Quality Management District (South Coast AQMD) in California passed the nation's first ZEHES for commercial-scale water heating equipment in 2024, phasing in zero-emission compliance targets for large water heaters, small boilers, and process heaters from 2026-2033.[45] The rule is currently the subject of litigation, but prevailed at the District Court level in 2025 and at the Ninth Circuit Court of Appeals in 2026.[46] California and Maryland are currently exploring statewide ZEHES regulatory options.[47,48]

All-Electric Building Code

All-electric building codes require that new buildings covered by the code are constructed with all-electric heating and appliances. New York was the first state in the nation to approve an all-electric new construction standard for large residential and commercial buildings in July 2025.[49] While the state's authority to pass and enforce this type of building code is under litigation, rulings by the District Court and the Second Circuit Court of Appeals favored the regulation.[50]

These and other policies can help states reach their climate and air quality goals. The next section provides an overview of the methods used in this study to estimate the emissions reduction potential of commercial building electrification.

---

[43] Regulatory Assistance Project, "To Save Energy, Cities Turn to Building Performance Standards," May 1, 2023.

[44] Institute for Market Transformation, "Map: Building Performance Standards," updated December 2025.

[45] South Coast AQMD, "Proposed Amended Rule 1146.2: Control of Oxides of Nitrogen from Large Water Heaters, Small Boilers, and Process Heaters," amended June 7, 2024.

[46] Public Health Law Center, "Rinnai America Corp. v. South Coast Air Quality Management District (2024)," accessed August 28, 2026.

[47] California Air Resources Board, "Zero-Emission Standards for Space and Water Heating Equipment," accessed March 13, 2026.

[48] Maryland Department of the Environment, "Clean Heat Rules," accessed March 13, 2026.

[49] New York Department of State, "Minutes of the NYS Fire Prevention and Building Code Council meeting," July 25, 2025.

[50] Public Health Law Center, "Mulhern Gas Co. v. Mosley (2023)," accessed August 28, 2026.

3. Overview of the Study Method

This study utilized NLR's ComStock tool to assess changes in energy use and associated air emissions from commercial heat electrification upgrades. It estimates the emissions reductions that could occur if commercial buildings in OTC states were electrified under several different scenarios, including "current" (2026) and "future" (2044) electricity grid cases. We also conducted a secondary analysis of GHG emissions from commercial HVAC refrigerant leaks. Assumptions and limitations of the modeling approach are described later in this section.

NLR ComStock Tool

We used ComStock 2025 Release 3 (November 2025) to download commercial building energy consumption data. ComStock is a physics-based tool that combines public and private data sources, statistical sampling methods, and building energy models to estimate commercial building energy consumption in the U.S.[51] It models energy consumption for the commercial building stock as it existed in 2018 as a baseline scenario, and for a variety of energy efficiency upgrades applied to the commercial building stock.

ComStock is preprogrammed with different energy efficiency and electrification upgrades, initially developed to align with and support external studies including the Los Angeles 100% Renewable Energy Study, the Advanced Building Construction Typology Report, and the Electrification Futures Study.[52] These upgrades include building envelope upgrades such as insulation and new windows, energy efficiency upgrades such as energy recovery, and electrification upgrades such as ASHPs – modeled individually or combined into packages. For this analysis, NESCAUM selected upgrade scenarios and packages with electrification and associated energy efficiency measures that did not include building envelope improvements, in order to isolate the impact of electrification on commercial building emissions.

Selecting ComStock Upgrade Scenarios

Data from the U.S. EIA's Commercial Buildings Energy Consumption Survey (CBECS) indicates that office, education, and mercantile (retail) buildings are the most prevalent commercial building typologies in the Northeast, while boilers and packaged heating units (RTUs)[53] are the most common heating equipment types (Figures 2 and 3).[54]

---

[51] NLR, "ComStock Reference Documentation: 2025 Release 3," November 2025.

[52] Ibid.

[53] While commercial packaged units can be located on the ground, the industry standard is to place them on rooftops. For simplicity, we refer to them as RTUs. *See* Trane, "Packaged Unit," accessed September 7, 2026.

[54] Synapse Energy Economics analysis of CBECs data; U.S. EIA, "2018 CBECS Survey Data," revised December 21, 2022.

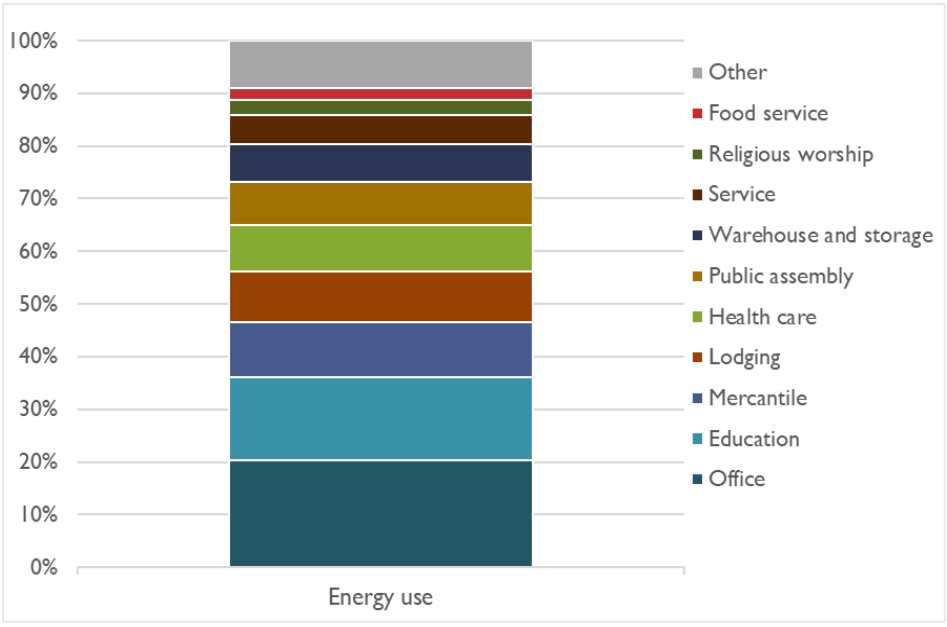


Figure 2. Percentage contribution of each building typology to total fuel consumption among commercial buildings in the Northeast.

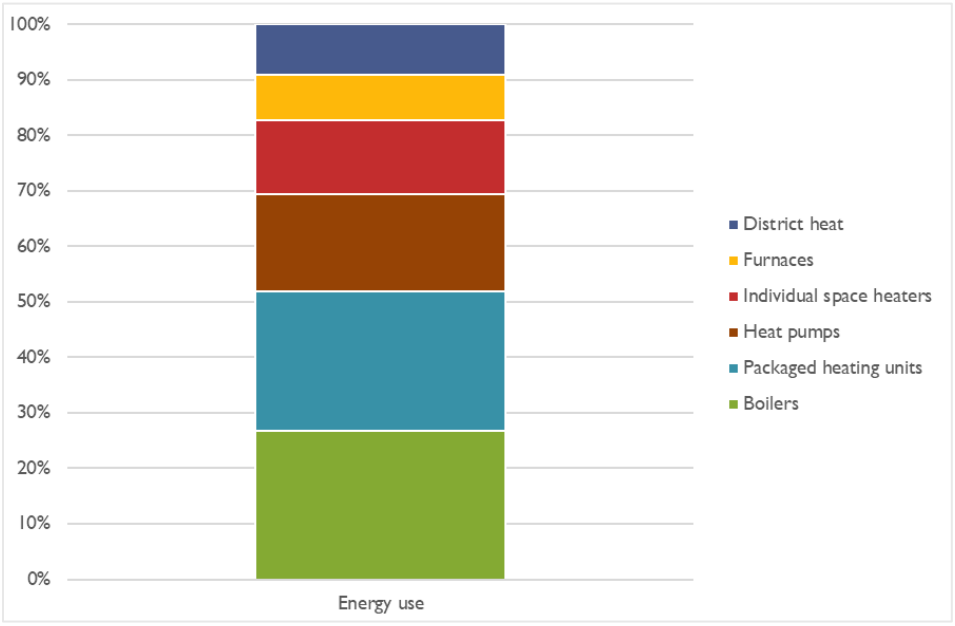


Figure 3. Percentage contribution of heating system type to total commercial energy consumption in the Northeast.

We used this assessment to determine the ComStock scenarios most relevant to NESCAUM and OTC states. In general, we chose scenarios that optimized reduction in fossil fuel consumption for heating without considering external factors such as cost or installation complexity, to assess the impact of “best practice” upgrades.

Table 3 describes the ComStock scenarios chosen and the reasoning behind them. Several of the ComStock scenarios model individual technology upgrades, while one scenario models a package of upgrades for multiple baseline technologies. We selected Package 5, described below, to represent a comprehensive suite of electrification upgrades across multiple technologies. Because some upgrades may apply to more than one type of baseline equipment (e.g., some gas RTUs could be updated to either HP RTUs or VRFs), individual upgrades cannot be directly combined outside of the packages provided by ComStock.

Table 3. ComStock Scenario Descriptions and Rationale

ComStock Scenario	Description	Rationale for Inclusion
Baseline	Model of actual commercial building stock as it existed in 2018.	The baseline scenario provides estimates of 2018 building stock energy use for comparison against electrification scenarios.
ASHP Boiler + Electric Backup ("HP Boiler")	Upgrades gas-fired boilers to ASHP boilers. The model assumes electric resistance boilers are used for backup when outdoor air temperature drops below a threshold. It applies to 33% of the building floor space included in the ComStock model.[55]	Boilers are the most prevalent type of heating equipment in the Northeast, according to CBECS. We selected the electric backup scenario (as opposed to gas backup) because we sought to model scenarios with zero onsite emissions.
Variable Speed HP RTU + Electric Backup + Energy Recovery ("HP RTU")	Upgrades RTUs that use gas furnaces or electric resistance to provide heat to high-efficiency variable speed HP RTUs with exhaust air heat and energy recovery.[56] This upgrade applies to 33% of building floor space in the ComStock model.	Packaged heating units are the second most prevalent type of commercial heating equipment in the Northeast. Electric backup and energy recovery represents the best-practice scenario to maximize emissions savings and energy efficiency.
VRF with Heat Recovery, a Dedicated Outdoor Air System (DOAS), and	Upgrades multizone variable air volume (VAV) systems or single-zone RTUs to a variable refrigerant flow (VRF) heat pump system. Assumptions include heat recovery, a DOAS for ventilation, and 25% upsizing for heating in cold climates	This upgrade includes energy efficiency and electrification upgrades applicable to nearly half of total ComStock building floor space. The upgrade without 25% upsizing assumes that VRF systems are sized to cooling load.

[55] Woldekidan, K., "End-Use Savings Shapes Measure Documentation: Boiler Replacement with Air-Source Heat Pump Boiler and Electric Boiler Backup," NLR, May 2024.

[56] CaraDonna, C., et al., "End-Use Savings Shapes Measure Documentation: Heat Pump Rooftop Units With Exhaust Air Energy Recovery," NLR, April 2024.

ComStock Scenario	Description	Rationale for Inclusion
25% Upsizing ("VRF")	(in warmer climates, VRF heat pumps are sized to cooling load). This upgrade is applicable to 49% of building floor space in the ComStock model.[57]	We selected the scenario with 25% upsizing, which allows VRF systems to be 25% larger than the design cooling load in heating-dominant areas, to account for the higher heating loads in many OTC states.
Package 5: HP RTU + HP Boiler + Demand Control Ventilation + Heat Recovery + Economizers ("Package 5")	Upgrades gas and electric RTUs to HP RTUs and existing boilers to ASHP boilers. The full suite of upgrades, including demand control ventilation, energy recovery, and economizers, is intended to create a desirable upgrade scenario that maximizes energy savings. The RTU and boiler upgrades apply to 62% of total floor area in the ComStock model.[58]	This scenario encompasses boilers and RTUs, the two most common commercial heating systems in the Northeast, and represents the best-case scenario for electrification and energy efficiency for those equipment types available in ComStock.

ComStock Limitations

While ComStock represents the most granular and robust model of commercial building stock publicly available, it has several key limitations. Importantly, ComStock data only accounts for 63% of total commercial building energy use because it excludes several building categories including colleges, universities, and many types of public buildings (Figure 4). Each upgrade applies to an even smaller portion of the 63% of buildings represented. For example, even Package 5, which includes multiple efficiency and electrification upgrades, only applies to 62% of the floor area within the 63% of total commercial building energy consumption represented in ComStock. Figure 4 from the ComStock Reference Documentation shows the commercial building types included in CBECS by energy consumption (nationwide) and a closer look at building categories excluded from ComStock.[59,60]

[57] Kim, J., et al., "End-Use Savings Shapes Measure Documentation: Variable Refrigerant Flow With 25% Upsizing Allowance for Heating," NLR, May 2024.

[58] Praprost, M., "End-Use Savings Shapes Upgrade Package Documentation: HP-RTU + ASHP Boiler + Demand Control Ventilation + Heat/Energy Recovery + Economizers," NLR, May 2024.

[59] NLR, "ComStock Reference Documentation: 2025 Release 3," pp. 10, November 2025.

[60] For context, commercial buildings in OTC states consume 1,174 TBtu per year. *See* U.S. EIA, "2018 CBECS Survey Data: Table C5. Consumption and Gross Energy Intensity by Census Region for Sum of Major Fuels," released December 21, 2022.

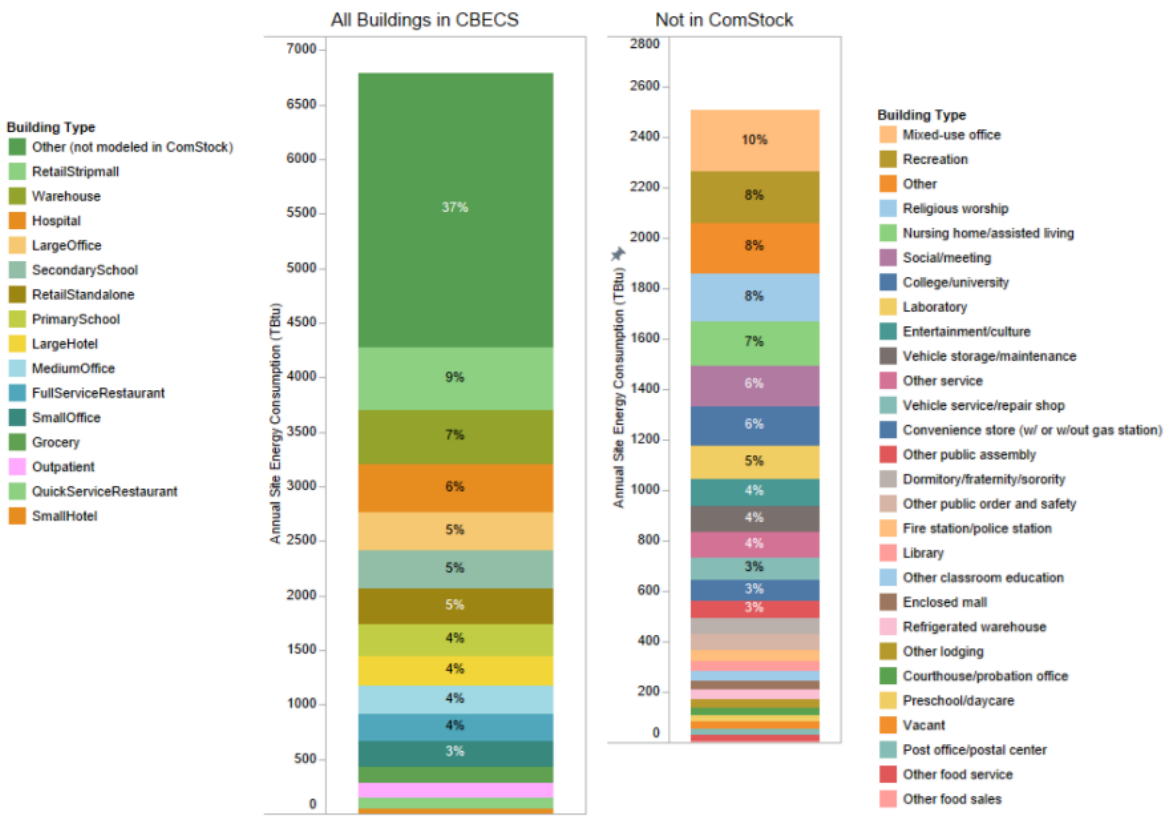


Figure 4. Commercial Energy Consumption Represented in ComStock

Given that educational institutions constitute the second-largest percentage of commercial building energy use in the Northeast, the exclusion of this sector means that our analysis likely underestimates the total emissions reduction potential from commercial building upgrades.[61] ComStock also does not include models for heat pump water heater upgrades,[62] limiting our analysis to space heating and cooling (we also excluded cooking from this analysis as it and water heating combined represent less than 10% of commercial building energy use).

Second, the model assumes that all upgrades are applied instantaneously to the 2018 U.S. commercial building stock. ComStock does not project changes in building stock or fuel use out to future years, so model outputs represent a theoretical snapshot – similar to NESCAUM's prior Residential Building Electrification Report. As such, electricity emissions estimates for the current (2026) and future (2044) grid cases do not fully align with the modeled 2018 building stock. Given that new construction only accounts for 1-2% of building stock annually[63] and there is no publicly accessible alternative dataset, we

[61] NLR, "ComStock Reference Documentation: 2025 Release 3," pp. 76, November 2025.

[62] Ibid.

[63] DiNola, R., "Future-Ready Buildings: Increase Asset Value and Reduce Real Estate Investment Risks by Preparing for Building Performance Standards Now," New Buildings Institute, April 18, 2022.

proceeded under the assumption that potential misalignment between data analysis years and building stock characteristics would be small. Relatedly, the instantaneous conversion assessed in this report does not represent a real-world scenario where retrofits happen over time, constrained by economic factors, equipment lifespans, grid and market readiness, and other variables. It is a simplified analysis intended to assess total emissions reduction potential, rather than a realistic emissions phase-down scenario or analysis of the impacts of any specific policy.

