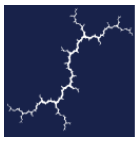
Refrigerant Emissions Impacts of Residential Building Electrification in the Northeast and Mid-Atlantic

Quantifying Leakage, Emissions Impacts, and the Role of Refrigerant Transitions

Prepared for Northeast States for Coordinated Air Use Management (NESCAUM)

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EXECUTIVE SUMMARY

While electrification of space and water heating is a critical strategy for reducing combustion-related carbon dioxide (CO_2) emissions, heat pumps rely on refrigerants—many of which are potent greenhouse gases—that may be released over the equipment lifecycle. This report estimates these impacts across the 13 Northeast and Mid-Atlantic jurisdictions that comprise the Ozone Transport Commission (OTC),[1] as a follow-on publication to the Northeast States for Coordinated Air Use Management (NESCAUM) and OTC report, *Residential Building Electrification in the Northeast and Mid-Atlantic: Criteria Pollutant and Greenhouse Gas Reduction Potential*,[2] and evaluates how evolving refrigerant choices influence the net climate benefits of residential electrification. Our analysis estimates that refrigerant leakage reduces GHG savings potential of whole-home electrification by approximately 3.3 percent on average across the OTC region under current refrigerant and grid conditions, and by 0.6 percent under future conditions that assume lower-GWP refrigerants and a cleaner electric grid. These findings indicate that the overall climate benefits of electrification substantially outweigh the greenhouse gas (GHG) emissions associated with refrigerant leakage.

Key Findings

Building electrification delivers substantial emissions reductions—even after accounting for refrigerants.

Our analysis evaluates refrigerant-related GHG impacts under three residential building electrification scenarios: Space Heating Electrification, Water Heating Electrification, and Whole Home Electrification. Each scenario is compared with a Baseline scenario that assumes no building electrification and reflects the continued use of heating and cooling equipment in existing residential buildings, including refrigerant-containing air conditioning equipment. These scenarios are assessed under current refrigerant and grid conditions (Current case) and under future conditions that assume lower-GWP refrigerants and a cleaner electric grid (Future case). It is important to note that the Current case assumes a mix of refrigerants prevalent in today's market (mostly "A2L" refrigerants with GWPs below 700) in both the baseline and electrification scenarios. This analysis does not estimate the impacts of refrigerant leakage from higher-GWP refrigerants present in the installed base of residential heating, ventilation, and air conditioning (HVAC) equipment manufactured before 2025.

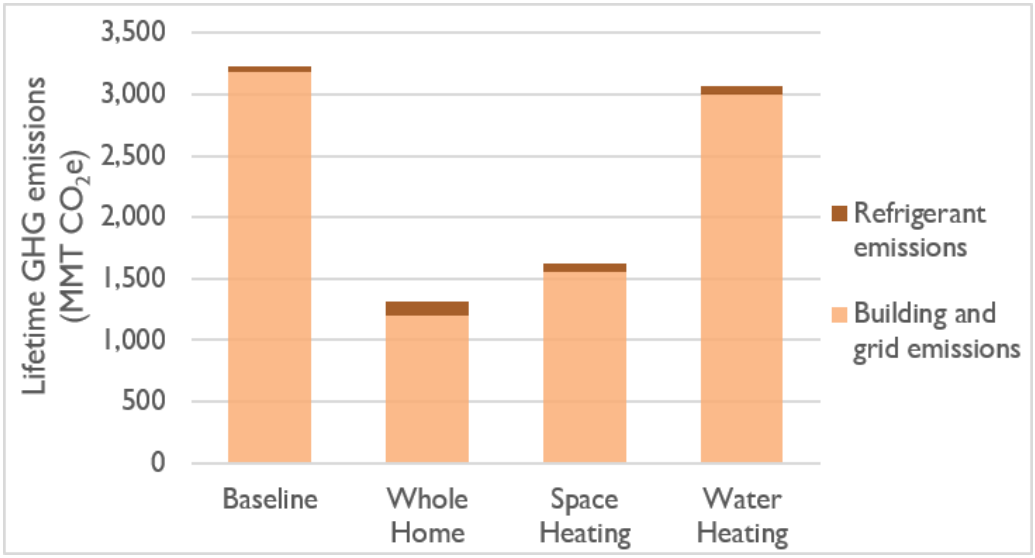
[1] OTC jurisdictions include Connecticut, Delaware, the District of Columbia, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and Virginia.

[2] NESCAUM. 2025. *Residential Building Electrification in the Northeast and Mid-Atlantic: Criteria Pollutant and Greenhouse Gas Reduction Potential*. Available at: https://www.nescaum.org/documents/25.03.03-ResStock-Updated-FINAL.pdf.

Across all scenarios, we find that replacing fossil fuel-based heating systems with heat pumps results in significant GHG reductions, even after accounting for increased emissions from refrigerant leakage. Refrigerant leakage slightly reduces these benefits but does not alter the overall conclusion that electrification is a highly effective building decarbonization strategy.

ES Figure 1 shows lifetime GHG emissions, measured in CO_2-equivalent (CO_2e), across the Baseline and three electrification scenarios, including building and grid emissions and refrigerant leakage emissions, under the Current case assumptions.

ES Figure 1. Lifetime (15-year) GHG emissions by scenario in the Current case, OTC region



The Whole Home Electrification scenario provides the greatest reduction in lifetime GHG emissions relative to the Baseline, reducing emissions from approximately 3,229 to 1,312 MMT CO_2e, a 59 percent decrease. ES Figure 2 shows the impact of refrigerant emissions on total GHG savings from Whole Home Electrification, in aggregate across the OTC region. In the graph, the bars represent total lifetime GHG savings for the Whole Home Electrification scenario compared to the Baseline scenario, while the hatched area represents the reduction in savings due to refrigerant leakage. The solid portions of the bars show GHG savings for Whole Home Electrification after accounting for refrigerant emissions.

ES Figure 2. Lifetime (15-year) GHG savings for the Whole Home Electrification scenario, OTC region



Our analysis finds that refrigerant leakage reduces lifetime GHG savings (assuming a 15-year lifespan for installed measures) for Whole Home Electrification by approximately 3.3 percent on average across all jurisdictions under a "Current" case, in which the residential building stock is electrified with the refrigerants in new equipment in 2026 and current electricity grid emissions,[3] and by 0.6 percent under a "Future" case, in which the residential building stock is electrified with lower-GWP refrigerants and a decarbonized grid modeled for 2044.

Operational and end-of-life refrigerant leakage are major contributors to direct refrigerant-related emissions over the equipment lifecycle.

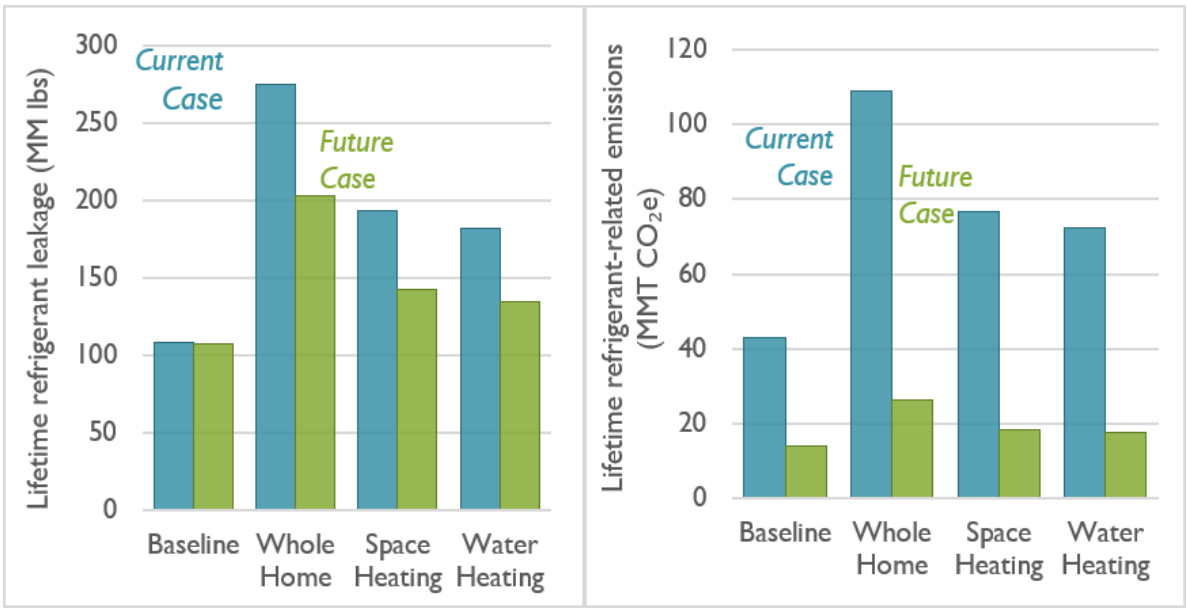
Through a literature review, we found that refrigerant losses during equipment installation are generally small (approximately 0.2 to 1 percent of refrigerant charge), while annual operational leak rates can be more substantial, typically ranging from 2 to 10 percent. Over the equipment lifetime, cumulative operational losses at the upper end of this range can approach or exceed end-of-life losses, which range from 18 to 99 percent depending on equipment management and refrigerant recovery practices. These findings highlight the importance of both reducing operational leakage and improving refrigerant recovery and end-of-life management to minimize refrigerant-related emissions from heat pumps.

[3] The Current case assumes 2024 electricity grid emissions, consistent with NESCAUM's Residential Building Electrification report. We assumed 2026 refrigerants for newly installed equipment in the Current case to account for the recent industry transition from higher-GWP refrigerants to lower-GWP A2Ls.

Refrigerant choice is the primary driver of emissions impacts, not leakage volume alone.