Methods Summary

We used the following steps to estimate the emissions and health impacts of commercial building electrification:

1) **Assess Changes in Commercial Building Energy Consumption:** Compile state-specific energy consumption outputs from the NLR ComStock tool[64] for baseline and upgrade scenarios.
2) **Collect and Calculate Emissions Factors for Fossil Fuel Combustion and Electricity Generation:** Compile fossil fuel combustion emissions factors for NO_x, $PM_{2.5}$, CO_2e, VOCs, and SO_2 from EPA's 2023 National Emissions Inventory Wagon Wheel Emission Factor Compendium.[65] Compile current (2026) and future (2044) electricity grid emissions factors for NO_x, CO_2e, and SO_2 from NLR's Standard Scenarios.[66] Estimate current and future electricity emissions factors for VOCs and $PM_{2.5}$ based on 2021 EPA eGRID emissions factors and power plant mixes.
3) **Estimate Total Emissions Changes for ComStock Scenarios:** Convert commercial building fossil fuel and electricity consumption into air emissions estimates for all baseline and upgrade ComStock scenarios. Combine modeled emissions savings from reducing onsite fossil fuel combustion with emissions increases from generating electricity for electrified heating to estimate net emissions changes associated with the electrification upgrade scenarios.
4) **Health Impacts Screening:** Use the U.S. EPA's Co-Benefits Risk Assessment Health Impacts Screening and Mapping (COBRA) tool[67] to estimate the potential health benefits associated with commercial building emissions reductions.
5) **Refrigerant Emissions:** Assess the impact of refrigerant leaks on CO_2e emissions for all scenarios based on existing literature on refrigerant leak rates and refrigerants expected to be in use in current (2026) and future (2044) years.

These steps are described in greater detail below.

[64] NESCAUM used the November 2025 ComStock release by state for this analysis.

[65] U.S. EPA, "2020 Air Emissions Data: Wagon Wheel Emission Factor Compendium," last updated June 2023.

[66] NLR, "Scenario Viewer: Standard Scenarios 2024," NLR/TP-6A40-92256, December 2024.

[67] U.S. EPA, "CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA)," accessed August 26, 2026.

Step 1: Assess Changes in Commercial Building Energy Consumption

We used ComStock Web Viewer to download and compile baseline (commercial building energy use in 2018) and upgrade (electrification scenario) energy use for each OTC state.[68] ComStock energy consumption outputs include district heat, electricity, gas, propane, and fuel oil, arranged by end use such as space heating, cooling, water heating, lighting, and equipment power. All outputs, including fossil fuel energy consumption, are reported in kilowatt hours (kWhs). We excluded district heating systems from this analysis, as they were minimally impacted (if at all) by the electrification upgrades.

We imported all data into an Excel spreadsheet for the baseline and upgrade scenarios for each OTC state. We then calculated the total difference in energy consumption between baseline and upgrade scenarios by summing energy consumption for each end use by fuel (in kWhs) and subtracting baseline energy consumption from upgrade energy consumption.

Step 2: Collect and Calculate Emissions Factors for Fossil Fuel Combustion and Electricity Generation

We then converted energy consumption data from the ComStock model into air emissions from onsite fossil fuel combustion and offsite electricity generation. While the ComStock model already includes some emissions estimates for electricity and fossil fuels, conducting our own calculations enabled us to utilize emissions factors that better supported air pollution impact analysis. For example, key limitations in the ComStock emissions factors include:

- Use of the 2022 release of the NLR Cambium dataset for CO_2e electricity emissions (rather than a more up-to-date model);
- No estimates for criteria air pollutant emissions from electricity generation;
- No VOC emissions estimates for any fuel; and
- Reporting of total particulate matter for gas and propane combustion but filterable particulate matter for fuel oil.[69]

Use of alternate emissions factors enabled our analysis to address these limitations and assess emissions of pollutants not already included in the ComStock datasets.

Fossil Fuel Emissions Factors

CO_2e

We calculated CO_2e emissions factors for onsite fossil fuel combustion using emissions factors for CO_2, N_2O (nitrous oxide), and CH_4 (methane) from the EPA AP-42 compilation of

[68] NLR, "ComStock Datasets," accessed March 16, 2026.
[69] NLR, "ComStock Reference Documentation: 2025 Release 3," pgs. 115-116, November 2025.

air emissions factors for natural gas,[70] propane,[71] and fuel oil.[72] To determine CO_2e for each fuel type, we converted CH_4 and N_2O emissions to CO_2 equivalencies using 100-year global warming potentials from EPA's Greenhouse Gas Equivalencies Calculator (28 for methane, 265 for N_2O)[73] and added them to the CO_2 emissions factors. We adopted a conservative approach where possible by selecting lower emissions factors for controlled gas burners as opposed to uncontrolled gas burners, and No. 2 fuel oil as opposed to higher-emitting fuel oil types.

Criteria Air Pollutants and VOCs

We used emissions factors from the 2023 NEI Wagon Wheel for NO_x, SO_2, $PM_{2.5}$, and VOCs.[74] We selected Wagon Wheel emissions factors from the Commercial/Institutional sector for natural gas, liquefied petroleum gas (as a proxy for propane), and distillate boilers (as a proxy for fuel oil).[75] In cases where the Wagon Wheel offered multiple options for emissions factors – i.e., a range and median – we chose the median value. We used the Wagon Wheel for criteria air pollutant emissions factors instead of the AP-42 compilation because the Wagon Wheel is significantly more up-to-date (last updated April 2026, compared to 1998 and 2010 for the AP-42 gas and fuel oil emissions factors, respectively). The Wagon Wheel does not provide estimates for CO_2e. Table 4 shows the fossil fuel emissions factors and sources used.

Table 4: Fossil Fuel Emissions Factors

Pollutant	Fuel Oil Combustion	Gas Combustion	Propane Combustion	Source
CO_2e	22,375 pounds (lbs)/1,000 gal	120,170 lbs/MMcf	12,744 lbs/1,000 gal	EPA's AP-42: Compilation of Air Emissions Factors
NO_x	20 lbs/1,000 gal	100 lbs/MMcf	14.23 lbs/1,000 gal	2023 NEI Wagon Wheel
SO_2	0.21 lbs/1,000 gal	0.6 lbs/MMcf	0.06 lbs/1,000 gal	2023 NEI Wagon Wheel
$PM_{2.5}$ (total)	2.13 lbs/1,000 gal	0.43 lbs/MMcf	0.04 lbs/1,000 gal	2023 NEI Wagon Wheel
VOCs	0.34 lbs/1,000 gal	5.5 lbs/MMcf	0.52 lbs/1,000 gal	2023 NEI Wagon Wheel

[70] U.S. EPA, "AP-42 1.4 Final Section – Supplement D: Natural Gas," July 1998, corrected April 2026.

[71] U.S. EPA, "AP-42 1.5 Final Section: Liquified Petroleum Gas," May 2025.

[72] U.S. EPA, "AP-42 1.3 Final Section – Supplement E: Fuel Oil," September 1999, corrected May 2010.

[73] U.S. EPA, "Greenhouse Gas Equivalencies Calculator," updated November 2024.

[74] U.S. EPA, "2023 Air Emissions Data: Wagon Wheel Emission Factor Compendium," last updated April 2026.

[75] The ComStock datasets only include gas-fired commercial boilers, so the Wagon Wheel distillate boiler emissions factors are applied to other oil-fired equipment in the ComStock models. The Wagon Wheel emissions factors for distillate boilers were the best available option, as other oil emissions factors were for distillate engines, which are not reflective of commercial heating equipment, and residual oil which is not commonly used. *See* U.S. EIA, "Table C6. Commercial sector energy consumption estimates, 2023," State Energy Data System (SEDS): 1960-2023, released June 27, 2025.

After compiling all fossil fuel emissions factors, we converted them from lbs/1,000 gallons and lbs/MMcf to lbs/kWh using conversion factors from the U.S. Energy Information Administration (EIA).[76]

Electricity Generation Emissions Factors

CO_2e, NO_x, and SO_2

To estimate the electricity emissions associated with commercial heat electrification, we downloaded state-by-state grid emissions factors for CO_2e, NO_x, and SO_2 from the 2024 NLR Standard Scenarios. The Standard Scenarios provide electricity generation, use, and emissions estimates, modeled under the assumption that utility asset expansion and operation occurs at the least possible cost within policy and reliability constraints.[77]

Emissions from electricity generation are expected to decline in the future, given that many OTC states have a goal to reach 100% clean energy within the next few decades (Table 5). To assess how emissions reductions from commercial heat electrification would change if the transition occurred today versus on a future decarbonized grid, we conducted separate analyses to assess electricity emissions in 2026 versus in 2044.

[76] U.S. EIA, "Units and Calculators Explained," accessed July 21, 2026.
[77] Gagnon, P., et al., "2024 Standard Scenarios Report: A U.S. Electricity Sector Outlook," NLR, 2024.

Table 5. OTC State Targets for Electricity Sector Decarbonization

State	Electricity Decarbonization Goal
CT	Eliminate GHG emissions from electricity by 2040[78]
DC	100% renewable electricity by 2032[79]
MA	Power sector GHG emissions 70% below 1990 levels in 2030,[80] 93% below 1990 levels in 2050[81]
MD	50% renewable electricity by 2030 and state planning to reach 100% clean power by 2040[82]
ME	80% renewable electricity by 2030, 100% renewable electricity by 2050[83]
NJ	50% renewable electricity by 2030,[84] 100% clean electricity by 2035[85]
NY	70% renewable electricity by 2030, 100% zero-emission electricity by 2040[86]
RI	100% renewable electricity by 2033[87]
PA	Goal articulated in PA climate plan for 100% renewable electricity by 2050[88]
VT	75% renewable electricity by 2032[89]
VA	100% zero carbon by 2050, net-zero carbon in electric sector by 2040[90]

The Standard Scenarios include a menu of electricity grid models based on different policies. For this analysis, we downloaded state-by-state data for the 2026 and 2044 cases under the "Mid-Case No Inflation Reduction Act (IRA)" scenario, which uses median values for future technology cost, fuel price, and electricity demand growth as model inputs. The Mid-Case No IRA scenario also assumes that the federal and state electricity sector policy landscape persists as it existed in August 2024, apart from IRA tax credits for the electric sector, which are excluded. As state and federal policy evolves and new load from data centers is added to the grid, the rate of electricity decarbonization may slow, impacting our estimates for the future 2044 case.

[78] State of Connecticut, "Senate Bill No. 10, Public Act No. 22-5: An Act Concerning Climate Change Mitigation," approved May 22, 2022.

[79] Council of the District of Columbia, "D.C. Law 22-257: Clean Energy DC Omnibus Amendment Act of 2018," effective March 22, 2019.

[80] Massachusetts Executive Office of Energy and Environmental Affairs, "Massachusetts Clean Energy and Climate Plan for 2025 and 2030," pp. 63, June 30, 2022.

[81] Massachusetts Executive Office of Energy and Environmental Affairs, "Clean Energy and Climate Plan for 2050," pp. 65, December 2022.

[82] Maryland General Assembly, "SB0516: Clean Energy Jobs Act of 2019," effective October 1, 2019.

[83] State of Maine, "S.P. 457 - L.D. 1494: An Act To Reform Maine's Renewable Portfolio Standard," approved June 26, 2019.

[84] New Jersey Legislature, "Bill A3723: Clean Energy Act," approved May 23, 2018.

[85] State of New Jersey, "New Jersey Energy Master Plan," 2024.

[86] New York State, "S6599/A8429: Climate Leadership and Community Protection Act," signed June 18, 2019.

[87] Rhode Island General Assembly, "S2274/H7277: Relating to Public Utilities and Carriers – Renewable Energy," signed June 29, 2022.

[88] Pennsylvania Department of Environmental Protection, "Pennsylvania Climate Action Plan 2021," pp. 85, September 2021.

[89] Vermont General Assembly, "30 V.S.A. § 8005: Renewable Energy Programs," accessed March 16, 2026.

[90] Virginia General Assembly, "SB 94: Virginia Energy Plan," signed April 11, 2020.

All emissions factors downloaded from the Standard Scenarios represent emissions from combustion for electricity generation only, and do not include pollution from precombustion activities like fuel processing and extraction (Table 6).

Table 6. CO_2e, NO_x, and SO_2 Electricity Grid Emissions Factors for the Current (2026) and Future (2044) Cases from the NLR Standard Scenarios, Mid-Case No IRA

State	CO_2e (lbs/MWh)		NO_x (lbs/MWh)		SO_2 (lbs/MWh)	
	Current (2026)	Future (2044)	Current (2026)	Future (2044)	Current (2026)	Future (2044)
DC	354	132	0.508	0.196	0.351	0.107
CT	506	340	0.237	0.114	0.077	0.025
DE	177	55.7	0.024	0.005	0.143	0.013
MA	390	199	0.457	0.047	0.283	0.038
MD	354	132	0.508	0.196	0.351	0.107
ME	140	121	0.179	0.063	0.388	0.083
NH	122	160	0.125	0.015	0.195	0.010
NJ	454	330	0.113	0.077	0.053	0.013
NY	303	0.00	0.267	0.003	0.089	0.011
PA	626	503	0.228	0.099	0.261	0.014
RI	396	121	0.215	0.066	0.379	0.023
VA	364	224	0.103	0.050	0.080	0.019
VT	27	0.00	0.140	0.000	0.110	0.002

$PM_{2.5}$ and VOCs

The NLR Standard Scenarios do not include emissions factors for $PM_{2.5}$ or VOCs. Instead, we estimated $PM_{2.5}$ and VOC electricity emissions factors by combining state-by-state[91] power plant emissions data from EPA's 2021 Emissions & Generation Resource Integrated Database (eGRID)[92] with current and future total electricity generation estimates for each state and fuel type from the NLR Standard Scenarios.

The 2021 eGRID dataset includes primary fuel utilized, amount of power produced, and $PM_{2.5}$ and VOC emissions generated by each power plant in every state. We aggregated that data to calculate total electricity generation by state in 2021 (in MWhs), as well as the total $PM_{2.5}$ and VOC emissions (in tons) produced by each fuel (biomass, coal, gas, oil, and clean energy).[93] We then calculated state-and-fuel-specific emissions factors (in lbs/MWh) by dividing each fuel's total VOC and $PM_{2.5}$ emissions (lbs) by the power it generated (MWhs) (Appendix A).

[91] Note: EPA's eGRID datasets include estimates for Washington, D.C., while the NLR Standard Scenarios do not. We used Maryland estimates from the Standard Scenarios for Washington's NOx, SO2, and CO_2e emissions factors. We used 2021 eGRID emissions factors for Washington's VOC and PM2.5 estimates, assuming the same emissions factors for 2026 and 2044.

[92] U.S. EPA, "eGRID PM2.5," last updated August 26, 2025.

[93] Clean energy in this context includes nuclear, geothermal, hydropower, solar, and wind.

The NLR Standard Scenarios provide state-specific estimates of total power plant energy output (in MWhs) for each fuel type in future years. We multiplied the state-and-fuel-specific emissions factors calculated from the 2021 eGRID data by their corresponding Standard Scenario power outputs for 2026 and 2044 to generate total $PM_{2.5}$ and VOC emissions for each fuel by state and year. We then aggregated emissions from all fuels in each state to generate state-specific estimates of total $PM_{2.5}$ and VOC emissions from electricity generation in 2026 and 2044. Lastly, we divided total $PM_{2.5}$ and VOC emissions by total estimated electricity generation for each year to generate state-specific $PM_{2.5}$ and VOC electricity emissions factors. These are listed in Table 7.

This method assumes that emissions factors by fuel and state remain static over time. This is unlikely to reflect reality if, for instance, new generator plants with lower emission rates are built, existing facilities apply pollution controls, or the mix of specific fuels within a primary fuel category (such as biomass) change. However, in the absence of plant-specific data for future years, this method provided the best approximation of 2026 and 2044 VOC and $PM_{2.5}$ emissions factors. An additional limitation is that the NLR Standard Scenarios do not include Washington, D.C., so we assumed that Washington's MWh output for each fuel category for 2026 and 2044 are the same as in 2021, resulting in the same VOC and $PM_{2.5}$ emissions factors for the current and future cases. Better information on Washington's electricity grid emissions would improve the analysis.

Table 7. $PM_{2.5}$ and VOC Electricity Grid Emissions Factors for Current (2026) and Future (2044) Cases, Calculated Using 2021 eGRID Data

State	$PM_{2.5}$ (lbs/MWh)		VOC (lbs/MWh)	
	Current (2026)	Future (2044)	Current (2026)	Future (2044)
DC	0.095	0.095	0.023	0.023
CT	0.026	0.015	0.007	0.005
DE	0.025	0.010	0.150	0.056
MA	0.203	0.032	0.234	0.041
MD	0.096	0.038	0.022	0.007
ME	0.026	0.004	0.023	0.002
NH	0.016	0.007	0.009	0.002
NJ	0.029	0.020	0.018	0.009
NY	0.048	0.001	0.030	0.004
PA	0.035	0.021	0.008	0.007
RI	0.094	0.010	0.023	0.003
VA	0.027	0.014	0.012	0.005
VT	0.016	0.000	0.010	0.001

Step 3: Estimate Total Emissions Changes for ComStock Scenarios

Emissions from Fossil Fuel Combustion

We next estimated state-specific changes in total emissions by fuel type for each upgrade scenario downloaded from ComStock. To estimate emissions changes from fossil fuel combustion pre- and post-upgrade, we converted the emissions factors in Table 4 to lbs/kWh, since all energy use outputs in ComStock are provided in kWh. We then multiplied each Comstock scenario's estimate of energy use per fuel (kWh) by each fuel's emissions factor (lbs/kWh) to generate state-by-state estimates of emissions from fossil fuel combustion (lbs) for each electrification upgrade. Finally, we calculated total change in emissions from each electrification upgrade scenario by subtracting total baseline fossil fuel emissions from total upgrade fossil fuel emissions.

Emissions from Electricity Consumption

To estimate changes in emissions from electricity use, we multiplied Comstock's estimates of electricity consumption for each upgrade (MWh) by the state-specific electricity emissions factors (lbs/MWh) shown in Tables 5 and 6. To assess only the impact of electrification (as opposed to the impact of a greening grid), we limited comparison of baseline and upgrade scenarios to the same year – i.e., we subtracted 2026 baseline electricity emissions from 2026 upgrade electricity emissions for the current case, and 2044 baseline from 2044 upgrade emissions for the future case. We generated two state-specific estimates of change in electricity emissions (in lbs) for each electrification upgrade, reflecting emissions impacts from instantaneous conversion in 2026 and in 2044.

Step 4: Screen for Health Benefits Associated with Emissions Reductions

To contextualize how these emissions reductions might impact human health, we conducted a health impacts screening using the U.S. EPA's COBRA tool (web version 5.2).[94] COBRA estimates how reducing criteria air pollutant emissions relative to emissions as they existed in 2023 might impact a variety of health outcomes including mortality, emergency room visits, asthma symptoms, and others.[95] Key caveats of COBRA include its intended use as a screening tool (rather than a sophisticated air emissions model) and its 2023 reference data, which is inconsistent with our 2026 ComStock analysis. However, it provides a valuable data point regarding the potential health benefits of commercial heating system upgrades.

[94] U.S. EPA, "CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA)," accessed August 26, 2026.

[95] U.S. EPA, "User's Manual for the Co-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA): Version 5.2," March 2025.

Step 5: Estimate the GHG Impacts of Refrigerant Emissions

We worked with Synapse Energy Economics to conduct a supplemental analysis of GHG emissions from refrigerant leakage associated with commercial building electrification. ComStock does not model the impacts of refrigerant leakage, but HVAC equipment used in commercial buildings relies on refrigerants that have high global warming potential (GWP) and create GHG emissions when leaked during equipment installation, operation, or at end of life. The purpose of this analysis was to assess how refrigerant leakage materially changes the GHG emissions benefits of commercial building electrification, and to evaluate how a transition to lower-GWP refrigerants could affect the results.

The analysis focuses exclusively on CO_2e emissions from refrigerant leakage, comparing GHG emissions for the baseline scenario and the four electrification upgrade scenarios under the current case (2026 grid and refrigerants expected to be used in new commercial heat pump equipment in 2026) and future case (2044 grid and a future transition to low- and ultra-low-GWP refrigerants). The baseline scenario includes existing commercial cooling equipment which already uses refrigerants. Therefore, the results are presented relative to the baseline scenario to reflect the incremental refrigerant-related emissions impacts of electrification.

This analysis is intended to provide an order-of-magnitude estimate of refrigerant-related GHG impacts from commercial building electrification. The results are sensitive to assumptions regarding system capacity, refrigerant charge rates, annual leak rates, end-of-life recovery, and future refrigerant market shares. Actual results will vary by building type, system design, installation quality, maintenance practices, and refrigerant recovery practices at equipment retirement.

The future case should also be interpreted as an illustrative scenario rather than a forecast. It assumes substantial adoption of low-GWP and ultra-low-GWP refrigerants by 2044, but the actual pace of the transition will depend on federal and state policies, manufacturer decisions, safety codes, equipment availability, and market acceptance.

Refrigerant Emission Calculations and Assumptions

We estimated total refrigerant charge by applying equipment refrigerant charge rates (see assumptions developed through a literature review and expert input below) to system capacity estimates from ComStock.[96] For each scenario, we estimated total combined heating and cooling system capacity (in tons). For scenarios involving HP boilers, we added HP boiler capacity to total cooling system capacity because ComStock assumes that HP boilers do not change existing cooling systems, although HP boiler systems can technically be configured to provide cooling.[97] For scenarios that did not involve HP boilers, we

[96] This analysis uses the ComStock 2025_3 dataset, released in November 2025. NLR, "ComStock Datasets," accessed March 16, 2026.

[97] Praprost, M., "End-Use Savings Shapes Upgrade Package Documentation: HP-RTU + ASHP Boiler + Demand Control Ventilation + Heat/Energy Recovery + Economizers," NLR, May 2024; Woldekidan, K.,

compared heating and cooling system capacities (in tons) and used the larger of the two to estimate total refrigerant charge, as other heat pump systems in the Comstock model provide both heating and cooling services, and therefore the same equipment capacity should not be counted separately for both services.[98]

Refrigerant mix differs by equipment type and case (Table 8). In the current case, HP RTUs and HP boilers are assumed to use a mix of R-410A, R-454B, and R-32, while VRF systems are assumed to rely primarily on R-410A and R-32. **Notably, we apply the same refrigerant mix to equipment in both the baseline scenario and upgrade scenarios.** This simplified assumption results in a conservative comparison of emissions between the electrification and baseline scenarios, because most existing heating and cooling systems currently use R-410A, which has the highest GWP in this analysis. In the future case, R-410A is assumed to be fully phased out of all commercial heat pump equipment, while natural refrigerants are assumed to account for 60% of HP RTU and HP Boiler refrigerants and 50% of VRF refrigerants.

Refrigerant charge rates also vary by refrigerant. R-410A systems are assumed to require 1.98 pounds of refrigerant per ton of capacity, R-454B systems 1.80 pounds per ton, and R-32 systems 1.66 pounds per ton.[99] For VRF systems, we assume higher charge rates due to longer refrigerant piping runs. Existing VRF systems using R-410A are assumed to require approximately 60% more refrigerant charge than conventional systems. For newer A2L VRF systems, we assume that hydronic piping and other design changes reduce this additional charge requirement by roughly half, resulting in an assumed 30% increase relative to conventional systems.

"End-Use Savings Shapes Measure Documentation: Boiler Replacement with Air-Source Heat Pump Boiler and Electric Boiler Backup," NLR, May 2024.

[98] Water-to-air heat pumps, a type of water-source heat pump, are not included in the system capacity estimates used in this refrigerant analysis. However, the estimated capacity of WAHPs is the same across the Baseline and all electrification scenarios and therefore is not expected to materially affect the estimated incremental refrigerant impacts relative to the baseline. WAHPs also represent a relatively small share of total heat pump capacity; for example, they account for approximately 5 percent of total heat pump capacity in the New York HP Boiler scenario.

[99] These refrigerant charge-rate assumptions were developed based on Rattenbury, J. M., "Enhanced Refrigerant Management and LEED-NC V4 EA Credit 6," 2020; and Hoover, et al., "Refrigerants: Taking the Chill Out of Heat Pumps," ACEEE Summer Study on Energy Efficiency in Buildings, 2024.

Table 8. Commercial Refrigerant Case Assumptions: Charge Rates and Refrigerant Share

Case	Refrigerant type	GWP	HP RTU	VRF	HP Boiler	Charge rate (lbs/ton)	VRF charge rate (lbs/ton)*
Current (2026)	R-410A	2,088	40%	50%	20%	1.98	2.57
	R-454B	466	50%	10%	40%	1.80	2.34
	R-32	675	10%	40%	40%	1.66	2.16
	Natural refrigerants	2	-	-	-	1.66	2.16
Future (2044)	R-410A	2,088	-	-	-	1.98	2.57
	R-454B	466	40%	50%	40%	1.80	2.34
	R-32	675	-	-	-	1.66	2.16
	Natural refrigerants	2	60%	50%	60%	1.66	2.16

Note: Natural refrigerants include propane, CO_2 and isobutane.
** Based on our literature review (see Figure 6 below), existing VRF systems using R-410A require approximately 60% more refrigerant charge than conventional systems. We assume that many new VRF systems using A2L refrigerants will incorporate hydronic piping within buildings, reducing the increase in refrigerant charge by roughly half on average (resulting in an overall increase of approximately 30%).*

Because our refrigerant charge estimates are based on total combined system capacity, we also examined how that capacity is determined under each scenario. Under the baseline, HP RTU, and VRF scenarios, aggregate cooling capacity exceeds aggregate heating capacity and therefore sets the total system capacity used to estimate refrigerant charge (Figure 5). In the VRF scenario, while cooling capacity still exceeds heating capacity, the electrification upgrade increases total cooling capacity above the baseline level. Under the HP Boiler and Package 5 scenarios, total system capacity is instead based on the sum of HP boiler capacity and the capacity of all cooling systems, because ComStock assumes that HP boilers do not replace or alter existing cooling systems.

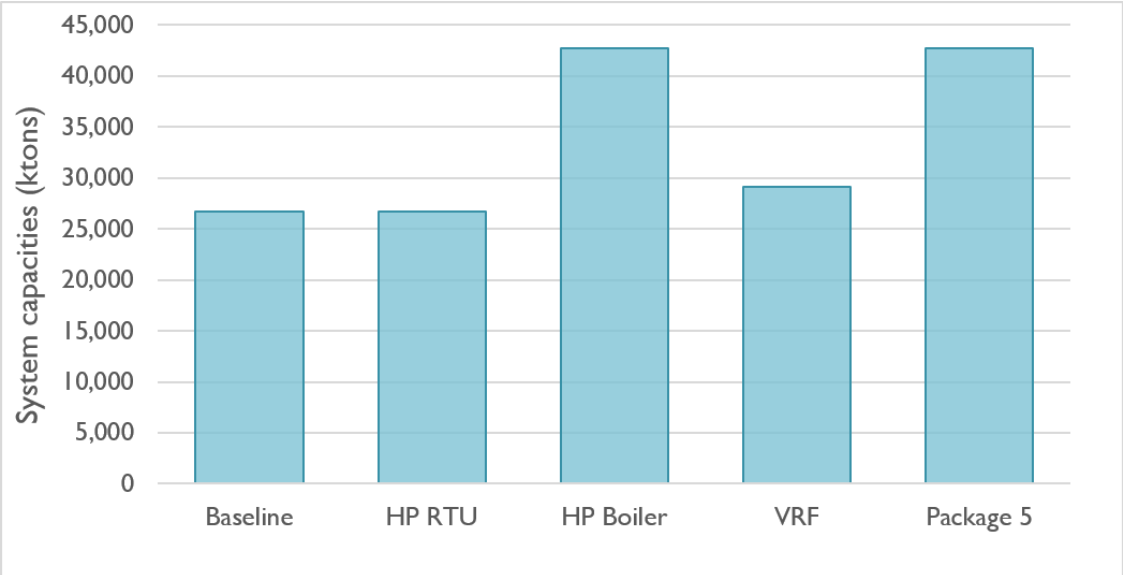


Figure 5. Total System Capacity Used to Estimate Refrigerant Charge by Scenario, OTC Region

Our analysis used a high-level approach to assess whether heating or cooling system is larger, aggregated at the state level for the baseline, HP RTU, and VRF scenarios. This provided a reasonable approximation of the total HVAC system capacity relevant to estimating refrigerant leakage. While an analysis at the individual building level could produce somewhat different results, the high prevalence of cooling systems in commercial buildings and our comparisons for selected scenarios indicate that the aggregate-level approach provides a reasonable estimate of overall refrigerant leakage.

One additional limitation is that our cooling capacity estimates excluded chillers, which are commonly used in large commercial buildings. Chillers were excluded because their system configurations and refrigerant types vary considerably, and a detailed assessment of chiller refrigerants was outside the scope of this analysis. This exclusion is expected to have only a small effect on the results because, among the scenarios analyzed, only the VRF scenario replaces some existing chiller capacity, and of that capacity, only a small share is replaced in the ComStock model. For example, in New York, approximately 8% of chiller capacity is replaced by VRF systems. As a result, the analysis slightly overestimates incremental refrigerant emissions in the VRF scenario because baseline chiller refrigerants are excluded, while refrigerants associated with the VRF systems that replace those chillers are included.

To calculate the total lifetime impact of refrigerant leakage over the equipment's lifespan, we developed refrigerant leak rate assumptions based on a literature review (Figure 6), market research, and expert feedback. We examined peer-reviewed literature, EPA's vintaging model and inventory, and the California Air Resources Board (CARB)'s refrigerant emissions savings tool to develop commercial HVAC refrigerant leak assumptions.[100]

The analysis assumes that refrigerants can leak at three points in the equipment lifecycle: installation, operation (annualized in this analysis), and end-of-life. Studies of refrigerant leak impacts in commercial HVAC equipment indicate that leak rates at installation are generally small (0.2% to 1%) and annual (operational) leak rates range from 2% to 9% of total refrigerant charge (Figure 6, left). End-of-life leak rates for commercial HVAC equipment range from 20% to as high as 56% (Figure 6, right).

[100] A detailed discussion of this review is provided in: Synapse Energy Economics, "Refrigerant Emissions Impacts of Residential Building Electrification in the Northeast and Mid-Atlantic: Quantifying Leakage, Emissions Impacts, and the Role of Refrigerant Transitions," September 2026.

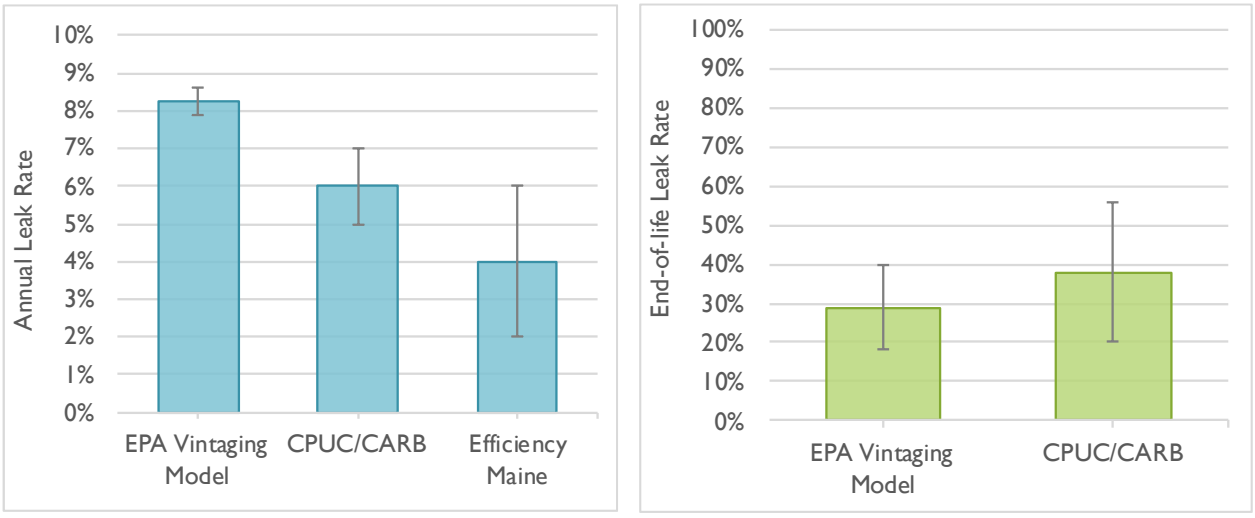


Figure 6. Commercial Leak Rates Reported in Selected Studies[101]

Table 9 presents our assumptions regarding refrigerant leakage by equipment type. We assume different leak rates by system type because of differences in system design, installation practices, and operating conditions. We developed these assumptions primarily based on our literature review, market research, and expert feedback. As outlined in Table 9, we assume a 0.5% installation leak rate for all commercial heat pump equipment across the current and future cases.[102] Annual leak rates are assumed to be 6% for HP RTUs, VRF systems, and HP boilers, which is approximately the average leak rate across the studies we reviewed (Figure 6). All equipment types are assumed to have a 15-year system life.

The current case assumes 50% end-of-life leak rates for synthetic refrigerants, and does not include natural refrigerants in baseline or upgrade equipment.[103] The future case assumes the same installation and annual leak rates as the current case, with lower end-of-life leak rates at 40% for synthetic refrigerants and 20% for natural refrigerants. The lower assumed end-of-life leak rate for synthetic refrigerants reflects anticipated improvements in refrigerant recovery, recycling, and end-of-life management practices over time. An even lower leak rate is assumed for natural refrigerants to reflect handling restrictions intended to reduce the likelihood of venting due to flammability.

[101] Sources: US EPA, "Annexes to the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2017," 2018; California Public Utilities Commission, "Refrigerant Avoided Cost Calculator," 2022; California Air Resources Board, "Public Hearing to Consider the Proposed Amendments to the Prohibitions on Use of Certain Hydrofluorocarbons in Stationary Refrigeration, Chillers, Aerosols-Propellants, and Foam End-Uses Regulation," Table 24, October 20, 2020; Efficiency Maine Trust, "Refrigerant Leakage Assessment," 2022.

[102] US EPA, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022 - ANNEX 3 Methodological Descriptions for Additional Source or Sink Categories," Table A-113, 2024.

[103] This assumption reflects the results of our literature review as well as industry expert input.

Table 9. Commercial Heating System Refrigerant Leak Rate Assumptions

Case	Equipment Type	Installation Leak Rate (%)	Annual Leak Rate (%)	End-of-Life Leak Rate (%) *Synthetic Refrigerants*	End-of-Life Leak Rate (%) *Natural Refrigerants*	System Life (Years)
Current	HP RTU	0.5%	6%	50%	N/A	15
	VRF	0.5%	6%	50%	N/A	15
	HP Boiler	0.5%	6%	50%	N/A	15
Future	HP RTU	0.5%	6%	40%	20%	15
	VRF	0.5%	6%	40%	20%	15
	HP Boiler	0.5%	6%	40%	20%	15

We combined these estimates of refrigerant charge rates, refrigerant mix, and leakage rates to estimate the refrigerant leakage, associated GHG emissions, and changes in GHG emissions savings, for each scenario.

4. Results

This section presents estimated energy and emissions impacts for the four commercial electrification scenarios evaluated: 1) HP Boiler with Electric Backup, 2) Variable Speed HP RTU with Electric Backup and Energy Recovery, 3) VRF with Heat Recovery, a DOAS, and 25% Upsizing, and 4) Package 5 – HP RTU and HP Boilers with Demand Control Ventilation, Heat Recovery, and Economizers. It then presents results from the COBRA health impacts screening and from Synapse Energy Economics' refrigerant GHG emissions analysis.

Baseline Energy Consumption

Table 10 shows energy consumption for the baseline scenario, reflecting Comstock's model of energy consumed by all commercial building end uses (including lighting, cooking, and other end uses in addition to space conditioning) based on the 2018 building stock, converted to megawatt-hours to allow for comparison. It does not include any energy efficiency or electrification upgrades.

Electricity provides the most energy used by commercial buildings at over 190 million MWhs across the OTC states. Gas consumption, primarily for space heating, comprises nearly 100 million MWhs of OTC commercial building energy use, followed by oil at nearly 14 million MWhs, and propane at 3 million MWhs. New York's commercial buildings consume the most energy across the board, for all fuels. Virginia is second-highest for electricity and gas, Massachusetts is second-highest for oil, and Pennsylvania is second-highest for propane.