ES Figure 3 compares total lifetime refrigerant leakage and associated GHG emissions across the OTC region. The results show that refrigerant mix has a much greater effect on GHG emissions than total leakage volume alone. Under the Current case, the electrification scenarios—Whole Home, Space Heating, and Water Heating—increase refrigerant-related GHG emissions relative to the Baseline scenario because they expand the use of heat pumps with A2L refrigerants. While these refrigerants have lower GWPs than previous high-GWP refrigerants such as R-410A, which were widely used in residential HVAC equipment manufactured before 2025, they still produce substantial GHG emissions when leaked. Under the Future case, which assumes a transition to ultra-low GWP refrigerants, refrigerant-related GHG emissions decline dramatically—by roughly 76 percent relative to the Current case, despite greater total refrigerant use. Future case emissions also fall well below those of the Current-case Baseline.

ES Figure 3. Lifetime (15-year) refrigerant leakage (left) and associated GHG emissions (right) by scenario, OTC region



Household-level results reinforce the importance of transitioning to low-GWP next-generation refrigerants.

For a representative household converting from gas heating to a heat pump in New York State,[4] the analysis estimates that refrigerant emissions:

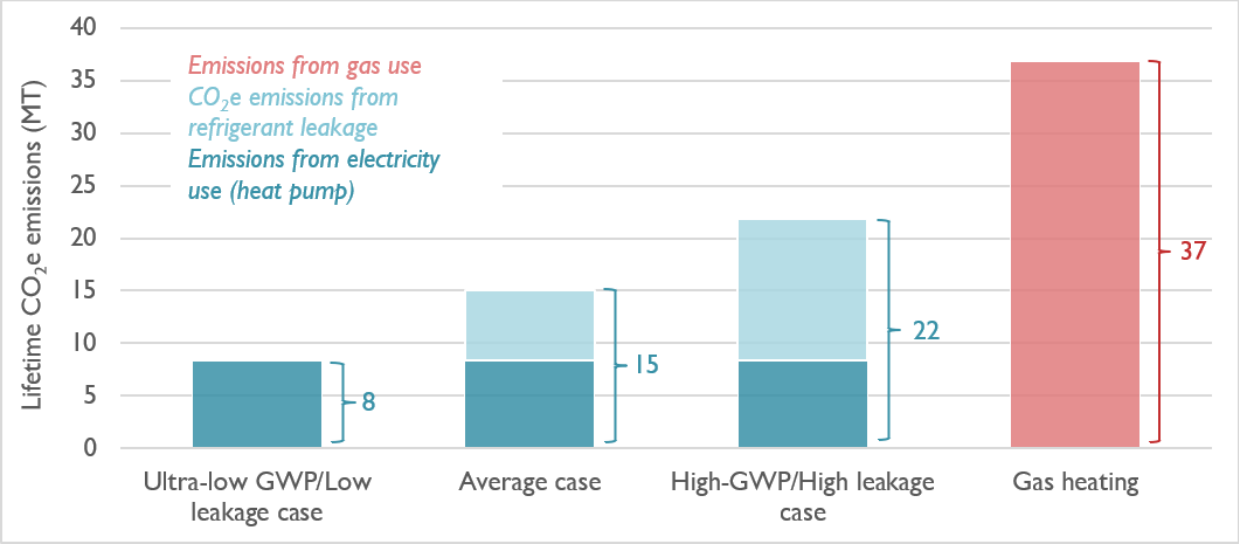
- Are negligible when using ultra-low-GWP refrigerants, even under high-leakage assumptions;

[4] This analysis includes a household-level sensitivity analysis that assesses the refrigerant emissions impacts for a "representative" individual home. For the purposes of this analysis, we assumed that the home was located in New York. New York has the largest population among the OTC states and is situated near the geographic center of the OTC region.

- Are modest when using low-GWP A2L refrigerants (e.g., R-32), ranging from approximately 1.5 to 3.7 metric tons of CO_2e over a 15-year period, depending on leakage assumptions; and
- Can reach approximately 5.5 to 13.5 metric tons of CO_2e over a 15-year period when using high-GWP refrigerants (e.g., R-410A), depending on leakage assumptions.

The analysis also compares total heat pump emissions, including both refrigerant-related emissions and electricity-use emissions (assuming the current electricity grid), with emissions from continued operation of a gas heating system over the same 15-year period (ES Figure 4). The gas-heating comparison does not include emissions associated with a separate air-conditioning system that may operate alongside the gas heating system. As a result, the comparison understates the relative GHG advantage of a heat pump that provides both heating and cooling. The results show that, for an average New York home, heat pumps provide substantial emissions reductions relative to gas heating across all scenarios, ranging from 40 to nearly 80 percent. Under worst-case assumptions of high-GWP refrigerants and high leakage rates, lifetime GHG emissions from heat pumps are still nearly 40 percent lower than emissions from gas heating. Under the most favorable refrigerant scenario that assumes ultra-low GWP refrigerants and low leakage rates, heat pump lifetime emissions are nearly 80 percent lower than those from gas heating (ES Figure 4). As the electric grid decarbonizes and lower-GWP refrigerants are adopted, the emissions advantage of heat pumps increases considerably, with lifetime emissions approaching very low levels under a zero-emission future grid paired with ultra-low-GWP refrigerants.

ES Figure 4. Lifetime (15-year) GHG emissions from household-level heat pumps and gas heating in New York, including refrigerant leakage sensitivity ranges



Policy Implications

1. **Building electrification is a robust decarbonization strategy.** Even when refrigerant leakage is included, residential building electrification delivers substantial net GHG reductions across all modeled scenarios, driven by the emissions benefits of fuel switching and grid decarbonization.

2. **Refrigerant transition policy significantly enhances the climate benefits of electrification.** Policies that accelerate the adoption of low- and ultra-low-GWP refrigerants, such as those implemented under the AIM Act and complementary state regulations, play a critical role in reducing refrigerant-related emissions from heat pumps.
3. **Improved refrigerant management can substantially reduce near-term emissions.** Improved refrigerant management practices are particularly important for reducing refrigerant-related GHG emissions from the existing stock of air conditioners and heat pumps, many of which use higher-GWP refrigerants such as R-410A**.** Reducing leakage during equipment operation and at end-of-life can meaningfully lower emissions. Key strategies include improved refrigerant recovery, technician training, and strengthened disposal requirements.
4. **Refrigerant emissions should be characterized and incorporated into climate planning and policy design.** Refrigerant leakage does not materially alter the overall climate benefits of electrification, but accounting for these emissions reinforces the importance of managing refrigerant transitions alongside building decarbonization efforts, ensuring that heat pumps achieve their full, long-term climate potential.

1. INTRODUCTION AND BACKGROUND

This report quantifies greenhouse gas (GHG) emissions associated with refrigerant leakage from residential building electrification for 13 Northeast and Mid-Atlantic jurisdictions that comprise the Ozone Transport Commission (OTC).[5] It is a follow-on publication to the Northeast States for Coordinated Air Use Management (NESCAUM) and OTC report, *Residential Building Electrification in the Northeast and Mid-Atlantic: Criteria Pollutant and Greenhouse Gas Reduction Potential*.[6] While electrification of space and water heating delivers substantial reductions in carbon dioxide (CO_2) emissions due to reduced combustion of fossil fuels, heat pumps rely on refrigerants that can contribute to climate impacts if leaked during installation, operation, servicing, or at the end of equipment life.

Hydrofluorocarbons (HFCs), the most common class of refrigerants used in air conditioning and heat pump systems, are potent GHGs. HFCs currently account for roughly 2 percent of global GHG emissions, and their global warming potentials (GWPs) are hundreds to thousands of times greater than that of CO_2 on a 100-year basis.[7] Because refrigerant losses can occur throughout the equipment lifecycle—including during installation, operation, servicing, and equipment retirement—refrigerant leakage should be considered in comprehensive electrification planning.

This analysis evaluates GHG emissions associated with refrigerant leakage from residential heat pumps used for space heating and water heating. It presents refrigerant type, charge size,[8] and leak rate assumptions for residential systems and provides a detailed refrigerant emissions impact analysis for several residential electrification scenarios.

2. EXISTING REFRIGERANTS

Historically, heat pumps and air conditioning (AC) systems in the U.S. have commonly used high-GWP HFCs as refrigerants. GWP is a measure of how much heat a unit of gas traps into the atmosphere relative to a unit of CO_2 over a specific time period (typically 100 years). A GWP greater than 1 indicates

[5] OTC jurisdictions include Connecticut, Delaware, the District of Columbia, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and Virginia.

[6] NESCAUM. 2025. *Residential Building Electrification in the Northeast and Mid-Atlantic: Criteria Pollutant and Greenhouse Gas Reduction Potential*. Available at: https://www.nescaum.org/documents/25.03.03-ResStock-Updated-FINAL.pdf.

[7] Climate and Clean Air Coalition. Hydrofluorocarbons (HFCs). Available at: https://www.ccacoalition.org/short-lived-climate-pollutants/hydrofluorocarbons-hfcs.

[8] Charge rates refer to the amount of refrigerant contained in an HVAC or refrigeration system, typically expressed as pounds of refrigerant per ton of system capacity.

that the gas has a greater warming effect than CO_2 over that timeframe.[9] In the residential and light-commercial sectors, R-410A—an HFC refrigerant with a high GWP (approximately 2,088 times more potent than CO_2)—is the most prevalent refrigerant in existing equipment, having been the primary refrigerant used in new AC and heat pump equipment since 2010.[10] Older systems manufactured before 2010 commonly use R-22 (GWP 1,810), which was fully phased out under the U.S. Clean Air Act in 2020 due to its ozone-depleting potential.[11]

According to EPA, R-410A accounts for 39 percent of the installed refrigerant stock by mass across the residential and commercial market for refrigerant-using equipment, which includes refrigeration, air conditioning, and heat pump systems. R-134a (GWP 1,430) accounts for the next-largest share at 24 percent, followed by R-22 at 14 percent.[12] Within this market, residential and light-commercial air conditioning represents the largest share of installed refrigerants at approximately 43 percent of the total, followed by large commercial air conditioning at about 20 percent. For HVAC equipment, R-410A dominates, accounting for 85 percent of the installed stock, with most of the remainder consisting of R-22 (13 percent).[13]

The policy context for refrigerants is shaped by the American Innovation and Manufacturing (AIM) Act,[14] which requires the phasedown of HFC production and consumption in the United States by 85 percent (compared to historical baseline levels) by 2036.[15] The AIM Act's phasedown schedule is broadly aligned with the Kigali Amendment to the Montreal Protocol, a 2016 international agreement aimed at reducing

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9 U.S. Environmental Protection Agency. "Understanding Global Warming Potentials." Available at: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials.