Table 10. Baseline Commercial Building Energy Consumption (MWh) by Fuel

State	Electricity	Gas	Oil	Propane	Total Energy
CT	6,289,606	3,315,144	1,490,004	151,848	11,246,602
DC	6,157,575	1,760,348	12,601	9,740	7,940,264
DE	1,133,164	410,319	46,470	26,793	1,616,746
MA	15,164,550	8,336,511	2,126,478	316,170	25,943,709
MD	15,954,531	6,089,881	516,758	123,495	22,684,665
ME	2,659,000	846,130	1,548,836	231,767	5,285,732
NH	2,287,020	928,828	823,884	316,498	4,356,231
NJ	15,645,969	11,399,925	407,771	71,415	27,525,081
NY	49,984,612	33,994,114	3,580,906	774,803	88,334,436
PA	34,516,783	20,019,880	1,880,175	437,635	56,854,473
RI	1,273,863	937,395	238,589	34,679	2,484,527
VA	39,196,681	11,576,291	673,403	211,807	51,658,181
VT	659,560	336,450	371,189	71,150	1,438,349
Total OTC	**190,922,915**	**99,951,215**	**13,717,066**	**2,777,800**	**307,368,996**

Changes in Energy Consumption

All heating electrification upgrade scenarios reduced total commercial building energy consumption across OTC states, with collective energy savings ranging from 26-74 million MWhs, or 8-24% of annual energy use represented in the ComStock model (Tables 11 and 12). Energy savings are the same across current and future cases, as the differences in grid and refrigerant composition only affect emissions, not energy use. As expected due to its combination of upgrades, Package 5 yielded the deepest total energy savings at a 24% reduction in commercial building energy use across OTC states, as well as the greatest fuel savings for gas and propane (64% and 68%, respectively). The VRF upgrade yielded the second-greatest total energy savings (16%) and exceeded Package 5 for fuel oil reductions, decreasing commercial building oil consumption by over 8 million MWhs, or 61%.[104] State-specific results are provided in Appendix B.

It is important to note that these reductions in energy consumption are applied across the commercial building stock modeled in ComStock, and not all buildings are eligible for each upgrade. Upgrades applied to individual commercial buildings would likely yield greater percent reductions in energy use because they would affect most, if not all, of a building's floor space. In contrast, Comstock's full building stock model for even Package 5, with its mix of electrification and efficiency upgrades, only applies to 62% of commercial floor area in ComStock, dampening the overall energy reductions available.

[104] Note: Total percent energy savings appear lower than fuel-specific savings (e.g., 16% energy savings compared to 60% oil use reduction) because total energy includes non-heating end-uses such as refrigeration and interior equipment that are unaffected by the upgrade measures.

We observed significant differences in delivered fuel impacts between the HP RTU and VRF upgrades – the HP RTU upgrade had a 30% greater impact on propane compared to fuel oil, while the VRF upgrade had a 20% greater impact on fuel oil compared to propane. This difference is likely driven by equipment configuration. Commercial RTUs are typically designed to combust gas, making propane the more natural choice for buildings without access to the gas system.[105] In contrast, the VAV systems being replaced by VRF may be connected to central boilers that run on oil, resulting in greater oil displacement.[106]

Table 11. Annual Reductions in Energy Consumption (MWh) for All Scenarios, OTC States

Scenario	Gas	Fuel Oil	Propane	Electricity	Total Energy
HP Boiler	38,816,687	-	-	(12,969,159)	**25,847,528**
Heat Pump RTU	24,406,832	5,014,335	1,850,452	9,121,389	**40,393,008**
VRF with 25% Upsizing	31,607,651	8,361,188	1,135,024	8,611,721	**49,715,584**
Package 5	63,842,461	6,597,095	1,881,313	1,835,361	**74,156,230**

Table 12. Percent Annual Reduction in Energy Consumption for All Scenarios, OTC States

Scenario	Gas	Fuel Oil	Propane	Electricity	Total Energy
HP Boiler	39%	-	-	(7%)	**8%**
Heat Pump RTU	24%	37%	67%	5%	**10%**
VRF with 25% Upsizing	32%	61%	41%	5%	**16%**
Package 5	64%	48%	68%	1%	**24%**

Despite transitioning some fossil fuel-based heat to electricity, all upgrades except the HP Boiler scenario reduced aggregate commercial electricity consumption across the OTC states by 2-9 million MWhs (1-5%). For the HP RTU upgrade, electricity savings were primarily due to higher-efficiency fans and cooling, and from transitioning inefficient electric resistance RTUs to high-efficiency heat pumps (Table 13).[107] Electricity savings from the VRF scenario were driven by higher-efficiency fans and cooling, with additional savings from efficient pumps and reduced electric resistance heating (Table 13).[108] The HP Boiler and Package 5 scenarios had similar increases in electricity use for heating, but

[105] SkillCat, "Packaged Rooftop Units: Everything You Need to Know is Here – Part 2," April 8, 2025.

[106] U.S. DOE, "Guidance Document on Space Heating Electrification for Large Commercial Buildings with Boilers," April 2024.

[107] CaraDonna, C., "End-Use Savings Shapes Measure Documentation: Heat Pump Rooftop Units With Exhaust Air Energy Recovery," NLR, April 2024.

[108] Note that the ComStock documentation combines all electric heating into a single figure for percent change and does not distinguish electric resistance savings separately – the documentation is unclear on whether transitioning electric resistance heating to heat pumps produces greater energy savings than fan or pump efficiency, even if total electricity use for heating increases with the electrification of fossil fuel equipment; Kim, J., et al., "End-Use Savings Shapes Measure Documentation: Variable Refrigerant Flow With 25% Upsizing Allowance for Heating," NLR, May 2024.

Package 5's heating increases were offset by savings from higher-efficiency cooling and fans not realized in the HP Boiler scenario.

Table 13. Annual Reductions in Energy Consumption (MWh) by Energy Use, OTC States

	Energy Use	HP Boiler	HP RTU	VRF	Package 5
Electricity	**Cooling**	4,204	4,132,766	5,474,104	6,622,758
	Heating	(12,829,083)	(4,352,074)	(8,025,781)	(12,629,192)
	Fans	19,872	10,148,586	11,689,034	10,244,467
	Heat Recovery	(346)	(806,540)	(1,076,560)	(2,266,689)
	Heat Rejection	31,439	0	47,647	76,511
	Pumps	(195,230)	0	488,225	(216,150)
	Other Electricity	(14)	(1,348)	15,053	3,656
	Total Electricity	**(12,969,159)**	**9,121,389**	**8,611,721**	**1,835,361**
Fuels	**Fuel Oil**	0	5,014,335	8,361,188	6,597,095
	Gas	38,816,687	24,406,832	31,607,651	63,842,461
	Propane	0	1,850,452	1,135,024	1,881,313
Total Energy Savings		**25,847,528**	**25,847,528**	**40,393,008**	**49,715,584**

Changes in Emissions

This section details key results and trends regarding estimated emissions impacts from the electrification scenarios. We focus on highlights for the current (2026) case, given that it is more temporally relevant, but include comparisons to the future (2044) case results and all data in the tables.

Baseline Emissions

Table 14 shows total baseline emissions from commercial building energy use, aggregated across OTC states. The current and future cases exclusively reflect changes in electricity grid emissions, showing emissions from the 2018 baseline building stock under a 2026 electricity grid, and under a 2044 electricity grid. Because electricity consumption is the largest share of commercial building energy consumption, greening the grid would significantly reduce the associated emissions. SO_2, $PM_{2.5}$, and VOC reductions are particularly significant, ranging from 58-83% reductions when comparing the current case to the future case. Greening the grid results in only moderate emissions reductions for CO_2e and NO_x (approximately 30% and 40% reductions, respectively), highlighting the need to address fuel consumption in commercial buildings through electrification upgrades in tandem with electricity decarbonization.

State-by-state baseline emissions are shown in Appendix C.

Table 14. Baseline Emissions (Metric Tons) Under Current and Future Cases, OTC States

Pollutant	Current Case	Future Case	Percent Change from Current to Future Case
CO_2e	56,649,376	40,243,634	(29%)
NO_x	40,365	24,460	(39%)
SO_2	14,705	2,554	(83%)
$PM_{2.5}$	5,249	1,963	(63%)
VOC	4,044	1,704	(58%)

OTC Region Emissions Impacts by Electrification Scenario

As previously noted, ComStock data accounts for 63% of commercial energy use and excludes several notable building categories including colleges and many public buildings. For the commercial buildings modeled in ComStock, all electrification upgrades had strong effects on reducing GHG emissions for all OTC states, by up to a 52% reduction for Package 5 under the current case (Vermont), and up to 63% under the future case (New York). NO_x emissions reductions were also significant and generally tracked with or exceeded the relative GHG savings. Collectively, OTC states could reduce 8-24% of GHG emissions and 11-29% of NO_x emissions from commercial buildings through the modeled electrification upgrades. All states except Massachusetts and Delaware also experienced reductions in VOC emissions across all scenarios.

SO_2 emissions were least affected by the electrification upgrades, with many states experiencing emissions increases – particularly in the HP Boiler scenario (see more below). This is likely due to most commercial building SO_2 emissions deriving from electricity generation (see Table 14), and these effects were diminished or reversed under the future grid. $PM_{2.5}$ benefits were slightly stronger for the OTC region compared to SO_2, although they still increased under the current case HP Boiler scenario.

Table 15 shows region-wide annual emissions reductions and Table 16 shows annual percent reductions associated with each upgrade under the current and future cases. All upgrades reduced annual NO_x, CO_2e, and VOC emissions under both cases. All upgrades except the HP Boiler scenario also yielded $PM_{2.5}$ and SO_2 reductions.

Table 15. Net Annual Emissions Reductions (Metric Tons) by Commercial Building Upgrade Scenario and Pollutant, OTC States, Current (2026) and Future (2044) Cases

Pollutant	HP RTU		HP Boiler		VRF		Package 5	
	Current	Future	Current	Future	Current	Future	Current	Future
NO_x	6,161	5,541	4,312	5,449	7,739	7,214	11,557	11,613
$PM_{2.5}$	345	219	(313)	(69)	411	310	213	235
CO_2e	7,787,000	7,087,180	4,538,415	5,715,104	9,644,906	9,009,725	13,868,963	13,851,056
SO_2	733	159	(900)	(97)	702	188	244	136
VOC	354	272	82	263	392	335	539	570

Table 16. Percent Reduction in Annual Emissions from Commercial Buildings by Upgrade Scenario and Pollutant, OTC States, Current (2026) and Future (2044) Cases

Pollutant	HP RTU		HP Boiler		VRF		Package 5	
	Current	Future	Current	Future	Current	Future	Current	Future
NO_x	15%	23%	11%	22%	19%	29%	29%	47%
$PM_{2.5}$	7%	11%	(6%)	(4%)	8%	16%	4%	12%
CO_2e	14%	18%	8%	14%	17%	22%	24%	34%
SO_2	5%	6%	(6%)	(4%)	5%	7%	2%	5%
VOC	9%	16%	2%	15%	10%	20%	13%	33%

The increases in $PM_{2.5}$ and SO_2 emissions in the HP Boiler scenario are because it is the only upgrade scenario that increases electricity use. This effect may be exaggerated due to ComStock's modeling, which only includes commercial buildings with gas boilers (not propane or fuel oil) in the HP Boiler scenario.

Note that Table 15 tracks emissions **reductions** (i.e., delta from the baseline), not **total** emissions overall, so while the clean, 2044 grid may result in a smaller absolute **reduction** for some upgrade scenarios, zero-emission electricity in 2044 would generate fewer **total** emissions compared to 2026 for all upgrade scenarios (see Table 14 for baseline emissions).[109] Table 16, which reports percent emissions reductions, shows stronger proportional emissions benefits for all upgrades under the future case, since there are fewer baseline emissions under a clean grid (i.e., the denominator is smaller).

HP RTU Upgrade

In the HP RTU scenario, gas furnace and electric resistance RTUs are upgraded to variable speed HP RTUs with energy recovery. If implemented in 2026, the HP RTU upgrade would reduce regional annual NO_x emissions by over 6,000 tons and CO_2e emissions by nearly 8 million tons (15% and 14%, respectively). The HP RTU upgrade also yields small reductions in $PM_{2.5}$, SO_2, and VOC emissions.

HP Boiler Upgrade

In the HP Boiler scenario, gas boilers are upgraded to HP boilers. If implemented in 2026, this scenario would reduce annual NO_x emissions by 4,312 tons, and CO_2e emissions by 4.5 million tons (11% and 8% reductions, respectively). As discussed above, the HP Boiler

[109] Because we assessed emissions changes rather than total emissions, emissions benefits for the HP RTU and VRF upgrades were smaller under the future case than the current case. Under a fossil-heavy grid, each kWh of electricity produced generates more air pollution; therefore, each kWh saved eliminates more air emissions than it would under a clean grid. Because the HP RTU and VRF upgrades reduced electricity use, the emissions impacts for these upgrades were stronger under the 2026 grid.

In contrast, emissions benefits for the HP Boiler and Package 5 upgrades were stronger under the future grid, because those upgrades either increased or only slightly decreased electricity consumption. Under these scenarios, a cleaner grid enhanced the emissions benefits of transitioning away from onsite fossil fuel combustion, since each kWh increase in electricity use produced less SO2 and PM2.5 pollution than it would under the 2026 grid.

scenario as modeled could increase $PM_{2.5}$ and SO_2 emissions slightly. HP Boiler emissions benefits are amplified (and disbenefits reduced) under a cleaner 2044 grid.

VRF Upgrade

The VRF scenario is the second-highest performing upgrade, upgrading multizone VAV systems and single-zone RTUs to VRF systems. If implemented in 2026, the VRF upgrade would reduce NO_x emissions by nearly 8,000 tons (or 19%) per year, and CO_2e emissions by over 9.6 million tons (17%) per year. It would also yield $PM_{2.5}$ and SO_2 emissions benefits comparable to the HP RTU scenario.

Package 5 Upgrade

Package 5 generates the greatest emissions benefits, upgrading buildings to either a HP RTU or HP boiler with additional energy efficiency enhancements. Package 5 would save 11,557 tons (29%) of NO_x and nearly 14 million tons (24%) of CO_2e per year if implemented in 2026. It would yield similar absolute emissions reductions but greater relative emissions reductions in 2044.

State-Level Emissions Impacts by Electrification Scenario

This section shows the state-level emissions impacts of each upgrade by pollutant. For brevity, this section only includes tables showing absolute emissions reductions; percent changes are presented in Appendix D.

Greenhouse Gas Emissions

All upgrades resulted in annual GHG savings (in CO_2e) for all states under current and future cases. New York and Pennsylvania yielded the greatest absolute emissions reductions compared to other OTC states, saving over 4.2 and 2.6 million tons of CO_2e emissions through Package 5, respectively (Table 17). New Hampshire and Vermont experienced the greatest relative benefits from the HP RTU, VRF, and Package 5 upgrades (CO_2e savings of 47% to 52%), while New York, New Jersey, and Vermont experienced the greatest benefits from the HP Boiler upgrade (13%, 11%, and 11% savings) (Table D1). Refrigerant impacts on CO_2e emissions are presented in later sections.

Table 17. Annual Reductions in CO_2e Emissions (Metric Tons) from Commercial Heating Upgrades

State	Current Case				Future Case			
	HP RTU	HP Boiler	VRF	Package 5	HP RTU	HP Boiler	VRF	Package 5
CT	407,433	140,383	514,332	626,364	388,511	177,562	508,429	631,664
DC	55,484	88,148	82,844	177,079	38,320	109,337	52,909	161,128
DE	45,137	15,586	40,724	65,746	39,207	17,540	34,560	59,779
MA	775,608	412,100	980,981	1,320,297	733,995	518,830	956,740	1,347,677
MD	533,989	256,569	687,051	894,751	419,481	322,903	536,295	801,635
ME	225,047	23,004	261,209	291,406	225,438	23,519	262,492	292,308
NH	214,115	36,368	234,589	265,943	215,034	34,952	233,804	266,222
NJ	740,212	568,619	952,549	1,451,653	696,519	667,123	923,829	1,475,563
NY	2,109,792	1,764,579	2,622,610	4,230,180	1,967,533	2,367,680	2,591,732	4,485,035
PA	1,572,014	693,846	1,763,017	2,605,921	1,462,353	843,590	1,679,071	2,595,613
RI	108,376	37,228	121,001	155,520	102,157	50,947	124,328	158,292
VA	936,050	483,310	1,297,760	1,691,633	734,649	561,948	1,018,586	1,483,145
VT	63,743	18,676	86,239	92,471	63,982	19,173	86,950	92,997
Total OTC	**7,787,000**	**4,538,415**	**9,644,906**	**13,868,963**	**7,087,180**	**5,715,104**	**9,009,725**	**13,851,056**

NO_x Emissions

Similar to GHG emissions reductions, New York and Pennsylvania yield the greatest absolute NO_x emissions savings across all upgrade scenarios, displacing over 3,500 and 2,100 tons of NO_x respectively through Package 5 under the current case (Table 18). In relative terms, New Hampshire and Delaware had the highest NO_x savings for the HP RTU upgrade compared to other states (38% and 37%, respectively), New Jersey had the greatest NO_x savings for the HP Boiler upgrade (26%), New Hampshire and Vermont benefited most from the VRF upgrade (40% and 39%, respectively), and Delaware had the greatest emissions reduction for Package 5 (56%) (Table D2).