10 TRANE. 2024. "A Complete Guide to HVAC Refrigerants." August 14. Available at: https://www.trane.com/residential/en/resources/blog/a-complete-guide-to-hvac-refrigerants/#410a-phaseout; North NJ HVAC. 2025. "Best Refrigerants for Heat Pumps: Efficiency and Environmental Impact." July 20. Available at: https://northnjhvac.com/refrigerants-heat-pumps-efficiency-environmental-impact.

11 U.S. EPA. "Phaseout of Ozone-Depleting Substances (ODS)." Available at: https://www.epa.gov/ods-phaseout; NYSERDA. 2021. *HFC Emissions Inventory and Mitigation Potential*. Available at: https://www.nyserda.ny.gov/-/media/Project/Nyserda/Files/Publications/Energy-Analysis/21-28-HFC-Emissions-Inventory-and-Mitigation-Potential-in-New-York-State.pdf.

12 R-134a is outside the scope of this report, which focuses on residential heat pump systems. R-134a is primarily used in automotive air conditioning, household refrigerators and freezers, and commercial chillers.

13 U.S. EPA. 2024. *Analysis of the U.S. Hydrofluorocarbon Reclamation Market: Stakeholders, Drivers, and Practices*. pp. 22 and 25. Available at: https://www.epa.gov/system/files/documents/2024-10/analysis-of-the-u.s.-hydrofluorocarbon-reclamation-market-stakeholders-drivers-and-practices.pdf.

14 U.S. EPA. 2026. "Background on HFCs and the AIM Act." Available at: https://www.epa.gov/climate-hfcs-reduction/background-hfcs-and-aim-act.

15 EPA has established consumption and production baseline levels of HFCs in the AIM Act. Production baseline is 382.5 million metric tons of carbon dioxide equivalent ($MMTCO_2e$) and consumption baseline of 302.5 $MMTCO_2e$. EPA. "Frequent Questions on the Phasedown of Hydrofluorocarbons." Available at: https://www.epa.gov/climate-hfcs-reduction/frequent-questions-phasedown-hydrofluorocarbons.

the production and consumption of high-GWP HFCs by 80 to 85 percent by 2047.[16] The AIM Act, enacted on December 27, 2020, directs the U.S. Environmental Protection Agency (EPA) to phase down the production and consumption of regulated HFCs, manage these HFCs and their substitutes, and facilitate the transition to next-generation technologies.[17] The AIM Act, along with state programs and manufacturer transitions already underway, are expected to influence refrigerant options and emissions outcomes over the long term.

The AIM Act's Technology Transitions Rule, establishes a GWP limit of 700 for most new residential and light commercial heating, ventilation, and air conditioning (HVAC) equipment, prohibiting the use of R-410A in most such new systems manufactured or imported beginning in 2025.[18] By 2026, HVAC manufacturers had largely transitioned to lower-GWP refrigerants such as R-32 (GWP 675) and R-454B (GWP 466), which offer similar performance to R-410A with significantly reduced climate impacts.[19]

In September 2025, EPA proposed a reconsideration of certain requirements under the Technology Transitions Rule ("Reconsideration Rule") promulgated under the AIM Act, including certain compliance deadlines and sector-specific HFC restrictions.[20] On May 26, 2026, EPA issued the final rule, which removed the deadline for installing residential and light commercial air-conditioning or heat pump systems that use refrigerants with a GWP above 700, provided that the systems use specified components that were domestically manufactured or imported into the United States before January 1, 2025. Despite this additional installation flexibility for qualifying higher-GWP equipment and components, the underlying manufacture and import requirements remain unchanged. Most new residential and light commercial HVAC equipment manufactured or imported on or after January 1, 2025, must use refrigerants with a GWP of 700 or less.[21]

16 U.S. EPA. 2026. "Background on HFCs and the AIM Act." Available at: https://www.epa.gov/hfcs/background-hfcs-and-aim-act.

17 Environmental Protection Agency. 2022. Regulatory Impact Analysis for Phasing Down Production and Consumption of HFCs. pp. 26-28. Available at: https://www.epa.gov/system/files/documents/2022-07/RIA%20for%20Phasing%20Down%20Production%20and%20Consumption%20of%20Hydrofluorocarbons%20%28HFCs%29.pdf.

18 EPA Technology Transition Program. 2023. Factsheet - Final Rule - Phasedown of Hydrofluorocarbons: Restrictions on the Use of Certain Hydrofluorocarbons under Subsection (i) of the American Innovation and Manufacturing Act of 2020. Available at: https://www.epa.gov/system/files/documents/2023-10/technology-transitions-final-rule-fact-sheet-2023.pdf.

19 Air Conditioning Contractors of America (ACCA). 2025. "EPA Proposes Rollback of Refrigerant Rule: What It Means for HVACR Contractors." ACCA Blog, October 1. Available at: https://hvac-blog.acca.org/epa-proposes-rollback-of-refrigerant-rule-what-it-means-for-hvacr-contractors/.

20 U.S. EPA. 2025. "EPA Proposes Reforming Biden Technology Transitions Rule to Lower Costs for American Families at the Grocery Store, Make Refrigerants Affordable, Safe and Accessible Again." Available at: https://www.epa.gov/newsreleases/epa-proposes-reforming-biden-technology-transitions-rule-lower-costs-american-families.

21 U.S. EPA. 2026. Phasedown of Hydrofluorocarbons: Reconsideration of Certain Regulatory Requirements Promulgated Under the Technology Transitions Provisions of the American Innovation and Manufacturing Act of 2020. Available at: https://www.govinfo.gov/content/pkg/FR-2026-05-26/pdf/2026-10387.pdf.

3. ALTERNATIVE REFRIGERANTS

In response to the climate risks posed by high-GWP HFCs, a new generation of low-GWP refrigerants is emerging, driven by the AIM Act and the global HFC phasedown under the Kigali Amendment. The primary alternatives expected to play a major role in the U.S. market include lower-GWP synthetic refrigerants such as R-32, R-454B, and R-1234yf (with GWPs below 700), as well as natural refrigerants such as propane (R-290) and CO_2 (R-744) (with GWPs close to zero).

Table 1 summarizes legacy refrigerants (now phased out or restricted), lower-GWP replacement refrigerants currently being installed, and next-generation refrigerants, along with their corresponding GWPs and safety classifications. The following discussion highlights the key characteristics, benefits, and potential concerns associated with newer refrigerants.

Table 1. GWP values of existing and alternative refrigerants for residential and light-commercial AC and heat pumps

Refrigerant	100-yr GWP	ASHRAE Safety Classification	Description
Legacy refrigerants and refrigerants being phased out			
R-22	1,810	A1 (*lower toxicity, no flame propagation*)	Synthetic hydrochlorofluorocarbon (HCFC) no longer installed in new equipment due to ozone-depleting properties
R-410A	2,088	A1	Synthetic HFC developed as a non-ozone-depleting alternative to R-22, but with high GWP
Replacement refrigerants (currently being deployed)			
R-1234yf	<1	A2L (*lower toxicity, lower flammability*)	Synthetic hydrofluoroolefin (HFO) with very low GWP; classified as a PFAS-containing refrigerant and under regulatory scrutiny in five EU countries
R-454B	466	A2L	Non-ozone depleting blend containing R-32 and R-1234yf, designed as a lower-GWP alternative to R-410A
R-32	675	A2L	Single-component HFC with zero ozone-depletion potential and lower GWP than R-22 and R-410A
Next-generation refrigerants			
R-290 (Propane)	3	A3 *(lower toxicity, higher flammability)*	Natural hydrocarbon refrigerant with very low GWP but high flammability
R-600a (Isobutane)	2	A3	Natural refrigerant with high thermal conductivity providing efficient cooling, but high flammability
R-744 (CO_2)	1	A1	Natural refrigerant requiring high-pressure system components
R-717 (Ammonia)	0	B2L (*higher toxicity, lower flammability*)	Natural refrigerant with zero GWP and very high efficiency, used mainly in industrial applications due to toxicity

Source: EPA. n.d. Technology Transitions GWP Reference Table. Available at: https://www.epa.gov/climate-hfcs-reduction/technology-transitions-gwp-reference-table; ASHRAE. 2019. Designation and Safety Classification of Refrigerants: ANSI/ASHRAE Addendum f to ANSI/ASHRAE Standard 34-2019. Available at: https://www.ashrae.org/file%20library/technical%20resources/standards%20and%20guidelines/standards%20addenda/34_2019_f_20191213.pdf; EPA. 2026. "Phaseout of Class II Ozone-Depleting Substances." Available at: https://www.epa.gov/ods-phaseout/phaseout-class-ii-ozone-depleting-substances; EPA. 2026. "Frequent Questions on the Phasedown of Hydrofluorocarbons." EPA Climate HFCs Reduction. Available at: https://www.epa.gov/climate-hfcs-reduction/frequent-questions-phasedown-hydrofluorocarbons; DNV. 2024. Refrigerants: Taking the Chill Out of Heat Pumps. p. 6. Available at: https://www.aceee.org/sites/default/files/proceedings/ssb24/assets/attachments/20240722160821125_d5e08544-1392-4f70-83dd-cab5934a66e5.pdf; NYS Department of Environmental Conservation. 2024. Natural Refrigerants Fact Sheet. Available at: https://dec.ny.gov/sites/default/files/2024-08/naturalrefrigerantsfactsheet.pdf.

R-32 (GWP 675) and R-454B (GWP 466) have emerged as interim options for new residential and light-commercial air conditioning and heat pump systems.[22] Both refrigerants are classified as A2L under safety standards established by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), meaning they have lower toxicity and lower flammability.[23] They offer modest performance improvements relative to R-410A in terms of efficiency, heating and cooling capacity, and required refrigerant charge.[24]

Certain refrigerants – including some A2Ls – contain per- and polyfluoroalkyl substances (PFAS), commonly referred to as "forever chemicals." These include several single-component refrigerants used in blends, such as R-134a, as well as HFO refrigerants, such as R-1234yf (which have ultra-low GWPs, generally less than 10). Because R-454B is a mixture of R-32 and R-1234yf, it contains PFAS compounds.[25] PFAS chemicals are highly persistent in the environment, so the use of R-454B and other HFO refrigerants may raise concerns as regulatory scrutiny of PFAS increases. In fact, five European countries (the Netherlands, Germany, Denmark, Norway and Sweden) proposed restrictions on PFAS-containing refrigerants in 2023, although those proposals have not yet been adopted.[26] R-32 is free of PFAS and would not be affected by such a ban.[27]

Natural refrigerants with ultra-low GWPs are among the most environmentally friendly options, having zero ozone depletion potential and no PFAS. Ammonia (R-717, GWP 0), isobutane (R-600a, GWP 2), propane (R-290, GWP 3), and carbon dioxide (R-744, GWP 1) are some common natural refrigerants in use today. While they are widely used outside the U.S., particularly in Europe, their adoption in the U.S. is constrained by safety codes and equipment requirements.[28] In the U.S., CO_2 is currently used in some heat pump water heaters while propane is used in some ACs and heat pumps. Natural refrigerants are

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[22] U.S. EPA. 2025. *Overview of R-454B Refrigerant Shortage and Current Status*. Available at: https://downloads.regulations.gov/EPA-HQ-OAR-2025-0005-0007/attachment_43.pdf.

[23] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). 2024. *ANSI/ASHRAE Standard 34-2024: Designation and Safety Classification of Refrigerants*. Available at: https://www.ashrae.org/technical-resources/standards-and-guidelines/ashrae-refrigerant-designations.

[24] A 2024 study indicates that R-32 provides about 8 percent higher cooling capacity and 7 percent higher heating capacity than R-410A, while R-454B offers about 3 percent higher cooling efficiency and 2 percent higher heating efficiency than R-32. The study also notes that both refrigerants reduce the required system refrigerant charge relative to R-410A—by approximately 16 percent for R-32 and 9 percent for R-454B. DNV. 2024. *Refrigerants: Taking the Chill Out of Heat Pumps*. p. 7. Available at: https://www.aceee.org/sites/default/files/proceedings/ssb24/assets/attachments/20240722160821125_d5e08544-1392-4f70-83dd-cab5934a66e5.pdf.

[25] Id. pp. 6-8.

[26] European Chemicals Agency. "ECHA supports PFAS restriction with targeted derogations". Available at: https://echa.europa.eu/es/-/echa-supports-pfas-restriction-with-targeted-derogations.

[27] DNV. 2024. *Refrigerants: Taking the Chill Out of Heat Pumps*. p. 7. Available at: https://www.aceee.org/sites/default/files/proceedings/ssb24/assets/attachments/20240722160821125_d5e08544-1392-4f70-83dd-cab5934a66e5.pdf.

[28] New York Department of Environmental Conservation. 2024. *Natural Refrigerants -The 'Future-Proof' Refrigerant Choice*. Available at: https://dec.ny.gov/sites/default/files/2024-08/naturalrefrigerantsfactsheet.pdf.

often less expensive than traditional refrigerants and have similar or improved performance. For example, propane performs similarly to R-22, R-404A, and R-134a.[29] However, the high flammability of propane is a significant barrier, and it is constrained by current U.S. charge-size limits of roughly 300 to 500 grams, which limit its broader adoption.[30] On the other hand, CO_2 is a non-toxic and non-flammable refrigerant that enables heat pumps to produce significantly higher output temperatures—about 90 to 120°C (194 to 248°F), compared with the typical 55 to 65°C (131 to 149°F) range of many other refrigerants.[31] However, CO_2 operates at much higher pressures, which introduces engineering and safety challenges.[32]

4. REFRIGERANT LEAKAGE

All HVAC and refrigeration systems that use refrigerants can experience leaks during equipment manufacture, operation, maintenance, and end of life.[33] Before the Clean Air Act Amendments of 1990 (Section 608), ozone-depleting substances (ODS) were often vented directly into the atmosphere when equipment was retired.[34] In 2016, the prohibition on venting was expanded to include HFC refrigerants, which are not ODS but are potent GHGs.[35] Growing concerns about the climate impacts of refrigerant emissions, along with tightening regulations, have brought the proper recovery, recycling, and destruction of refrigerants into greater focus.

Refrigerants in HVAC systems can leak during initial installation, through ongoing operational losses due to component wear or improper charging, and at end of life when equipment is serviced, dismantled, or removed. To quantify emissions impacts from refrigerant leaks, it is important to understand refrigerant leak rates (the rates at which HVAC systems lose refrigerant) at each stage of equipment life.

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[29] DNV. 2024. *Refrigerants: Taking the Chill Out of Heat Pumps*. Oslo: DNV. p. 8. Available at: https://www.aceee.org/sites/default/files/proceedings/ssb24/assets/attachments/20240722160821125_d5e08544-1392-4f70-83dd-cab5934a66e5.pdf.

[30] Id.

[31] Lyd. 2025. "How hot does water from CO_2 heat pump get?" Available at: https://www.lydheatpump.com/How-hot-does-water-get-from-CO2-heat-pump-id49025136.html; Zhang, Z., Ma, X., Ma, Y., & Zhang, Z. 2019. "Recent advances in transcritical CO_2 (R744) heat pump system: A review." *Energies, 12*(3), 457. Available at: https://doi.org/10.3390/en12030457.

[32] BuildOps. 2023. "What is the primary design challenge for CO_2 refrigeration systems." August 14, Available at: https://buildops.com/resources/co2-refrigeration-systems-design/.

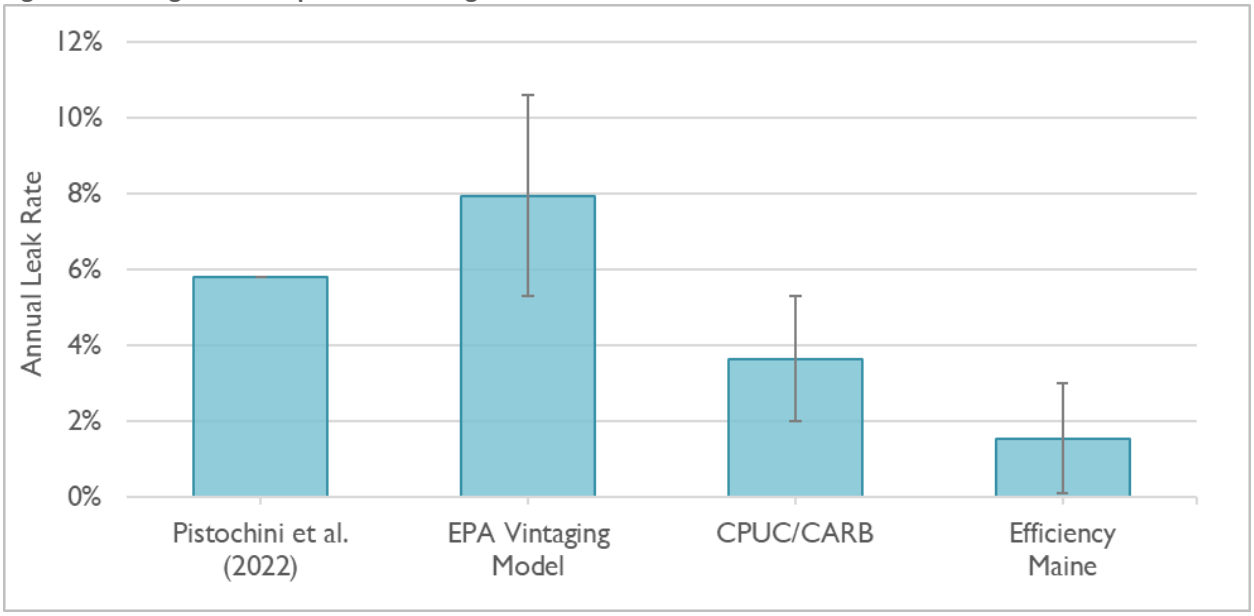
[33] Id.

[34] EPA. Clean Air Act Section 608. Available at: https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-82/subpart-F.

[35] Id.

Studies of refrigerant leak impacts in HVAC equipment indicate that installation-related losses are generally small (0.2 to 1 percent),[36] annual operational leak rates range from 2 to 10 percent of refrigerant charge, and end-of-life leak rates can be substantial, ranging from 18 to 99 percent. Figure 1 summarizes representative annual leak rates from our review of the literature, including state agency estimates from the California Air Resources Board (CARB) and California Public Utilities Commission (CPUC), while Figure 2 presents end-of-life leak rates. Whisker plots in both figures indicate the low and high ends of the leakage estimates. Additional details on the studies we reviewed are provided in Appendix A.