Table 18. Annual Reductions in NO_x Emissions (Metric Tons) from Commercial Heating Upgrades

State	Current Case				Future Case			
	HP RTU	HP Boiler	VRF	Package 5	HP RTU	HP Boiler	VRF	Package 5
CT	335	158	444	546	321	186	439	550
DC	63	53	98	163	39	83	56	140
DE	33	15	29	50	32	15	28	49
MA	705	269	867	1,113	616	498	815	1,172
MD	563	150	725	844	402	243	513	713
ME	206	18	232	262	208	21	240	267
NH	199	29	214	243	196	33	216	242
NJ	527	683	737	1,264	515	712	729	1,271
NY	1,808	1,439	2,229	3,561	1,684	1,965	2,202	3,783
PA	1,071	934	1,290	2,172	957	1,090	1,203	2,162
RI	91	37	106	134	88	44	108	136
VA	503	514	694	1,124	426	544	588	1,045
VT	57	13	74	80	58	16	78	83
Total OTC	**6,161**	**4,312**	**7,739**	**11,557**	**5,541**	**5,449**	**7,214**	**11,613**

SO_2 Emissions

Most states saw SO_2 emissions reductions for most upgrades except the HP Boiler scenario (Table 19). Pennsylvania, Maryland, and Virginia experienced the greatest absolute SO_2 savings through non-boiler upgrades – up to 239 tons per year for Pennsylvania's HP RTU upgrade. Delaware, Maryland, and Virginia experienced the greatest relative SO_2 emissions savings at up to 11% for a 2026 VRF upgrade in Virginia (Table D3). SO_2 benefits may be greater for these Mid-Atlantic states because they have higher cooling and smaller heating loads compared to other OTC states. As such, they experience the largest percent decreases in electricity use under non-boiler upgrades (sometimes double the regionwide average) and smaller increases in electricity use under the HP Boiler upgrade (3-4% compared to the regionwide 7%, Appendix B) – minimizing conversions from low-SO_2 gas equipment to higher-SO_2 electricity.

Maine, Rhode Island, and Vermont experienced increases in SO_2 emissions across most or all upgrades under the current case. These SO_2 increases were driven by high percent increases in electricity use post-electrification; Vermont and Maine, for example, experienced 9% and 5% increases in electricity consumption for VRF, compared to decreases in electricity consumption for many of the other states (Appendix B). Maine and Rhode Island's increases in SO_2 emissions were also driven by their grids having the highest SO_2 emissions of all OTC states (0.388 and 0.379 lbs/MWh respectively, compared to an OTC average of 0.182 lbs/MWh for 2026).[110]

[110] NLR, "Scenario Viewer: Standard Scenarios 2024," NLR/TP-6A40-92256, December 2024.

Table 19. Annual Reductions in SO_2 Emissions (Metric Tons) from Commercial Heating Upgrades

State	Current Case				Future Case			
	HP RTU	HP Boiler	VRF	Package 5	HP RTU	HP Boiler	VRF	Package 5
CT	11	(16)	6	2	5	(4)	5	3
DC	27	(33)	47	26	8	(10)	15	8
DE	7	(2)	7	7	1	0	1	1
MA	66	(155)	42	(32)	13	(18)	11	3
MD	183	(103)	241	151	57	(30)	75	49
ME	(6)	(10)	(23)	(15)	0	(2)	(3)	(1)
NH	6	(7)	(2)	3	2	0	2	2
NJ	22	(38)	17	(2)	8	(5)	7	5
NY	53	(165)	24	(51)	16	(10)	16	15
PA	239	(311)	186	35	18	(9)	17	15
RI	9	(19)	(4)	(3)	1	(1)	1	1
VA	116	(41)	161	124	30	(7)	41	35
VT	(1)	(2)	(2)	(2)	0	0	1	1
Total OTC	**733**	**(900)**	**702**	**244**	**159**	**(97)**	**188**	**136**

$PM_{2.5}$ Emissions

$PM_{2.5}$ savings were greatest for the HP RTU and VRF upgrades, with Massachusetts experiencing the largest absolute $PM_{2.5}$ decreases under the current and future cases (71 and 34 tons, respectively), followed by Maryland and New York (Table 20). Unlike with SO_2, where Mid-Atlantic states experienced the strongest relative savings for non-boiler upgrades, New England states including New Hampshire, Maine, and Vermont yielded the highest relative $PM_{2.5}$ savings for non-boiler upgrades across both grids. New Hampshire showed the highest relative savings under the current case (over 30% $PM_{2.5}$ emissions reductions across all three non-boiler scenarios), and Vermont experienced the highest relative savings for VRF and Package 5 under the future case (61% and 49% savings, respectively) (Table D4). All states in the OTC region are in attainment for the $PM_{2.5}$ NAAQS, and absolute emissions reductions are small, with a lower emissions reduction potential compared to pollutants like CO_2e and NO_x.

Table 20. Annual Changes in $PM_{2.5}$ Emissions (Metric Tons) from Commercial Heating Upgrades

State	Current Case				Future Case			
	HP RTU	HP Boiler	VRF	Package 5	HP RTU	HP Boiler	VRF	Package 5
CT	19	(5)	27	20	18	(2)	27	20
DC	8	(9)	13	8	8	(9)	13	8
DE	2	0	2	2	1	0	1	1
MA	71	(111)	63	4	34	(15)	42	29
MD	53	(27)	70	47	23	(10)	30	23
ME	15	(1)	20	19	16	0	21	20
NH	12	0	14	13	12	0	14	13
NJ	15	(19)	16	4	12	(13)	14	6
NY	53	(86)	65	10	31	6	60	49
PA	46	(37)	54	30	34	(20)	45	29
RI	6	(4)	3	3	4	0	4	4
VA	43	(13)	60	50	24	(5)	33	31
VT	3	0	5	4	4	0	6	4
Total OTC	**345**	**(313)**	**411**	**213**	**219**	**(69)**	**310**	**235**

VOC Emissions

Every state except Massachusetts and Delaware experienced VOC savings across all upgrade scenarios and grid cases (Table 21). New York and Pennsylvania showed the greatest absolute reductions in VOC emissions for Package 5 (168 and 111 annual tons under the current case). Connecticut and Pennsylvania experienced the highest relative VOC savings from the HP Boiler and Package 5 upgrades (42% and 36% for the Package 5 current case, respectively), and New Hampshire experienced the greatest relative VOC benefit from the HP RTU upgrade (27%) (Table D5).

Massachusetts and Delaware were the only states to experience VOC emissions increases under any of the upgrades. In particular, the Massachusetts HP Boiler upgrade increased electricity demand, and caused a 6% increase, or 101 tons of additional VOC emissions, compared to the second-highest increase in Delaware of 2% and 2 tons. Both states' VOC emissions increases may have been driven by the relatively high proportions of biomass on their 2026 electric grids (15% and 13% respectively, compared to under 8% for most other states) combined with particularly high-VOC biomass mixes. Electricity VOC emissions factors for Massachusetts and Delaware were 0.234 lbs/MWh and 0.150 lbs/MWh respectively, compared to 0.030 lbs/MWh or below for every other state (Table 7).[111]

[111] NESCAUM analysis and estimates of EPA eGRID emissions factors and NLR Standard Scenarios power plant generation.

Table 21. Annual Reductions in VOC Emissions (Metric Tons) from Commercial Heating Upgrades

State	Current Case				Future Case			
	HP RTU	HP Boiler	VRF	Package 5	HP RTU	HP Boiler	VRF	Package 5
CT	12	10	15	23	11	10	15	23
DC	3	3	5	9	3	3	5	9
DE	9	(2)	9	10	4	0	4	5
MA	74	(101)	61	20	32	6	36	47
MD	26	10	34	42	19	14	24	36
ME	5	1	4	6	5	1	5	7
NH	6	2	6	8	6	2	6	8
NJ	32	29	41	66	29	35	39	67
NY	96	48	105	168	84	100	102	190
PA	50	56	58	111	48	58	57	111
RI	4	1	4	6	3	2	4	6
VA	36	25	49	69	25	29	35	58
VT	2	1	2	3	2	1	2	3
Total OTC	**354**	**82**	**392**	**539**	**272**	**263**	**335**	**570**

Health Impacts Screening

We conducted a supplemental analysis to screen for the health benefits potential associated with these commercial building electrification upgrades. We used the U.S. EPA's COBRA tool (web version 5.2), which models the health impact of reducing emissions of criteria air pollutants $PM_{2.5}$, SO_2, NO_x, and VOCs.[112] Table 22 summarizes avoided health harms across OTC states under each upgrade scenario and their associated costs (see state-specific health impacts in Appendix E). We only modeled emissions benefits for the current case to maintain as much consistency as possible with COBRA's 2023 reference data.

Importantly, while most COBRA health effects and their economic values occur in the year of analysis (i.e., they assume that emissions reductions occurred in 2023), avoided mortality and its associated economic values span twenty years. Nonfatal heart attacks are assumed to occur in the year of analysis, but also accrue economic benefits over several years.[113] Table 22 is limited to OTC state impacts, and does not include health benefits that would be experienced by neighboring states from emissions reductions in the OTC region.

[112] U.S. EPA, "CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA)," accessed August 26, 2026.
[113] Ibid.

Table 22. Estimated Health Benefits Associated with Commercial Heating Upgrades (Current Grid), Aggregate Across OTC States

Health Benefit	HP RTU	HP Boiler	VRF	Package 5
$ Health Benefits (Low)*	$751,996,000	$296,607,000	$927,879,000	$1,229,707,000
$ Health Benefits (High)*	$1,122,581,000	$306,089,000	$1,375,658,000	$1,728,191,000
Mortality (Low)	47	18	58	76
Mortality (High)	73	18	89	111
Asthma Symptoms	37,425	19,051	46,480	64,579
Asthma Onset	232	124	288	405
Incidence, Hay Fever/Rhinitis	1,499	803	1,865	2,618
ER Visits, Respiratory	86	48	107	152
Hospital Admits, Respiratory	5	2	7	9
Nonfatal Heart Attacks	15	0	19	21
Work Loss Days	3,159	81	3,819	4,250
Hospital Admits, Alzheimer's Disease	14	(2)	17	17
Hospital Admits, Parkinsons Disease	2	0	2	2

*Dollar amounts are in $2023 using a 2% discount rate for future economic benefit. High and low ranges for health benefits are based on high and low estimates of avoided premature mortality using different assumptions of air pollution sensitivity.

This model indicates that implementing any of these upgrades could yield meaningful health benefits across the OTC region, from 18 (HP Boiler upgrade) to 111 (Package 5) avoided premature deaths over 20 years. In the first year of implementation, tens of thousands of asthma symptoms could be avoided, as well as up to 152 emergency room visits. The long-term economic value of these benefits ranges from nearly $300 million (HP Boiler, low estimate) to $1.7 billion (Package 5, high estimate) regionwide.

Refrigerant Leakage and Associated GHG Emissions

The supplemental refrigerant analysis conducted by Synapse Energy Economics shows that refrigerant leakage volumes change only modestly across the upgrade scenarios, and that refrigerant GHG emissions are highly sensitive to refrigerant GWP. This distinction is important because the volume of refrigerant leakage is not the primary determinant of climate impact. Rather, climate impact depends on the amount of refrigerant leaked *and* its GWP. Figure 7 presents total refrigerant leakage and associated GHG emissions by scenario, and Figure 8 shows the incremental differences in refrigerant leakage and associated GHG emissions between each electrification scenario and the baseline.

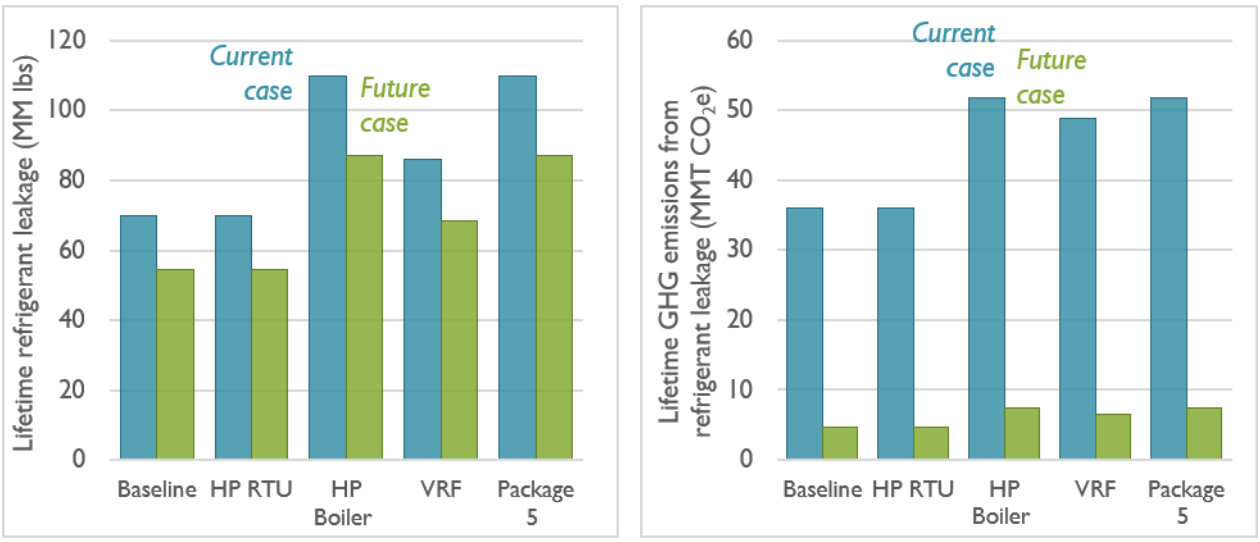


Figure 7. Aggregate Lifetime Refrigerant Leakage (Left) and Associated GHG Emissions (Right), by Scenario, OTC Region

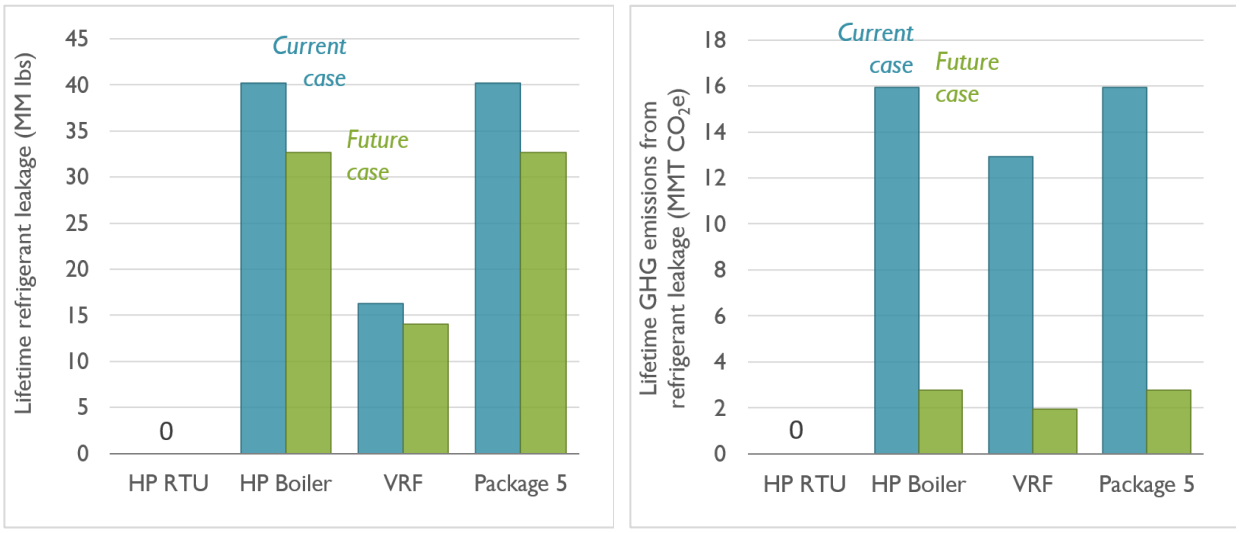


Figure 8. Lifetime Refrigerant Leakage (Left) and Associated GHG Emissions (Right) Relative to the Baseline by Electrification Scenario, OTC Region

Region-wide, refrigerant leakage and associated GHG emissions are essentially unchanged relative to the baseline under the HP RTU scenario (Figures 7 and 8). In this scenario, aggregate cooling capacity remains greater than heating capacity, and total system capacity is therefore approximately the same as in the baseline.

In contrast, the HP Boiler and Package 5 scenarios result in substantially higher refrigerant leakage because HP boiler capacity is added to the total capacity of cooling systems, including existing and new cooling systems. As shown in Figure 8, both scenarios result in approximately 40 million pounds of additional lifetime refrigerant leakage relative to the baseline in the current case and approximately 33 million pounds in the future case,

equivalent to increases of approximately 58% and 60%, respectively. Associated GHG emissions increase by approximately 44% in the current case and 60% in the future case, corresponding to about 16 million metric tons CO_2e and 3 million metric tons CO_2e, respectively. The much smaller absolute GHG impact in the future case reflects the transition to lower-GWP refrigerants.

The VRF scenario also increases refrigerant leakage and associated GHG emissions relative to the baseline, although the increases are smaller than those in the HP Boiler and Package 5 scenarios (Figures 7 and 8). In the current case, VRF refrigerant leakage is approximately 23% greater than in the baseline, resulting in approximately 36% higher associated GHG emissions. In the future case, refrigerant leakage is approximately 26% greater than the baseline, with approximately 42% greater associated GHG emissions. These increases reflect the higher modeled refrigerant charge of VRF systems, which can require longer refrigerant piping runs and larger total refrigerant charges than conventional heat pump systems.

Across all scenarios, OTC region-wide refrigerant-related GHG emissions are substantially lower in the future case than in the current case. Percentage increases in refrigerant leakage relative to the baseline are generally similar between the current and future cases, although absolute leakage is lower in the future case. Total refrigerant leakage declines by approximately 20-22% in the future case, largely because of the transition to lower-GWP refrigerants with lower assumed end-of-life leakage rates. GHG emissions from refrigerant leakage decline much more sharply — by approximately 85-87% — because the future case assumes a transition away from high-GWP refrigerants such as R-410A toward low- and ultra-low-GWP refrigerants.

Figure 9 compares lifetime GHG emissions from OTC-region commercial buildings across all scenarios in the current case, including emissions from fossil fuel combustion in building heating systems, grid-related emissions from electricity use, and refrigerant emissions. Refrigerant emissions represent a relatively small share of total lifetime emissions across all scenarios, while building combustion and grid emissions remain the primary component of overall emissions from commercial buildings. In the current case, refrigerant emissions account for approximately 4% of total lifetime GHG emissions in the baseline, 5% in the HP RTU scenario, and 6% in the HP Boiler and VRF scenarios, and 7% in the Package 5 scenario.

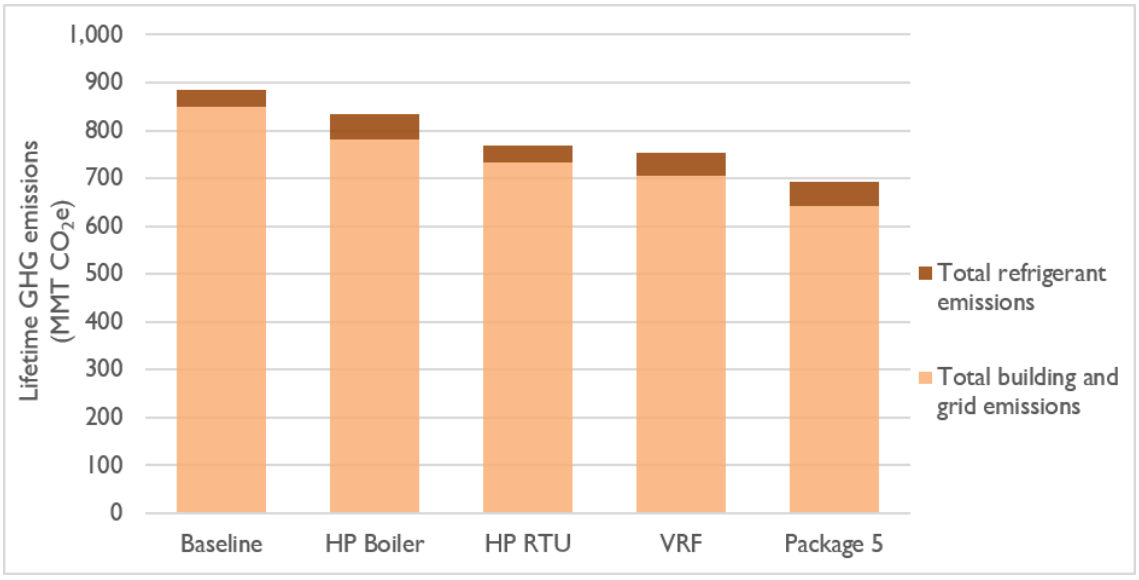


Figure 9. Lifetime (15-Year) GHG Emissions - Current Case, OTC Region

In the future case, lifetime GHG emissions are lower across all scenarios, reflecting lower grid- and refrigerant-related emissions (Figure 10). Package 5 continues to achieve the lowest lifetime emissions, followed by the VRF and HP RTU scenarios. Refrigerant emissions account for only a small share of total emissions in the future case — generally about 1-2% of lifetime GHG emissions, depending on the scenario — with building combustion- and grid-related emissions accounting for the vast majority of GHG emissions. More specifically, refrigerants account for 0.8% of lifetime GHG emissions in the baseline scenario, 0.9% in the HP RTU scenario, 1.4% in the HP Boiler and VRF scenarios, and 1.8% in the Package 5 scenario.

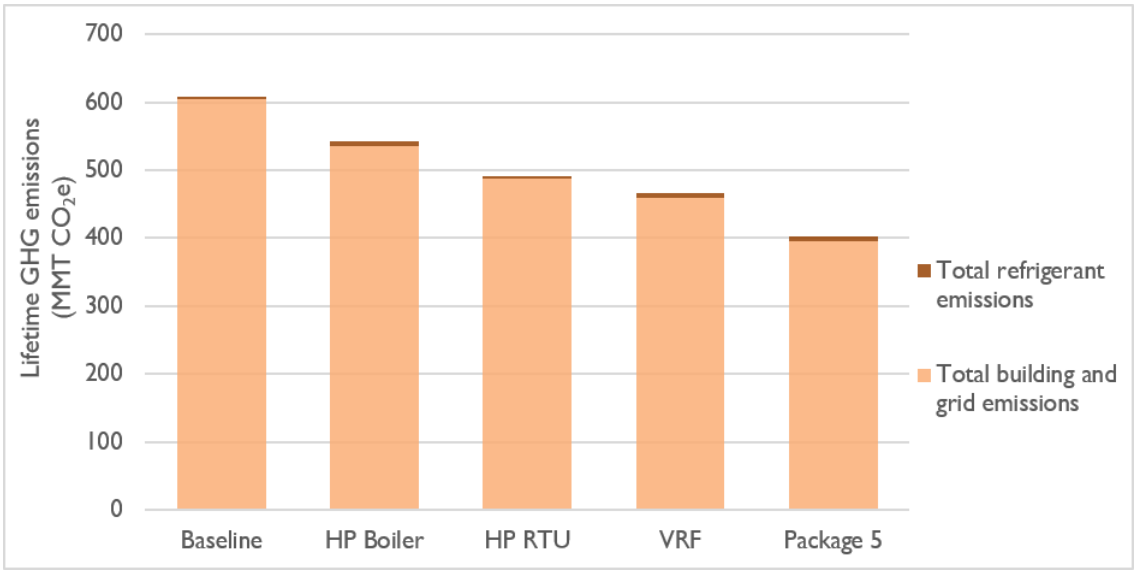


Figure 10. Lifetime (15-Year) GHG Emissions - Future Case, OTC Region

Refrigerant Effects on GHG Emissions Savings

The following results illustrate the net GHG savings from building electrification after accounting for the incremental GHG emissions associated with refrigerant leakage relative to the baseline. Our analysis indicates that the largest refrigerant-related impacts occur in the HP Boiler and Package 5 scenarios, reflecting their higher total refrigerant charge relative to the baseline. The VRF scenario also increases refrigerant emissions, though to a lesser extent, while incremental refrigerant impacts in the HP RTU scenario are essentially zero relative to the baseline. Overall, refrigerant emissions remain a relatively small component of total GHG emissions, but they reduce the net GHG savings achieved through building electrification to varying degrees across scenarios.

HP RTU Refrigerant Results

As discussed in the previous section, our analysis indicates that in the HP RTU scenario, there is essentially no change in refrigerant-related GHG emissions relative to the baseline scenario. Consequently, refrigerant leakage does not affect GHG savings in this scenario.

HP Boiler Refrigerant Results

Figure 11 shows how refrigerant leakage affects lifetime GHG savings under the HP Boiler scenario, aggregated across the OTC region. Because the HP Boiler scenario has substantially higher refrigerant leakage relative to the baseline, GHG emissions associated with refrigerant leakage reduce GHG savings from the scenario by approximately 23.4% in the current case and 3.2% in the future case. The much smaller impact in the future case reflects the transition to low- and ultra-low-GWP refrigerants, which substantially reduces refrigerant-related GHG emissions.

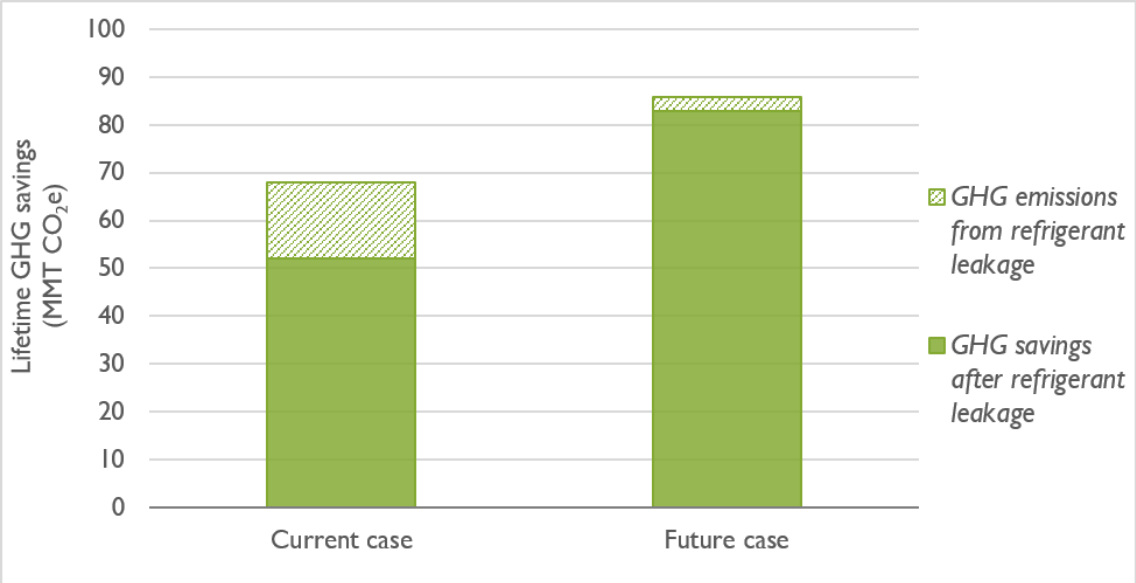


Figure 11. Change in Lifetime (15-Year) GHG Savings Under the HP Boiler scenario, OTC region

State-level GHG savings impacts for the HP Boiler scenario before and after accounting for refrigerant leakage are presented in Appendix F. In the current case, reductions in GHG savings due to refrigerant leakage range from 10.6% in Vermont to 30.5% in Pennsylvania, with an OTC region-wide reduction of 23.4% (Table F1). In the future case, reductions in GHG savings are much smaller, ranging from 1.8% in Vermont to 4.4% in Pennsylvania, with an OTC region-wide reduction of 3.2% (Table F2).

VRF Refrigerant Results

Figure 12 shows how refrigerant leakage affects lifetime GHG savings under the VRF scenario, aggregated across the OTC region. Because the VRF scenario has higher refrigerant leakage relative to the baseline scenario, GHG emissions associated with refrigerant leakage reduce GHG savings from the scenario by approximately 8.9% in the current case and 1.4% in the future case. The smaller impact in the future case reflects the transition to low- and ultra-low-GWP refrigerants (e.g., CO_2 and propane), which substantially reduces refrigerant-related GHG emissions.

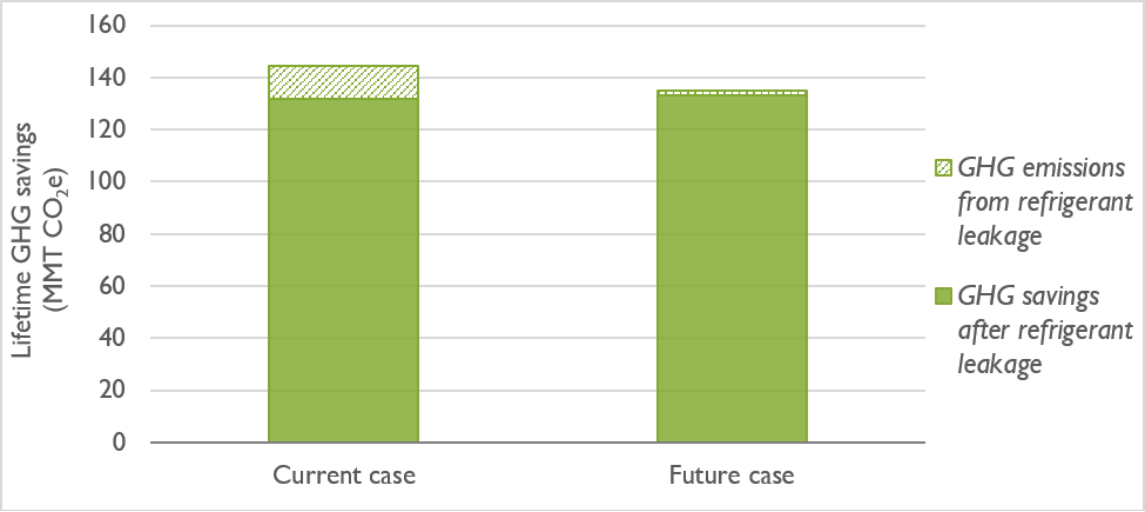


Figure 12. Change in Lifetime (15-Year) GHG Savings Under the VRF scenario, OTC region

State-level GHG savings impacts for the VRF scenario before and after accounting for refrigerant leakage are presented in Appendix F. In the current case, reductions in GHG savings due to refrigerant leakage range from 5.4% in Vermont to 13.6% in Washington D.C., with an OTC region-wide reduction of 8.9% (Table F3). In the future case, reductions in GHG savings are smaller, ranging from 0.8% in Maine and Vermont to 3.2% in Washington D.C., with an OTC region-wide reduction of 1.4% (Table F4).

Package 5 Refrigerant Results

Figure 13 shows how refrigerant leakage affects lifetime GHG savings under the Package 5 scenario, aggregated across the OTC region. GHG emissions associated with refrigerant leakage reduce GHG savings from Package 5 by approximately 7.7% in the current case and 1.3% in the future case. The much smaller impact in the future case reflects the

transition to low- and ultra-low-GWP refrigerants, which substantially reduces refrigerant-related GHG emissions.

Compared with the HP Boiler scenario, the percentage reduction in GHG savings is smaller under Package 5 even though both scenarios have relatively large incremental refrigerant emissions. Package 5 combines the effects of the HP RTU and HP Boiler measures and therefore achieves substantially greater overall GHG savings before accounting for refrigerant leakage. As a result, refrigerant emissions represent a smaller share of total GHG savings under Package 5 than under the HP Boiler scenario.

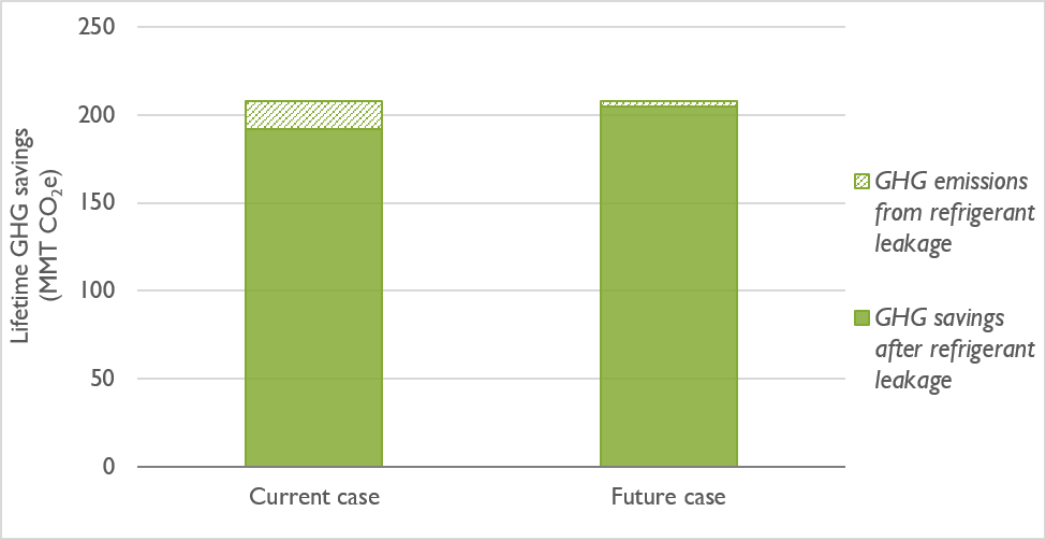


Figure 13. Change in Lifetime (15-Year) GHG Savings Under the Package 5 scenario, OTC region

State-level GHG savings impacts for Package 5 before and after accounting for refrigerant leakage are presented in Appendix F. In the current case, reductions in GHG savings due to refrigerant leakage range from 0.9% in Maine to 15.1% in Washington, D.C., with an OTC region-wide reduction of 7.7% (Table F5). In the future case, reductions are substantially smaller, ranging from 0.2% in Maine to 2.9% in Washington, D.C., with an OTC region-wide reduction of 1.3% (Table F6).

5. Discussion

Summary of Findings

This analysis assessed the emissions reduction potential that could be achieved through different commercial heating upgrade scenarios provided by NLR's ComStock tool. Assuming current (2026) electricity grid emissions, electrification upgrades have the potential to reduce total NO_x emissions from commercial buildings across OTC states by 11-29% and GHG emissions by 8-24%, depending on the electrification upgrade. Most states would also experience reductions in SO_2, $PM_{2.5}$, and VOC emissions with all

upgrades except the HP Boiler scenario. That scenario results in increased electricity demand and would increase collective SO_2 and $PM_{2.5}$ emissions by 6%.

All upgrades result in GHG savings, collectively reducing GHG emissions from commercial buildings by 4.5 million (HP Boiler) to 13.9 million (Package 5) tons annually across OTC states under the current grid. The collective GHG emissions reductions that could be realized in the Package 5 scenario are equivalent to removing over 3.2 million gas-powered vehicles – more than all the gas-powered cars registered in Delaware, Maine, and New Hampshire combined – from OTC state roads for a year.[114,115] All upgrades also deliver meaningful health benefits, including avoided premature mortality, asthma incidents, and emergency room visits, as assessed by EPA's COBRA tool.

Electricity grid cases were based on the policy landscape as it existed in 2024, assuming no IRA implementation. The policy and regulatory landscape continues to evolve, with federal regulations and programs beyond the IRA being rolled back, and some states looking to alter their climate targets.[116] As such, the grid may decarbonize at a slower pace than modeled in the NLR Standard Scenarios, which would affect the future case emissions estimates.

States also face different situations regarding existing electrical infrastructure, with varying space on their grids for additional load, and distinct costs associated with upgrading electrical infrastructure to accommodate electrified commercial buildings. Each state's ability to electrify commercial buildings depends on these and other factors, creating variable decarbonization timelines in contrast with the blanket assumption of instantaneous conversion overnight for all states in this analysis. However, it is important to note that nearly all the electrification scenarios modeled in this report resulted in lower electricity consumption due to the high efficiency of heat pumps compared to inefficient baseline central air conditioning and electric resistance heating.

Comparison with Residential Building Electrification Report

While electrifying commercial buildings has meaningful emissions impacts – particularly on GHGs and NO_x – the total reductions associated with electrifying commercial buildings were significantly lower than those associated with electrifying residential buildings estimated in our prior Residential Building Electrification Report (Table 23). This result was unexpected, given that residential and commercial buildings represent similar percentages of total OTC region emissions in the National Emissions Inventory, at 13% and 12%, respectively.

[114] U.S. EPA, "Greenhouse Gas Equivalencies Calculator," accessed February 25, 2026.
[115] U.S. DOE, "Vehicle Registration Counts by State – 2024," accessed February 25, 2026.
[116] DiGangi, D., "New York Needs More Time to Meet Climate Goals, Gov. Hochul Says," Utility Dive, March 12, 2026.