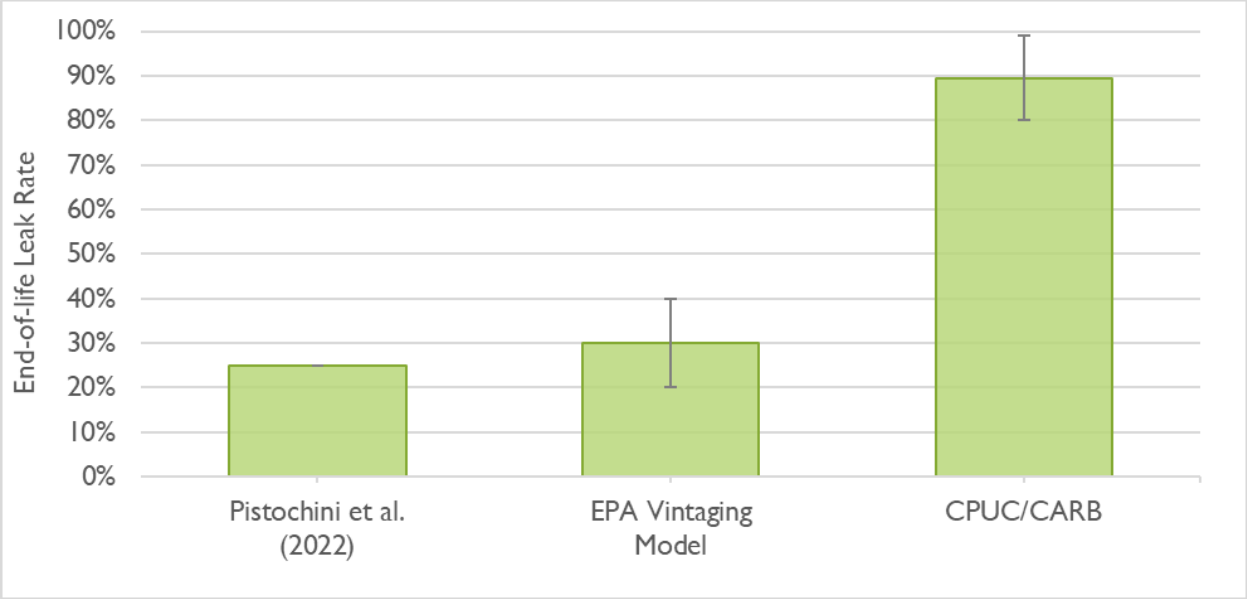
Figure 1. Average annual operational refrigerant leak rates identified in the literature



Sources: Pistochini et.al. 2022. "GHG emission forecasts for electrification of space heating in residential homes in the US". Energy Policy, 163, 112813. Available at: https://www.sciencedirect.com/science/article/pii/S0301421522000386; US EPA. 2019. Annexes to the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2017. Available at: https://www.epa.gov/sites/default/files/2019-04/documents/us-ghg-inventory-2019-annexes.pdf; California Public Utilities Commission. Refrigerant Avoided Cost Calculator. Available at: https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/demand-side-management/acc-models-latest-version/2022-acc-refrigerant-calculator-v1b-updated.xlsx; California Air Resources Board. 2020. 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. Available at: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2020/hfc2020/isor.pdf?_ga=2.118543945.191712348.1765217516-1991801106.1757016463; Efficiency Maine Trust. 2022. Refrigerant Leakage Assessment. Available at: https://www.efficiencymaine.com/docs/EMT_Refrigerants_Report_FINAL_2022-3-14.pdf.

[36] US EPA. 2024. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022 - ANNEX 3 Methodological Descriptions for Additional Source or Sink Categories*. Table A-113. Available at: https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-annex-3-additional-source-or-sink-categories-part-a.pdf.

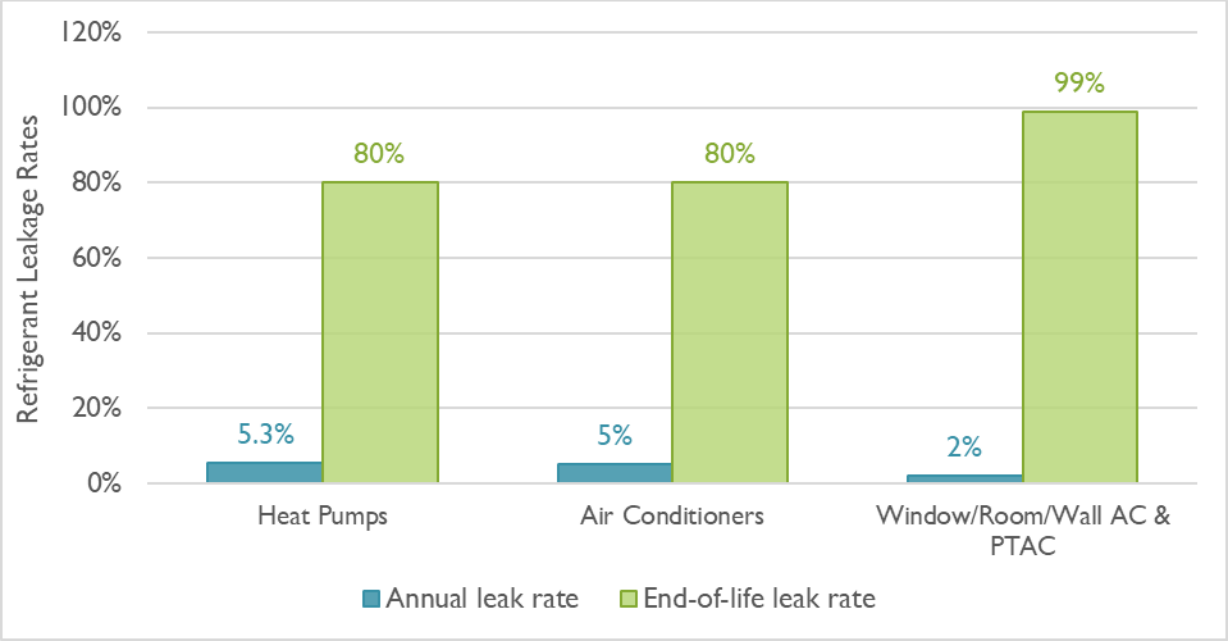
Figure 2. Average end-of-life refrigerant leak rates identified in the literature



Sources: Pistochini et.al. 2022. "GHG emission forecasts for electrification of space heating in residential homes in the US". Energy Policy, 163, 112813. Available at: https://www.sciencedirect.com/science/article/pii/S0301421522000386; US EPA. 2019. Annexes to the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2017. Available at: https://www.epa.gov/sites/default/files/2019-04/documents/us-ghg-inventory-2019-annexes.pdf; California Public Utilities Commission. Refrigerant Avoided Cost Calculator. Available at: https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/demand-side-management/acc-models-latest-version/2022-acc-refrigerant-calculator-v1b-updated.xlsx; California Air Resources Board. 2020. 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. Available at: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2020/hfc2020/isor.pdf?_ga=2.118543945.191712348.1765217516-1991801106.1757016463; Efficiency Maine Trust. 2022. Refrigerant Leakage Assessment. Available at: https://www.efficiencymaine.com/docs/EMT_Refrigerants_Report_FINAL_2022-3-14.pdf.

Leak rates also differ by refrigerant and system type. As previously noted, we expect lower end-of-life leakage rates for more highly flammable A3 refrigerants. Figure 3 compares the average annual and end-of-life leak rates by system type, as developed by CARB. With current A1 and A2L refrigerants, small packaged systems such as window, room, and wall ACs and packaged terminal air conditioner (PTAC) units have very high estimated refrigerant losses at end of life. This is likely because these units are frequently discarded without effective refrigerant recovery, releasing refrigerants directly into the atmosphere.

Figure 3. Annual and end-of-life refrigerant leak rate by system type, as percentage of full system charge



Source: California Air Resources Board. 2020. 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. Available at: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2020/hfc2020/isor.pdf?_ga=2.118543945.191712348.1765217516-1991801106.1757016463

5. GHG EMISSIONS IMPACTS FROM REFRIGERANTS

We conducted two complementary analyses to evaluate the GHG emissions impacts of refrigerant leakage across the 13 jurisdictions in the OTC region: Connecticut, Delaware, the District of Columbia, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and Virginia. The first, a **state-level scenario analysis**, estimates the extent to which refrigerant GHG emissions reduce the total emissions benefits of residential building electrification. The second, a **household-level sensitivity analysis**, considers how much refrigerant-related emissions can vary under different leakage rates and refrigerant mix assumptions. These analyses are discussed below.

5.1. State-level scenario analysis of refrigerant impacts

In March 2025, NESCAUM and the OTC released an updated report estimating the criteria pollutant and GHG reduction potential of residential building electrification across the 13 Northeast and Mid-Atlantic jurisdictions that comprise the OTC.[37] That analysis used NREL's ResStock model to estimate emissions

[37] NESCAUM. 2025. Residential Building Electrification in the Northeast and Mid-Atlantic: Criteria Pollutant and Greenhouse Gas Reduction Potential. Available at: https://www.nescaum.org/documents/25.03.03-ResStock-Updated-FINAL.pdf.

impacts from Space Heating Electrification, Water Heating Electrification, and Whole Home Electrification scenarios based on modeled household energy consumption. The study found that residential electrification would significantly reduce CO_2 emissions, even after accounting for the power plant emissions due to increased electricity demand, with even greater long-term benefits as the electric grid decarbonizes. However, the CO_2 results reported in the NESCAUM/OTC study did not account for GHG emissions associated with potential refrigerant leakage from heat pumps and heat pump water heaters.

Scenarios

As a follow-on to the March 2025 study, Synapse Energy Economics conducted an updated analysis on behalf of NESCAUM to incorporate refrigerant-related emissions into the evaluation framework. Specifically, we estimated GHG emissions from refrigerant leakage and calculated net GHG impacts for the same scenarios and states analyzed in the original NESCAUM study:

- **Baseline –** Residential building stock as it existed in 2018.
- **Space Heating Electrification –** Residential furnaces and boilers currently fueled by oil, gas, propane, and electric resistance, as well as central air conditioners, are replaced by high-efficiency variable-speed heat pumps.
- **Water Heating Electrification –** Water heaters currently fueled by oil, gas, propane, or electric resistance are converted to one of three types of heat pump water heaters, based on size (50, 66, and 80 gallons).
- **Whole Home Electrification –** Furnaces and water heaters fueled by oil, gas, propane, or electric resistance, and central air conditioners, are replaced by heat pumps as specified in the above scenarios. This scenario also assumes that fossil fuel clothes dryers and cooking appliances are converted to heat pump and induction technology.