Table 23. OTC Region Emissions Reductions (Tons) from Residential and Commercial Building Electrification (Current Grid Results)

Pollutant	Residential Electrification			Commercial Electrification			
	Water Heating	Space Heating	Whole-Home	Heat Pump RTU	Heat Pump Boiler	VRF	Package 5
NO_x	9,761	86,717	106,027	6,161	4,312	7,739	11,557
$PM_{2.5}$	212	2,678	3,262	345	(313)	411	213
CO_2e	12.4M	109M	132M	7.8M	4.5M	9.6M	13.9M
SO_2	342	(3,858)	(2,928)	733	(900)	702	244
VOC	504	3,123	4,124	354	82	392	539

We propose several explanations for this discrepancy:

- **Incomplete Commercial Building Inventory:** When comparing total baseline energy consumption between the ComStock and ResStock models, total commercial energy consumption in ComStock represents only a small fraction (33%, in aggregate for OTC states) of total residential energy consumption in ResStock. Part of this difference may be due, as noted in Section 3, to ComStock's exclusion of 37% of commercial buildings included in the national Commercial Building Energy Consumption Survey (CBECS). This exclusion encompasses education buildings, which represent the second-highest category of energy consumption for commercial buildings in the Northeast.
- **Lack of Water Heating Upgrade Scenarios:** The Residential Electrification Report estimates emissions benefits from upgrading to zero-emission water heating because the ResStock tool includes upgrades to heat pump water heaters and whole-home electrification. Emissions estimates in this Commercial Electrification Report exclude water heating because ComStock does not include water heating in any upgrade scenarios.[117] The baseline ComStock scenario shows that water heating comprises less than 9% of total commercial building energy use in all OTC states.
- **Less Energy Use for Heating and Cooling:** Analysis of the baseline scenarios in ResStock and ComStock shows that commercial buildings in the ComStock model apply a lower percentage of total energy consumption toward space heating and cooling (55%-68% for OTC states) than residential buildings in the ResStock model (64%-74% for OTC states). The remainder of commercial building energy consumption is for water heating, as noted above, as well as other end uses such as lighting and ventilation, which were not included in the analysis.
- **Lower Penetration of Upgrade Technologies:** Documentation for the ResStock version used in the Residential Electrification analysis does not detail the percentage of residential floor space each upgrade applies to.[118] However, the heat pump and whole-home electrification upgrades apply to all homes with or without ducts that heat with electric resistance, gas, oil, or propane. Based on RECS data,

[117] NLR, "ComStock Reference Documentation: 2025 Release 3," pp. 76, November 2025.
[118] NLR, "End-Use Savings Shapes: Residential Round 1," 2022.

this would represent over 90% of U.S. homes.[119] In contrast, Package 5 – which has the highest applicability of the upgrade scenarios we assessed in ComStock – only accounts for 62% of modeled commercial floorspace. Following Package 5, the VRF upgrade accounts for 49% of commercial floorspace, and the remaining upgrades represent 33% each (see details in Section 3). The diversity of commercial building functions and heating equipment types means that any single upgrade applies to less of the total commercial building stock than a parallel scenario might in the residential model.

These differences highlight the complexity of electrifying commercial buildings and the need for diverse heating solutions and improved modeling to understand the full emissions reduction potential of commercial building decarbonization.

Refrigerant Leakage and Emissions Key Findings

The commercial refrigerant analysis supports five key findings.

First, electrification of heating systems in commercial buildings remains a strong GHG reduction strategy after accounting for refrigerant leakage. Refrigerant leakage has essentially no incremental effect on GHG savings in the HP RTU scenario, while the largest impacts occur in the HP Boiler scenario because of its higher total refrigerant charge relative to the baseline. In the current case, refrigerant emissions reduce GHG savings by approximately 23.4% in the HP Boiler scenario, 7.7% in Package 5, and 8.9% in the VRF scenario. These impacts are substantially smaller in the future case.

Second, refrigerant GWP is a major driver of refrigerant-related climate impacts from commercial HVAC equipment. Although refrigerant leakage can increase substantially in some electrification scenarios, associated GHG emissions fall when lower-GWP and ultra-low-GWP refrigerants are assumed. As a result, the effect of refrigerant leakage on GHG savings is much smaller in the future case across all scenarios.

Third, VRF systems warrant particular attention because they can require larger refrigerant charges than conventional packaged systems. Design strategies that reduce refrigerant charge, such as using hydronic distribution within buildings where feasible, can help reduce refrigerant-related emissions.

Fourth, the refrigerant impacts estimated for the HP Boiler and Package 5 scenarios partly reflect how these measures are modeled in ComStock. In these scenarios, HP boiler capacity is added to refrigerant-containing cooling systems because the ComStock HP Boiler scenario does not replace or modify existing cooling equipment. However, reverse-cycle chillers and other reversible air-to-water heat pump systems can provide both heating and cooling and, in suitable applications, could replace some cooling equipment that would otherwise remain in place. The incremental refrigerant impacts of the HP Boiler

[119] U.S. EIA, "Table HC6.1 – Space Heating in U.S. Homes, by Housing Unit Type, 2020," March 2023.

and Package 5 scenarios could therefore be lower under such configurations. Future analyses could explore this potential.

Fifth, improved refrigerant management and accelerated refrigerant transitions can further enhance the climate benefits of commercial heat pumps. Policies and programs that reduce operational leakage, strengthen refrigerant recovery at end of life, improve technician training, and support the adoption of low- and ultra-low-GWP refrigerants can help ensure that commercial electrification achieves its full GHG reduction potential.

Looking Ahead

While this report examined the theoretical emissions reduction potential if commercial heating equipment were electrified overnight, in reality this will be a gradual transition. More time gives policymakers and building owners the flexibility needed to implement more strategic, resource-efficient energy efficiency and electrification upgrades. For example, NYSERDA recommends that building owners implement energy load reduction and waste heat recovery measures before electrification, in order to maximize energy efficiency and minimize strain on the electricity grid.[120]

Building on this report, future studies could:

- Examine a more complete ComStock dataset (if one is released), to capture a broader swath of the commercial building stock;
- Measure the emissions benefit of building envelope improvements as an option for commercial building energy upgrades;
- Examine the emissions impacts of phasing in upgrades over time rather than instantaneous electrification; and/or
- Assess the effect of commercial building electrification on the electricity grid and the potential for additional local or regional infrastructure needs.

Taken together, these areas of future study would help build a more complete picture of the tradeoffs and opportunities involved in decarbonizing the commercial building sector.

[120] NYSERDA, RMI, Building Energy Exchange, Urban Land Institute, "Retrofit Playbook for Large Buildings," accessed March 16, 2026.

6. Appendices

Appendix A. 2021 State-and-Fuel-Specific Electricity Emissions Factors for VOCs and $PM_{2.5}$ (lbs/MWh)*

State	Biomass		Coal		Gas		Oil		Clean Energy**	
	$PM_{2.5}$	VOC	$PM_{2.5}$	VOC	$PM_{2.5}$	VOC	$PM_{2.5}$	VOC	$PM_{2.5}$	VOC
CT	0.027	0.030	-	-	0.018	0.007	0.656	0.114	0.000	0.000
DC	0.165	0.016	-	-	0.075	0.030	-	-	0.000	0.000
DE	0.146	1.130	0.264	0.037	0.037	0.010	0.010	0.060	0.000	0.000
MA	0.992	1.486	-	-	0.024	0.015	1.194	0.024	0.000	0.000
MD	0.015	0.109	0.089	0.029	0.057	0.039	2.563	0.114	0.000	0.000
ME	0.321	0.321	-	-	0.019	0.006	0.082	0.030	0.000	0.000
NH	0.114	0.087	0.235	0.048	0.032	0.009	0.105	0.064	0.000	0.000
NJ	0.030	0.168	0.122	0.021	0.051	0.020	1.368	0.425	0.000	0.000
NY	0.153	0.584	-	-	0.085	0.058	0.408	0.107	0.000	0.000
PA	0.054	0.198	0.168	0.010	0.032	0.008	0.219	0.072	0.000	0.000
RI	0.212	0.043	-	-	0.036	0.020	4.650	0.006	0.000	0.000
VA	0.078	0.191	0.192	0.035	0.046	0.013	0.670	0.046	0.000	0.000
VT	0.198	0.300	-	-	-	-	0.503	0.103	0.001	0.000

*Emissions factors for fuels can vary considerably from state to state. This is due to interstate variability in power plants and fuel composition (e.g., biomass encompasses a range of fuels including wood, municipal solid waste, and landfill gas, which may have significantly different emissions). Blanks mean that the state uses zero or negligible levels of that fuel in electricity generation.

**Clean energy includes geothermal, hydropower, nuclear, solar, and wind.

Appendix B. Reductions in Fuel Consumption by State

Table B1. Reductions (MWh) in Fuel Consumption by State, HP Boiler and HP RTU

State	HP Boiler		HP RTU			
	Electricity	Gas	Electricity	Gas	Oil	Propane
CT	(493,746)	1,412,737	251,295	883,554	666,132	114,149
DC	(210,393)	679,379	170,425	149,532	3,933	1,211
DE	(35,459)	102,692	107,619	156,049	15,929	20,819
MA	(1,227,631)	3,506,242	478,634	2,084,319	1,067,740	230,414
MD	(658,668)	2,018,880	1,137,011	1,686,203	99,546	109,504
ME	(56,905)	148,334	(43,259)	172,371	654,544	153,920
NH	(81,321)	227,666	52,759	274,920	466,161	209,941
NJ	(1,747,458)	5,171,683	775,100	3,026,279	111,291	43,950
NY	(4,389,389)	13,188,467	1,035,364	8,960,447	1,014,200	488,258
PA	(2,682,152)	8,107,408	1,964,207	4,611,182	515,470	266,708
RI	(109,988)	317,343	49,851	322,007	147,446	22,028
VA	(1,234,699)	3,829,057	3,162,218	1,976,718	105,249	148,904
VT	(41,350)	106,799	(19,834)	103,253	146,692	40,647
Total OTC	**(12,969,159)**	**38,816,687**	**9,121,389**	**24,406,832**	**5,014,335**	**1,850,452**

Table B2. Reductions (MWh) in Fuel Consumption by State, VRF and Package 5

State	VRF				Package 5			
	Electricity	Gas	Oil	Propane	Electricity	Gas	Oil	Propane
CT	78,404	1,168,540	1,061,539	98,026	(70,382)	2,330,261	797,379	114,929
DC	297,241	186,454	5,324	1,209	158,384	834,390	6,243	1,224
DE	111,863	141,949	7,520	20,259	108,294	260,274	22,801	21,400
MA	278,823	2,891,190	1,496,217	178,308	(314,929)	5,668,562	1,230,843	234,814
MD	1,496,934	2,181,159	129,926	103,728	924,596	3,751,784	195,830	109,522
ME	(141,872)	166,012	887,671	85,746	(99,765)	327,329	821,640	155,588
NH	(45,053)	310,162	585,260	162,579	15,985	507,502	509,811	215,487
NJ	509,494	4,319,822	272,033	18,978	(424,167)	8,272,487	177,366	44,128
NY	224,728	11,154,557	2,207,680	172,434	(1,854,848)	22,336,897	1,469,051	499,126
PA	1,503,612	5,743,027	1,140,223	92,328	184,642	12,825,376	771,206	269,671
RI	(26,669)	430,157	177,769	19,079	(22,223)	642,649	157,203	22,394
VA	4,383,338	2,793,356	157,389	149,837	3,273,492	5,870,671	255,647	151,292
VT	(59,122)	121,266	232,636	32,512	(43,720)	214,278	182,076	41,739
Total OTC	**8,611,721**	**31,607,651**	**8,361,188**	**1,135,024**	**1,835,361**	**63,842,461**	**6,597,095**	**1,881,313**

Table B3. Percent Reduction in Fuel Consumption by State

State	HP Boiler		HP RTU				VRF				Package 5			
	Electr.	Gas	Electr.	Gas	Oil	Prop.	Electr.	Gas	Oil	Prop.	Electr.	Gas	Oil	Prop.
CT	(8%)	43%	4%	27%	45%	75%	1%	35%	71%	65%	(1%)	70%	54%	76%
DC	(3%)	39%	3%	8%	31%	12%	5%	11%	42%	12%	3%	47%	50%	13%
DE	(3%)	25%	9%	38%	34%	78%	10%	35%	16%	76%	10%	63%	49%	80%
MA	(8%)	42%	3%	25%	50%	73%	2%	35%	70%	56%	(2%)	68%	58%	74%
MD	(4%)	33%	7%	28%	19%	89%	9%	36%	25%	84%	6%	62%	38%	89%
ME	(2%)	18%	(2%)	20%	42%	66%	(5%)	20%	57%	37%	(4%)	39%	53%	67%
NH	(4%)	25%	2%	30%	57%	66%	(2%)	33%	71%	51%	1%	55%	62%	68%
NJ	(11%)	45%	5%	27%	27%	62%	3%	38%	67%	27%	(3%)	73%	43%	62%
NY	(9%)	39%	2%	26%	28%	63%	0%	33%	62%	22%	(4%)	66%	41%	64%
PA	(8%)	40%	6%	23%	27%	61%	4%	29%	61%	21%	1%	64%	41%	62%
RI	(9%)	34%	4%	34%	62%	64%	(2%)	46%	75%	55%	(2%)	69%	66%	65%
VA	(3%)	33%	8%	17%	16%	70%	11%	24%	23%	71%	8%	51%	38%	71%
VT	(6%)	32%	(3%)	31%	40%	57%	(9%)	36%	63%	46%	(7%)	64%	49%	59%
Total OTC	**(7%)**	**39%**	**5%**	**24%**	**37%**	**67%**	**5%**	**32%**	**61%**	**41%**	**1%**	**64%**	**48%**	**68%**

Appendix C. State-by-State Baseline Commercial Building Emissions (Metric Tons), Current and Future Cases

State	Current Case					Future Case				
	CO_2e	NO_x	SO_2	$PM_{2.5}$	VOC	CO_2e	NO_x	SO_2	$PM_{2.5}$	VOC
CT	2,442,982	1,541	225	111	55	1,969,375	1,190	78	81	48
DC	1,311,047	1,688	981	267	78	690,919	815	301	267	78
DE	182,133	90	74	14	81	119,696	80	7	6	33
MA	4,781,545	4,941	1,961	1,449	1,689	3,463,142	2,120	274	273	362
MD	3,813,666	4,734	2,546	710	210	2,206,888	2,472	783	289	107
ME	758,561	745	472	70	43	734,524	604	105	43	17
NH	567,691	529	206	37	23	607,508	415	13	28	16
NJ	5,385,762	2,611	389	221	221	4,503,800	2,358	102	163	162
NY	14,033,188	12,120	2,053	1,189	988	7,165,316	6,123	285	133	397
PA	13,960,314	7,079	4,117	600	308	12,033,246	5,074	235	387	280
RI	464,094	326	220	60	22	305,192	240	15	12	11
VA	8,771,900	3,769	1,426	507	319	6,275,469	2,818	355	273	189
VT	176,493	192	34	14	8	168,558	150	2	9	5
Total OTC	**56,649,376**	**40,365**	**14,705**	**5,249**	**4,044**	**40,243,634**	**24,460**	**2,554**	**1,963**	**1,704**

Appendix D. State-by-State Percent Reductions in Air Emissions from Commercial Heating Upgrades

Table D1. Percent Reduction in GHG Emissions from Commercial Heating Upgrades

State	Current Grid				Future Grid			
	HP RTU	HP Boiler	VRF	Package 5	HP RTU	HP Boiler	VRF	Package 5
CT	17%	6%	21%	26%	20%	9%	26%	32%
DC	4%	7%	6%	14%	6%	16%	8%	23%
DE	25%	9%	22%	36%	33%	15%	29%	50%
MA	16%	9%	21%	28%	21%	15%	28%	39%
MD	14%	7%	18%	23%	19%	15%	24%	36%
ME	30%	3%	34%	38%	31%	3%	36%	40%
NH	38%	6%	41%	47%	35%	6%	38%	44%
NJ	14%	11%	18%	27%	15%	15%	21%	33%
NY	15%	13%	19%	30%	27%	33%	36%	63%
PA	11%	5%	13%	19%	12%	7%	14%	22%
RI	23%	8%	26%	34%	33%	17%	41%	52%
VA	11%	6%	15%	19%	12%	9%	16%	24%
VT	36%	11%	49%	52%	38%	11%	52%	55%
Total OTC	**14%**	**8%**	**17%**	**24%**	**18%**	**14%**	**22%**	**34%**

Table D2. Percent Reduction in NOx Emissions from Commercial Heating Upgrades

State	Current Grid				Future Grid			
	HP RTU	HP Boiler	VRF	Package 5	HP RTU	HP Boiler	VRF	Package 5
CT	22%	10%	29%	35%	27%	16%	37%	46%
DC	4%	3%	6%	10%	5%	10%	7%	17%
DE	37%	17%	32%	56%	40%	19%	35%	61%
MA	14%	5%	18%	23%	29%	23%	38%	55%
MD	12%	3%	15%	18%	16%	10%	21%	29%
ME	28%	2%	31%	35%	34%	3%	40%	44%
NH	38%	6%	40%	46%	47%	8%	52%	58%
NJ	20%	26%	28%	48%	22%	30%	31%	54%
NY	15%	12%	18%	29%	28%	32%	36%	62%
PA	15%	13%	18%	31%	19%	21%	24%	43%
RI	28%	11%	33%	41%	37%	18%	45%	57%
VA	13%	14%	18%	30%	15%	19%	21%	37%
VT	30%	7%	39%	42%	39%	11%	52%	55%
Total OTC	**15%**	**11%**	**19%**	**29%**	**23%**	**22%**	**29%**	**47%**

Table D3. Percent Reduction in SO_2 Emissions from Commercial Heating Upgrades

State	Current Grid				Future Grid			
	HP RTU	HP Boiler	VRF	Package 5	HP RTU	HP Boiler	VRF	Package 5
CT	5%	(7%)	3%	1%	7%	(6%)	6%	4%
DC	3%	(3%)	5%	3%	3%	(3%)	5%	3%
DE	10%	(3%)	10%	10%	12%	(2%)	12%	13%
MA	3%	(8%)	2%	(2%)	5%	(7%)	4%	1%
MD	7%	(4%)	9%	6%	7%	(4%)	10%	6%
ME	(1%)	(2%)	(5%)	(3%)	0%	(2%)	(3%)	(1%)
NH	3%	(3%)	(1%)	2%	14%	(1%)	12%	15%
NJ	6%	(10%)	4%	(1%)	7%	(5%)	7%	5%
NY	3%	(8%)	1%	(2%)	6%	(3%)	6%	5%
PA	6%	(8%)	5%	1%	8%	(4%)	7%	6%
RI	4%	(8%)	(2%)	(1%)	8%	(6%)	4%	5%
VA	8%	(3%)	11%	9%	8%	(2%)	12%	10%
VT	(2%)	(6%)	(7%)	(4%)	23%	3%	31%	31%
Total OTC	**5%**	**(6%)**	**5%**	**2%**	**6%**	**(4%)**	**7%**	**5%**

Table D4. Percent Reduction in $PM_{2.5}$ Emissions from Commercial Heating Upgrades

State	Current Grid				Future Grid			
	HP RTU	HP Boiler	VRF	Package 5	HP RTU	HP Boiler	VRF	Package 5
CT	17%	(4%)	24%	18%	23%	(3%)	33%	25%
DC	3%	(3%)	5%	3%	3%	(3%)	5%	3%
DE	12%	(2%)	11%	14%	15%	(1%)	12%	19%
MA	5%	(8%)	4%	0%	12%	(6%)	15%	10%
MD	7%	(4%)	10%	7%	8%	(3%)	10%	8%
ME	22%	(1%)	28%	27%	37%	0%	49%	46%
NH	32%	(1%)	37%	34%	42%	0%	51%	46%
NJ	7%	(9%)	7%	2%	7%	(8%)	9%	3%
NY	4%	(7%)	5%	1%	23%	5%	45%	37%
PA	8%	(6%)	9%	5%	9%	(5%)	12%	7%
RI	10%	(7%)	6%	5%	32%	(3%)	36%	33%
VA	8%	(3%)	12%	10%	9%	(2%)	12%	11%
VT	25%	(2%)	37%	30%	39%	1%	61%	49%
Total OTC	**7%**	**(6%)**	**8%**	**4%**	**11%**	**(4%)**	**16%**	**12%**

Table D5. Percent Reduction in VOC Emissions from Commercial Heating Upgrades

State	Current Grid				Future Grid			
	HP RTU	HP Boiler	VRF	Package 5	HP RTU	HP Boiler	VRF	Package 5
CT	21%	18%	27%	42%	23%	22%	30%	48%
DC	4%	4%	6%	11%	4%	4%	6%	11%
DE	11%	(2%)	11%	12%	13%	0%	13%	16%
MA	4%	(6%)	4%	1%	9%	2%	10%	13%
MD	13%	5%	16%	20%	18%	13%	23%	33%
ME	11%	1%	9%	14%	30%	7%	31%	41%
NH	27%	7%	26%	35%	37%	11%	39%	51%
NJ	14%	13%	18%	30%	18%	22%	24%	42%
NY	10%	5%	11%	17%	21%	25%	26%	48%
PA	16%	18%	19%	36%	17%	21%	20%	40%
RI	18%	6%	18%	26%	32%	22%	40%	56%
VA	11%	8%	15%	22%	13%	15%	18%	31%
VT	21%	9%	24%	33%	35%	17%	43%	56%
Total OTC	**9%**	**2%**	**10%**	**13%**	**16%**	**15%**	**20%**	**33%**

Appendix E. State-by-State Health Effects from OTC-Wide Adoption of Upgrade Scenarios

*Table E1. State-by-State Health Effects from OTC-Wide Adoption of HP RTU Upgrade**

State	$ Health Benefits (Low)	$ Health Benefits (High)	Mortality (Low)	Mortality (High)	Asthma Symptoms	Asthma Onset	Incidence, Hay Fever & Rhinitis	ER Visits, Respiratory	Nonfatal Heart Attacks	Work Loss Days	Hospital Admits, Alzheimers	Hospital Admits, Parkinsons
CT	$53,474,599	$76,135,871	3	5	2,465	15	101	6	1	182	1	0
DE	$10,338,824	$14,482,638	1	1	521	3	21	1	0	30	0	0
DC	$4,766,045	$7,189,264	0	0	403	3	16	1	0	26	0	0
ME	$10,347,816	$14,838,131	1	1	344	2	14	0	0	27	0	0
MD	$59,985,256	$85,363,732	4	5	3,646	23	147	9	1	210	1	0
MA	$137,050,499	$219,195,069	9	14	5,806	36	230	13	4	694	6	0
NH	$14,567,410	$21,175,498	1	1	562	3	23	2	0	49	0	0
NJ	$127,474,021	$179,380,599	8	11	7,098	44	287	17	2	437	1	0
NY	$153,061,798	$246,642,455	10	16	7,637	46	299	15	4	931	2	1
PA	$120,712,450	$173,655,557	8	11	5,539	35	224	14	2	362	1	0
RI	$18,486,206	$28,622,785	1	2	745	5	30	2	0	74	1	0
VT	$3,835,452	$5,312,635	0	0	135	1	6	0	0	9	0	0
VA	$37,895,655	$50,586,661	2	3	2,525	16	102	7	1	128	0	0
All OTC	**$751,996,029**	**$1,122,580,893**	**47**	**73**	**37,425**	**232**	**1,499**	**86**	**15**	**3,159**	**14**	**2**

*Positive numbers indicate the economic value of the health impacts shown and number of health incidents avoided. Not all health outcomes modeled in COBRA are shown in this table.

Table E2. State-by-State Health *Effects from OTC-Wide Adoption of HP Boiler Upgrade**

State	$ Health Benefits (Low)	$ Health Benefits (High)	Mortality (Low)	Mortality (High)	Asthma Symptoms	Asthma Onset	Incidence, Hay Fever & Rhinitis	ER Visits, Respiratory	Nonfatal Heart Attacks	Work Loss Days	Hospital Admits, Alzheimers	Hospital Admits, Parkinsons
CT	$23,597,613	$24,923,666	1	2	1,330	9	57	4	0	12	0	0
DE	$5,997,849	$7,486,018	0	0	327	2	13	1	0	11	0	0
DC	$2,631,420	$3,354,331	0	0	252	2	10	1	0	8	0	0
ME	$2,804,859	$1,356,152	0	0	146	1	6	0	(0)	(9)	(0)	(0)
MD	$33,532,500	$41,567,988	2	3	2,256	14	93	6	0	66	0	0
MA	$3,680,065	($37,738,781)	(0)	(3)	1,416	11	69	5	(2)	(350)	(3)	(0)
NH	$4,333,142	$2,695,629	0	0	246	2	11	1	(0)	(12)	(0)	(0)
NJ	$68,273,168	$81,763,237	4	5	4,269	27	176	11	1	111	0	0
NY	$59,361,517	$71,415,989	4	4	3,513	22	146	7	0	116	0	0
PA	$65,501,043	$81,763,769	4	5	3,357	21	139	9	1	111	0	0
RI	$3,146,667	($166,858)	0	(0)	272	2	12	1	(0)	(24)	(0)	(0)
VT	$1,566,155	$1,458,556	0	0	71	0	3	0	(0)	(1)	(0)	(0)
VA	$22,181,222	$26,209,728	1	2	1,595	10	66	4	0	42	0	0
All OTC	**$296,607,220**	**$306,089,423**	**18**	**18**	**19,051**	**124**	**803**	**48**	**0**	**81**	**(2)**	**0**

*Positive numbers indicate the economic value of the health impacts shown and number of health incidents avoided. Not all health outcomes modeled in COBRA are shown in this table. Some negative numbers indicating increases in health incidents may be due to increases in some pollutants for some states based on current grid fuel composition.

*Table E3. State-by-State Health Effects from OTC-Wide Adoption of VRF Upgrade**

State	$ Health Benefits (Low)	$ Health Benefits (High)	Mortality (Low)	Mortality (High)	Asthma Symptoms	Asthma Onset	Incidence, Hay Fever & Rhinitis	ER Visits, Respiratory	Nonfatal Heart Attacks	Work Loss Days	Hospital Admits, Alzheimers	Hospital Admits, Parkinsons
CT	$53,474,599	$76,135,871	3	5	2,465	15	101	6	1	182	1	0
DE	$10,338,824	$14,482,638	1	1	521	3	21	1	0	30	0	0
DC	$4,766,045	$7,189,264	0	0	403	3	16	1	0	26	0	0
ME	$10,347,816	$14,838,131	1	1	344	2	14	0	0	27	0	0
MD	$59,985,256	$85,363,732	4	5	3,646	23	147	9	1	210	1	0
MA	$137,050,499	$219,195,069	9	14	5,806	36	230	13	4	694	6	0
NH	$14,567,410	$21,175,498	1	1	562	3	23	2	0	49	0	0
NJ	$127,474,021	$179,380,599	8	11	7,098	44	287	17	2	437	1	0
NY	$153,061,798	$246,642,455	10	16	7,637	46	299	15	4	931	2	1
PA	$120,712,450	$173,655,557	8	11	5,539	35	224	14	2	362	1	0
RI	$18,486,206	$28,622,785	1	2	745	5	30	2	0	74	1	0
VT	$3,835,452	$5,312,635	0	0	135	1	6	0	0	9	0	0
VA	$37,895,655	$50,586,661	2	3	2,525	16	102	7	1	128	0	0
All OTC	**$751,996,029**	**$1,122,580,893**	**47**	**73**	**37,425**	**232**	**1,499**	**86**	**15**	**3,159**	**14**	**2**

*Positive numbers indicate the economic value of the health impacts shown and number of health incidents avoided. Not all health outcomes modeled in COBRA are shown in this table.

*Table E4. State-by-State Health Effects from OTC-Wide Adoption of Package 5 Upgrade**

State	$ Health Benefits (Low)	$ Health Benefits (High)	Mortality (Low)	Mortality (High)	Asthma Symptoms	Asthma Onset	Incidence, Hay Fever & Rhinitis	ER Visits, Respiratory	Nonfatal Heart Attacks	Work Loss Days	Hospital Admits, Alzheimers	Hospital Admits, Parkinsons
CT	$89,371,053	$120,393,885	6	8	4,312	27	178	11	1	250	1	0
DE	$18,415,571	$25,074,937	1	2	947	6	39	3	0	49	0	0
DC	$8,385,459	$12,166,178	0	1	733	5	30	2	0	41	0	0
ME	$15,904,551	$20,699,550	1	1	570	4	23	0	0	29	0	0
MD	$105,863,437	$145,819,030	6	9	6,606	41	268	16	1	330	1	0
MA	$184,604,164	$260,999,002	12	17	8,810	56	359	20	3	644	6	0
NH	$22,691,351	$30,137,537	1	2	938	6	38	3	0	55	0	0
NJ	$222,582,645	$301,956,455	14	19	12,763	80	519	31	4	666	2	0
NY	$249,500,655	$382,966,722	16	25	12,884	79	512	25	5	1,325	4	1
PA	$211,461,121	$294,392,998	13	19	9,980	63	406	25	3	567	2	0
RI	$26,963,259	$37,780,679	2	2	1,201	8	50	3	0	79	1	0
VT	$6,306,754	$8,171,428	0	1	234	1	10	1	0	12	0	0
VA	$67,656,601	$87,632,326	4	5	4,601	30	187	12	1	203	0	0
All OTC	**$1,229,706,620**	**$1,728,190,726**	**76**	**111**	**64,579**	**405**	**2,618**	**152**	**21**	**4,250**	**17**	**2**

Appendix F. State-Level Changes in GHG Emissions Savings with Refrigerant Leakage

Table F1. Current Case: State-Level Changes in GHG Emissions Savings, HP Boiler Scenario

State	Current case			
	GHG savings before refrigerant leak (MMT CO_2e)	Increase in GHG emissions from refrigerant leakage (MMT CO_2e)	GHG emissions savings after refrigerant leakage (MMT CO_2e)	Reduction in GHG savings due to refrigerant leakage (%)
CT	2.1	0.5	1.6	24.6%
DC	1.3	0.4	0.9	30.4%
DE	0.2	0.1	0.2	22.2%
MA	6.2	1.3	4.9	21.1%
MD	3.8	0.9	2.9	24.6%
ME	0.3	0.0	0.3	11.8%
NH	0.5	0.1	0.5	13.7%
NJ	8.5	2.3	6.2	26.8%
NY	26.5	5.0	21.5	18.9%
PA	10.4	3.2	7.2	30.5%
RI	0.6	0.1	0.5	17.7%
VA	7.2	2.0	5.2	27.6%
VT	0.3	0.0	0.3	10.6%
OTC Region	**68**	**16**	**52**	**23.4%**

Table F2. Future Case: State-Level Changes in GHG Emissions Savings, HP Boiler Scenario

State	Future case			
	GHG savings before refrigerant leak (MMT CO_2e)	Increase in GHG emissions from refrigerant leakage (MMT CO_2e)	GHG emissions savings after refrigerant leakage (MMT CO_2e)	Reduction in GHG savings due to refrigerant leakage (%)
CT	2.7	0.1	2.6	3.4%
DC	1.6	0.1	1.6	4.3%
DE	0.3	0.0	0.3	3.4%
MA	7.8	0.2	7.6	2.9%
MD	4.8	0.2	4.7	3.4%
ME	0.4	0.0	0.3	2.0%
NH	0.5	0.0	0.5	2.5%
NJ	10.0	0.4	9.6	4.0%
NY	35.5	0.9	34.6	2.5%
PA	12.7	0.6	12.1	4.4%
RI	0.8	0.0	0.7	2.2%
VA	8.4	0.3	8.1	4.1%
VT	0.3	0.0	0.3	1.8%
OTC Region	**86**	**3**	**83**	**3.2%**

Table F3. Current Case: State-Level Changes in GHG Emissions Savings, VRF Scenario

State	Current case			
	GHG savings before refrigerant leak (MMT CO_2e)	Increase in GHG emissions from refrigerant leakage (MMT CO_2e)	GHG emissions savings after refrigerant leakage (MMT CO_2e)	Reduction in GHG savings due to refrigerant leakage (%)
CT	7.7	0.6	7.1	8.1%
DC	1.2	0.2	1.1	13.6%
DE	0.6	0.1	0.5	10.3%
MA	14.7	1.3	13.5	8.5%
MD	10.3	1.2	9.1	11.7%
ME	3.9	0.2	3.7	5.5%
NH	3.5	0.2	3.3	6.1%
NJ	14.3	1.2	13.1	8.5%
NY	39.3	3.3	36.1	8.3%
PA	26.4	2.1	24.4	7.8%
RI	1.8	0.1	1.7	7.6%
VA	19.5	2.4	17.0	12.5%
VT	1.3	0.1	1.2	5.4%
OTC Region	**145**	**13**	**132**	**8.9%**

Table F4. Future Case: State-Level Changes in GHG Emissions Savings, VRF Scenario

State	Future case			
	GHG savings before refrigerant leak (MMT CO_2e)	Increase in GHG emissions from refrigerant leakage (MMT CO_2e)	GHG emissions savings after refrigerant leakage (MMT CO_2e)	Reduction in GHG savings due to refrigerant leakage (%)
CT	7.6	0.1	7.5	1.2%
DC	0.8	0.0	0.8	3.2%
DE	0.5	0.0	0.5	1.9%
MA	14.4	0.2	14.2	1.3%
MD	8.0	0.2	7.9	2.3%
ME	3.9	0.0	3.9	0.8%
NH	3.5	0.0	3.5	0.9%
NJ	13.9	0.2	13.7	1.3%
NY	38.9	0.5	38.4	1.3%
PA	25.2	0.3	24.9	1.2%
RI	1.9	0.0	1.8	1.1%
VA	15.3	0.4	14.9	2.4%
VT	1.3	0.0	1.3	0.8%
OTC Region	**135**	**2.0**	**133**	**1.4%**

Table F5. Current Case: State-Level Change in GHG Emissions Savings, Package 5 Scenario

State	Current case			
	GHG savings before refrigerant leak (MMT CO_2e)	Increase in GHG emissions from refrigerant leakage (MMT CO_2e)	GHG emissions savings after refrigerant leakage (MMT CO_2e)	Reduction in GHG savings due to refrigerant leakage (%)
CT	9.4	0.5	8.9	5.5%
DC	2.7	0.4	2.3	15.1%
DE	1.0	0.1	0.9	5.3%
MA	19.8	1.3	18.5	6.6%
MD	13.4	0.9	12.5	7.1%
ME	4.4	0.0	4.3	0.9%
NH	4.0	0.1	3.9	1.9%
NJ	21.8	2.3	19.5	10.5%
NY	63.5	5.0	58.5	7.9%
PA	39.1	3.2	35.9	8.1%
RI	2.3	0.1	2.2	4.2%
VA	25.4	2.0	23.4	7.9%
VT	1.4	0.0	1.4	2.1%
OTC Region	**208**	**15.9**	**192**	**7.7%**

Table F6. Future Case: State-Level Change in GHG Emissions Savings, Package 5 Scenario

State	Future case			
	GHG savings before refrigerant leak (MMT CO_2e)	Increase in GHG emissions from refrigerant leakage (MMT CO_2e)	GHG emissions savings after refrigerant leakage (MMT CO_2e)	Reduction in GHG savings due to refrigerant leakage (%)
CT	9.5	0.1	9.4	1.0%
DC	2.4	0.1	2.3	2.9%
DE	0.9	0.0	0.9	1.0%
MA	20.2	0.2	20.0	1.1%
MD	12.0	0.2	11.9	1.4%
ME	4.4	0.0	4.4	0.2%
NH	4.0	0.0	4.0	0.3%
NJ	22.1	0.4	21.7	1.8%
NY	67.3	0.9	66.4	1.3%
PA	38.9	0.6	38.4	1.4%
RI	2.4	0.0	2.4	0.7%
VA	22.2	0.3	21.9	1.6%
VT	1.4	0.0	1.4	0.4%
OTC Region	**208**	**2.8**	**205**	**1.3%**