Each of these scenarios was evaluated under two emissions cases:

- **Current Refrigerants/Current Grid ("Current") case –** Electrification scenarios applied to the baseline building stock, using refrigerants currently prevalent in the market as of 2026 and the 2024 grid emissions intensity.[38]
- **Future Refrigerants/Future Grid ("Future") case –** Electrification scenarios applied to the baseline building stock in a future year (2044), assuming lower-GWP refrigerants dominate the market, and the electric grid has significantly lower emissions intensity.

[38] NESCAUM's initial analysis was conducted in 2024 using 2024 grid assumptions. We chose to use the 2026 refrigerant market for this follow-on analysis to account for the market transition to A2L refrigerants spurred by EPA's Technology Transitions Rule beginning in 2025. As such, while the refrigerant and grid assumptions are based on slightly different years, this follow-on report better reflects current market conditions than it would with 2024 refrigerants that have since been phased out in most new equipment.

Methods and Assumptions

We used annual energy consumption outputs (in million British Thermal Units, or MMBtu) from the ResStock model used in the original NESCAUM study, along with assumed system capacity factors (tons of system capacity per MMBtu of energy consumption), to estimate space heating, space cooling, and water heating system capacities (in tons) by state.[39] We derived the capacity factors from system capacity and energy consumption data for each state based on the ResStock model.[40]

We then estimated total refrigerant charge by applying refrigerant-specific charge rates (see Table 2) and calculated total GHG impacts using the estimated charges, along with assumed leak rates and scenario-specific refrigerant stock shares. For R-410A, we applied a charge rate of 1.98 lbs. per ton of capacity, consistent with values reported for LEED-certified buildings.[41] For R-32 and R-454B, we scaled this R-410A rate using capacity improvement factors from a 2024 study of refrigerant leakage impacts, resulting in lower charges per ton.[42] For natural refrigerants (propane, CO_2, ammonia, and isobutane), limited data led us to assume a uniform charge rate equal to the midpoint between the R-32 and R-410A values shown in Table 2.

Table 2. Refrigerant charge rate assumptions

Type	Charge rate (lbs./ton of capacity)
R-410A	1.98
R-454B	1.80
R-32	1.66
Propane/CO_2/Ammonia/Isobutane	1.82

Source: Rattenbury, J. M. 2020. Enhanced refrigerant management and LEED-NC v4 EA credit 6; Hoover, et al.. 2024. "Refrigerants: Taking the Chill Out of Heat Pumps." In Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings.

To estimate the GHG emissions associated with refrigerant leakage, we drew on the literature review discussed in Section 4, supplemented by consultations with industry experts. Based on this combined input, we developed the refrigerant assumptions shown in Table 3 for use in the emissions analysis.

[39] The original NESCAUM study used outputs from the "2022.1" version of ResStock. This analysis includes cooling system capacities because space cooling systems also use refrigerants.

[40] We used the "ResStock Dataset 2024.2" version for the capacity and consumption data for this analysis because the "2022.1" version of ResStock does not include system capacity data. ResStock datasets are available at: https://resstock.nlr.gov/datasets.

[41] Rattenbury, J. M. 2020. *Enhanced refrigerant management and LEED-NC v4 EA Credit 6*. Available at: https://pdhonline.com/courses/m496/m496content.pdf.

[42] Hoover, et al.. 2024. "Refrigerants: Taking the Chill Out of Heat Pumps." In Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings. Available at: https://www.aceee.org/sites/default/files/proceedings/ssb24/assets/attachments/20240722160821125_d5e08544-1392-4f70-83dd-cab5934a66e5.pdf

Table 3. Refrigerant leak and stock share assumptions

Case	Refrigerant type	GWP	Share of the HVAC and water heating stock (%)	Leak rate at installation	Annual leak rate (%)	End-of-life leak rate (%)
Current	R-410A	2,088	20%	0.5%	5%	80%
Current	R-454B	466	40%	0.5%	5%	80%
Current	R-32	675	40%	0.5%	5%	80%
Current	Propane/CO_2/Ammonia/Isobutane	2	0%	0.5%	5%	20%
Future	R-410A	2,088	0%	0.5%	5%	60%
Future	R-454B	466	25%	0.5%	5%	60%
Future	R-32	675	25%	0.5%	5%	60%
Future	Propane/CO_2/Ammonia/Isobutane	2	50%	0.5%	5%	20%

Across all refrigerant types and scenarios, we assume a 0.5 percent installation leak rate and a 5 percent annual leak rate. For A1 and A2L refrigerants currently in use, we apply an 80 percent end-of-life leak rate in 2026, consistent with assumptions developed by CARB. For highly flammable, ultra-low-GWP A3 refrigerants (e.g., R-290 propane and R-600a isobutane), we assume a substantially lower end-of-life leak rate of 20 percent, reflecting expected handling restrictions and a reduced likelihood of venting due to flammability.[43] For NESCAUM's Future case, we assume a 60 percent end-of-life leak rate for A1 and A2L refrigerants, reflecting anticipated improvements in refrigerant recovery, recycling, and end-of-life management practices over time. Although operational leak rates may also decline over time as equipment designs and servicing practices improve, the analysis conservatively assumes the same annual operational leak rate across Current and Future cases due to uncertainty regarding the magnitude of potential improvements.

We assume different distributions of refrigerant shares under the Current and Future cases across all electrification scenarios. Under the Current case, which represents a mix of refrigerants prevalent in today's market, we assume a 20 percent share for R-410A, reflecting its recent production phaseout under the AIM Act and the continued sale of existing R-410A equipment stock manufactured or imported prior to January 1, 2025. We assume that the remaining 80 percent of refrigerant stock consists of newer A2L refrigerants, R-454B and R-32, with an equal 40/40 percent split. **Notably, we apply this refrigerant mix even for the baseline scenario, which assumes no electrification upgrades.** This is a simplified assumption that results in a conservative comparison of emissions between the measure scenarios and the baseline, because most existing heating and cooling systems currently use R-410A. Under the Future case, we assume that ultra-low-GWP refrigerants—including propane, CO_2, ammonia, and isobutane—account for 50 percent of refrigerants used in HVAC and water heating

[43] This expectation assumes enhanced safety protocols for flammable refrigerants like propane (*see* Marley Mary, "Refrigerant Flammability: A Growing Risk for Facility Safety," Unison Risk Advisors, November 5, 2025; and Berg Chilling Systems, "Ensuring Safety in Propane Refrigeration: Protecting People and Property in Industry," accessed July 30, 2026), and improvements in refrigerant management practices and enforcement over the 18-year period between 2026 and 2044.

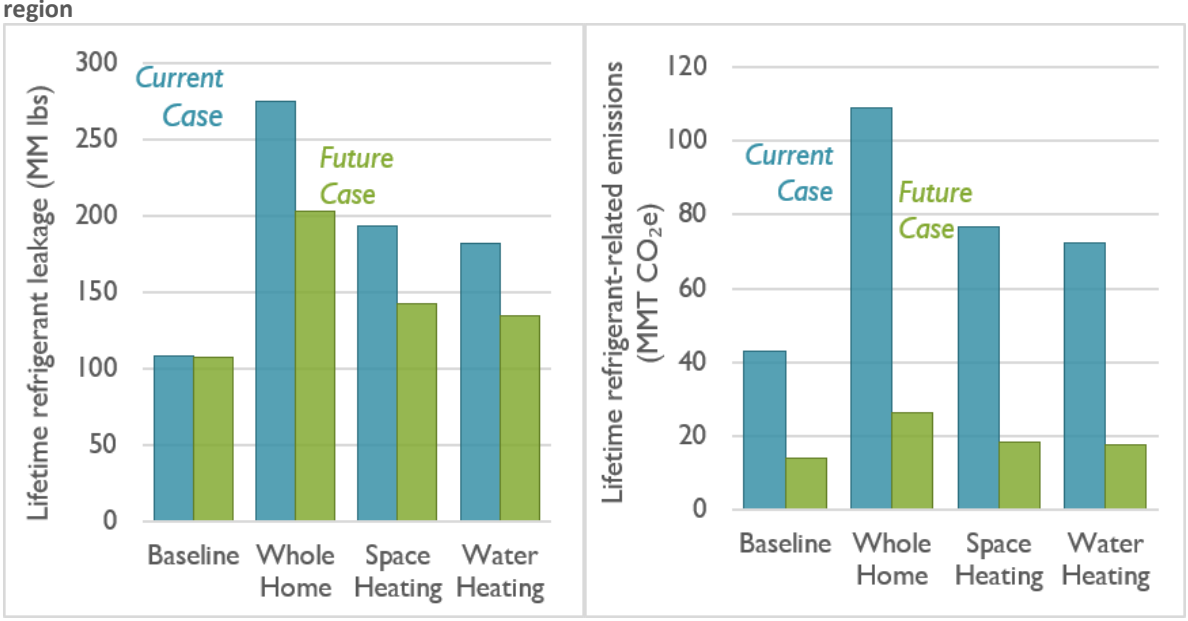
equipment. We assume the remaining 50 percent consists of R-454B and R-32, split evenly between the two refrigerants.

Finally, to ensure a consistent comparison across scenarios, it is important to note that the baseline scenario includes households with fossil fuel-based space heating systems and conventional air conditioners, and therefore includes refrigerant emissions associated with those air conditioning systems. Accordingly, we present results as the **incremental refrigerant-related impacts of electrification scenarios relative to the baseline**, net of refrigerant emissions from baseline air conditioning equipment.

Results – Total Refrigerant Leakage and Emissions Across All Scenarios

Figure 4 shows total lifetime refrigerant leakage (million pounds, left panel) and associated GHG emissions (million metric tons of CO_2e, right panel), aggregated across all OTC jurisdictions by scenario. The results show that differences across scenarios are driven primarily by assumptions about refrigerant mix rather than by total leakage alone. Under the Current case, the electrification scenarios—Whole Home, Space Heating, and Water Heating—lead to substantial increases in refrigerant-related GHG emissions relative to the Baseline scenario, reflecting the expanded use of heat pumps with higher-GWP refrigerants. In contrast, under the Future case, which assumes a transition to lower-GWP refrigerants, refrigerant-related GHG emissions decline dramatically—by roughly 76 percent relative to the Current case. Notably, these Future case emissions also fall substantially below the Baseline scenario under the Current case, even though the electrification scenarios involve greater total refrigerant use.

Figure 4. Lifetime (15-year) refrigerant leakage (left) and associated GHG emissions (right) by scenario, OTC region



Changes in total refrigerant leakage between the two cases, shown in the left panel of Figure 4, primarily reflect differences in refrigerant mix and associated leakage assumptions. In the Baseline

scenario, total leakage under the Future case (about 107.6 million pounds) is only slightly lower—by roughly 0.5 percent—than under the Current case (about 108.1 million pounds). Although natural refrigerants account for 50 percent of the refrigerant share in the Future case, the analysis assumes the same annual leak rate (5 percent) for natural refrigerants, R-454B, and R-32. As a result, operating leakage remains largely unchanged. The modest reduction in the Baseline scenario is therefore primarily attributable to lower assumed end-of-life leakage, with natural refrigerants assumed to have a 20 percent end-of-life leak rate compared with 60 percent for synthetic refrigerants.

In contrast, the electrification scenarios show larger reductions in lifetime leakage between the Current and Future cases, ranging from roughly 275 (Current) to 200 (Future) million pounds in the Whole Home scenario, from about 190 to 140 million pounds in the Space Heating scenario, and from approximately 180 to 135 million pounds in the Water Heating scenario—reductions of roughly 26 percent. These larger reductions occur because the electrification scenarios increase heat pump deployment, which causes a greater share of the equipment stock to be subject to the Future refrigerant assumptions, including lower end-of-life leak rates.

GHG emissions impacts from refrigerant leakage are highly sensitive to refrigerant GWP, leading to much larger differences between the Current and Future cases, as shown in Figure 4. In the electrification scenarios, refrigerant-related GHG emissions decline by approximately 76 percent from the Current case to the Future case: from about 109 to 26 million metric tons of carbon dioxide equivalent (MMT CO_2e) in the Whole Home scenario, from roughly 77 to 19 MMT CO_2e in the Space Heating scenario, and from approximately 72 to 18 MMT CO_2e in the Water Heating scenario. As a result, even though residential building electrification increases refrigerant use, the adoption of lower-GWP refrigerants substantially mitigates the associated climate impacts. In fact, refrigerant-related emissions in the Future case electrification scenarios are lower than those in the Baseline Current case, despite the substantially greater deployment of heat pumps containing refrigerants.

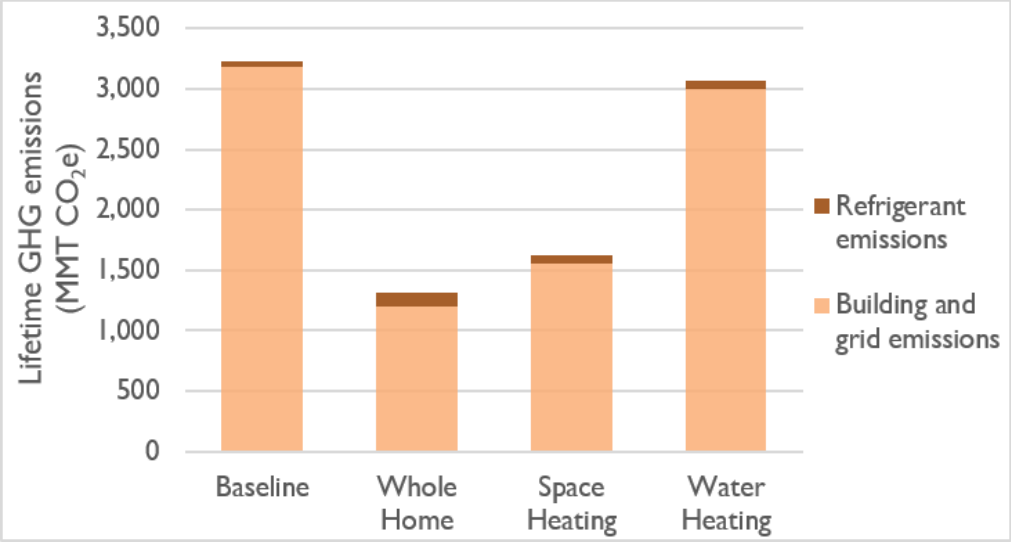
Results - Refrigerant Impacts on GHG Emissions Savings

Figure 5 shows lifetime GHG emissions across the Baseline and three electrification scenarios, including building and grid emissions and refrigerant leakage emissions under Current case assumptions. The central finding is that the increased GHG emissions from refrigerant leakage associated with electrification are small relative to the reductions in building and grid emissions achieved through heat pump adoption.

The Whole Home electrification scenario provides the greatest reduction in lifetime GHG emissions relative to the Baseline, reducing emissions from approximately 3,229 to 1,312 MMT CO_2e, representing a 59 percent decrease. The Space Heating scenario reduces lifetime GHG emissions by approximately half relative to the Baseline, while the Water Heating electrification scenario has a comparatively smaller impact of 5 percent. Refrigerant-related emissions represent a relatively small share of total lifetime emissions across all scenarios, ranging from approximately 1 percent in the Baseline to 8

percent in the Whole Home scenario. Although refrigerant emissions account for a larger percentage of total emissions in scenarios with greater electrification, they remain a small share of total emissions and therefore do not undermine the significant GHG benefits associated with residential building electrification.

Figure 5. Lifetime (15-year) GHG emissions by scenario in the Current case, OTC region



The Future case results shown in Figure 6 follow the same general pattern as the Current case results, with the Whole Home scenario producing the greatest reduction in lifetime GHG emissions, followed by the Space Heating and Water Heating scenarios. Under the Future case assumptions of a transition to ultra-low GWP refrigerants, however, refrigerant emissions represent an even smaller share of lifetime GHG emissions across all scenarios.

Figure 6. Lifetime (15-year) GHG emissions by scenario in the Future case, OTC region

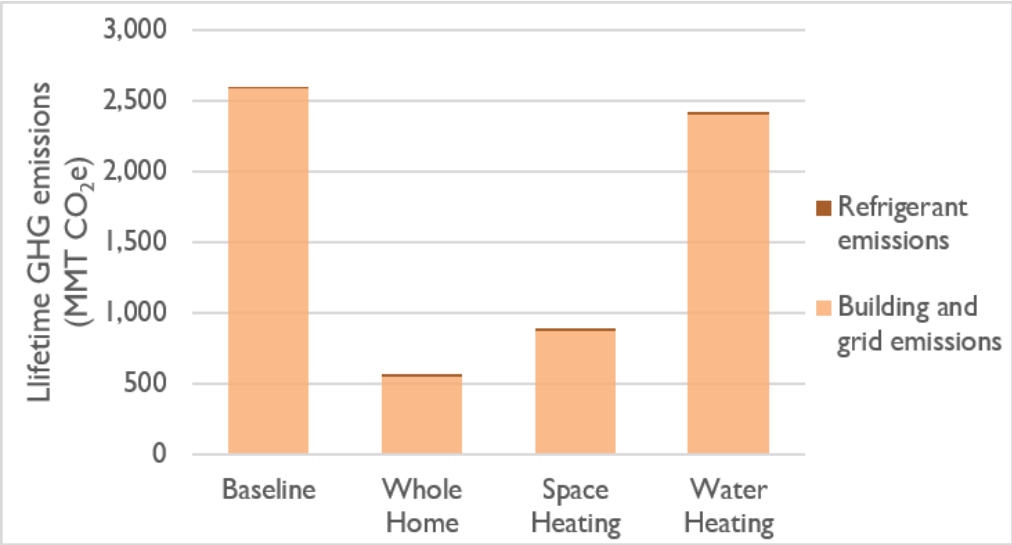


Figure 7 shows the impact of refrigerant emissions on total GHG savings from Whole Home Electrification, in aggregate across the OTC region. In the graph, the bars represent total lifetime GHG savings for the Whole Home Electrification scenario compared to the Baseline scenario, while the hatched area represents the reduction in savings due to refrigerant leakage. The solid portion of the bars shows the GHG savings for Whole Home Electrification after accounting for refrigerant emissions. Our analysis finds that the GHG emissions associated with refrigerant leakage reduce the total GHG savings from Whole Home Electrification by approximately 3.3 percent in the Current case and by about 0.6 percent in the Future case. The smaller impact in the Future case reflects the expected transition to low- and ultra-low-GWP refrigerants (e.g., CO_2 and propane), which reduces the GHG effects of refrigerant emissions.

Figure 7. Lifetime (15-year) GHG savings for the Whole Home Electrification scenario, OTC region



Table 4 and Table 5 present state-level GHG emissions savings for the Whole Home Electrification scenario before and after accounting for refrigerant leakage. In the Current case, refrigerant leakage reduces GHG emissions savings (from the NESCAUM Residential Report) by a small amount: from a low of 1.9 percent in Delaware to a high of 4.8 percent in Maine, with a region-wide reduction of 3.3 percent (Table 4). In the Future case, the reduction is smaller, ranging from 0.1 percent in Virginia to 1.2 percent in Maine, with a region-wide reduction of 0.6 percent (Table 5). Detailed jurisdiction-specific results for all electrification scenarios are provided in Appendix B.

Table 4. Current Case: state-by-state GHG emissions savings for the Whole Home Electrification scenario

State	Current Case			
	CO_2 savings before refrigerant leakage (MMT CO_2)	GHG emissions increase from refrigerant leakage (MMT CO_2e)	GHG emissions savings after refrigerant leakage (MMT CO_2e)	Reduction in GHG savings due to refrigerant leakage (%)
CT	111.4	3.7	107.6	3.3%
DC	12.3	0.4	11.9	3.4%
DE	25.3	0.5	24.8	1.9%
MA	203.5	7.8	195.7	3.8%
MD	130.2	2.7	127.5	2.1%
ME	63.3	3.1	60.2	4.8%
NH	55.9	2.2	53.8	3.8%
NJ	234.3	6.4	227.9	2.7%
NY	582.7	20.9	561.8	3.6%
PA	343.6	12.5	331.1	3.6%
RI	37.9	1.3	36.6	3.5%
VA	152.6	3.2	149.3	2.1%
VT	30.8	1.4	29.4	4.7%
Region-Wide	**1,983.7**	**66.1**	**1,917.7**	**3.3%**

Note: "CO_2 savings before refrigerant leakage" reflects reductions in combustion- and electricity-related CO_2 emissions before accounting for refrigerant leakage impacts. "GHG emissions increase from refrigerant leakage" represents incremental refrigerant-related emissions under the electrification scenario relative to the Baseline, expressed in CO_2e.

Table 5. Future Case: state-by-state GHG savings for the Whole Home Electrification scenario

State	Future Case			
	CO_2 savings before refrigerant leakage (MMT CO_2)	GHG emissions increase from refrigerant leakage (MMT CO_2e)	GHG emissions savings after refrigerant leakage (MMT CO_2e)	Reduction in GHG savings due to refrigerant leakage (%)
CT	113.8	0.8	113.0	0.7%
DC	11.2	0.1	11.1	0.6%
DE	20.7	0.0	20.7	0.2%
MA	220.0	1.6	218.3	0.7%
MD	113.7	0.2	113.4	0.2%
ME	59.2	0.7	58.5	1.2%
NH	56.4	0.5	55.9	0.8%
NJ	249.6	1.1	248.6	0.4%
NY	658.3	4.3	654.0	0.7%
PA	358.8	2.4	356.4	0.7%
RI	37.5	0.3	37.2	0.7%
VA	110.1	0.1	110.0	0.1%
VT	31.4	0.3	31.1	1.1%
Region-Wide	**2,040.7**	**12.4**	**2,028.3**	**0.6%**

Note: "CO_2 savings before refrigerant leakage" reflects reductions in combustion- and electricity-related CO_2 emissions before accounting for refrigerant leakage impacts. "GHG emissions increase from refrigerant leakage" represents incremental refrigerant-related emissions under the electrification scenario relative to the Baseline, expressed in CO_2e.

5.2. Household-level analysis of refrigerant impacts

We conducted a household-level sensitivity analysis to show the potential range of refrigerant leakage and associated GHG impacts resulting from different refrigerant types and leak rate assumptions. This analysis is based on a scenario in which an "average" New York household[44] switches from a gas heating system to a heat pump in 2026 and operates the system over a 15-year period.[45] It does not account for potential additional GHG emissions from an existing air conditioning system that may operate alongside the gas heating system. These emissions could also be reduced or eliminated by a heat pump providing both heating and cooling, making this comparison conservative with respect to the GHG benefits of switching to a heat pump.

We estimated and compared the cumulative emissions impacts of operating a heat pump over a 15-year period under multiple refrigerant scenarios with emissions from continued use of a gas heating system. Details of the scenarios and key assumptions are presented in Table 6. We developed three refrigerant

[44] For the purposes of identifying a "representative" individual home, we assumed that the home was located in New York. New York has the largest population among the OTC states and is situated near the geographic center of the OTC region.

[45] This analysis uses refrigerant emissions rates for 2026, while using 2024 grid emissions rates to remain consistent with the grid emissions assumptions used for the Current case in NESCAUM's original ResStock report.

scenarios—ultra-low GWP, low GWP, and high GWP—and applied both low- and high-leakage sensitivity assumptions, resulting in six scenarios. The assumed leakage rate ranges are based on our literature review and consultation with industry experts (see Section 4). The total system capacity (tons) reflects the average heat pump size for households in New York, based on outputs from the ResStock model.[46]

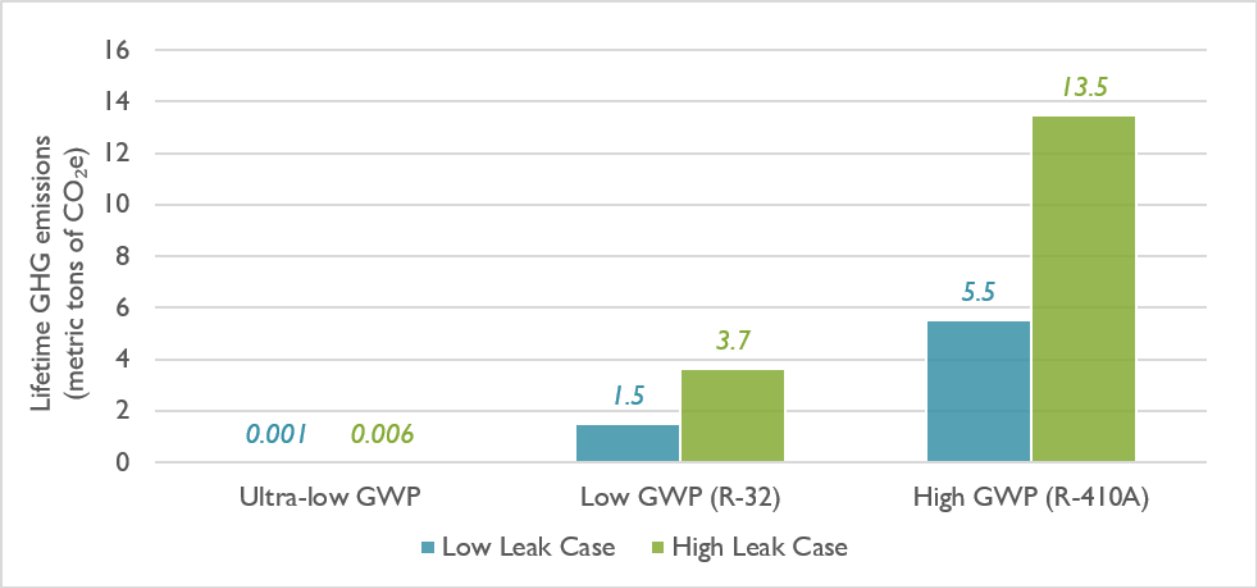
Table 6. Illustrative household-level sensitivity analysis assumptions

Scenario	Refrigerant and sensitivity	GWP	Heat Pump System size (tons)	System life	Charge rate (lbs./ton)	Total charge (lbs.)	Leak rate at installation (%)	Annual leak rate (%)	End-of-life leak rate (%)
Ultra-low GWP	*Propane/CO2/Ammonia/Isobutane*								
	Low Leak	1.5	3.3	15	1.82	5.9	0.5%	2%	0%
	High Leak	1.5	3.3	15	1.82	5.9	0.5%	8%	20%
Low GWP	*R-32*								
	Low Leak	675	3.3	15	1.66	5.4	0.5%	2%	60%
	High Leak	675	3.3	15	1.66	5.4	0.5%	8%	100%
High GWP	*R-410A*								
	Low Leak	2,088	3.3	15	1.98	6.4	0.5%	2%	60%
	High Leak	2,088	3.3	15	1.98	6.4	0.5%	8%	100%

Figure 8 illustrates the cumulative 15-year GHG emissions from refrigerant leakage for an average New York household under the six sensitivity scenarios, all of which use the same current grid emissions assumption. The results show that both refrigerant type and leak rate assumptions materially influence total emissions. Under the ultra-low-GWP scenario, refrigerant-related emissions are negligible in both the low- and high-leak cases. In contrast, for low-GWP refrigerants such as R-32, cumulative emissions increase to about 1.5 metric tons of CO_2e in the low-leak case and 3.7 metric tons of CO_2e in the high-leak case. The largest impacts occur under the high-GWP (R-410A) scenario, where emissions rise to approximately 5.5 metric tons of CO_2e in the low-leak case and 13.5 metric tons of CO_2e in the high-leak case.

[46] The data are available in "metadata_and_annual_results" files available at: https://resstock.nrel.gov/datasets.

Figure 8. Cumulative GHG emissions impacts from refrigerant leakage for an average household in the high-leak and low-leak cases over 15 years



To fully assess lifetime emissions impacts from heat pumps, it is also necessary to account for the grid emissions associated with the electricity they consume, in addition to refrigerant leakage emissions. In New York, an average household uses approximately 46 MMBtu of gas annually for space heating, emitting approximately 2.4 metric tons of CO_2 per year, or approximately 37 metric tons over 15 years.[47] If this household converts from a gas heating system to a heat pump, it would consume about 3,800 kilowatt-hours (kWh) per year, assuming a coefficient of performance (COP) of 2.85 (285 percent) based on ResStock model results.[48] Assuming the current grid emissions rate remains constant, this electricity use results in approximately 0.56 metric tons (1,228 pounds) of CO_2 per year, or 8.35 metric tons over a 15-year equipment lifetime.[49]

When these current grid emissions impacts are combined with refrigerant-related emissions, the total lifetime emissions from a heat pump range from approximately 8 metric tons of CO_2e under an ultra-low-GWP refrigerant/low leakage scenario to approximately 22 metric tons under a high-GWP refrigerant/high-leakage scenario, using R-410A.

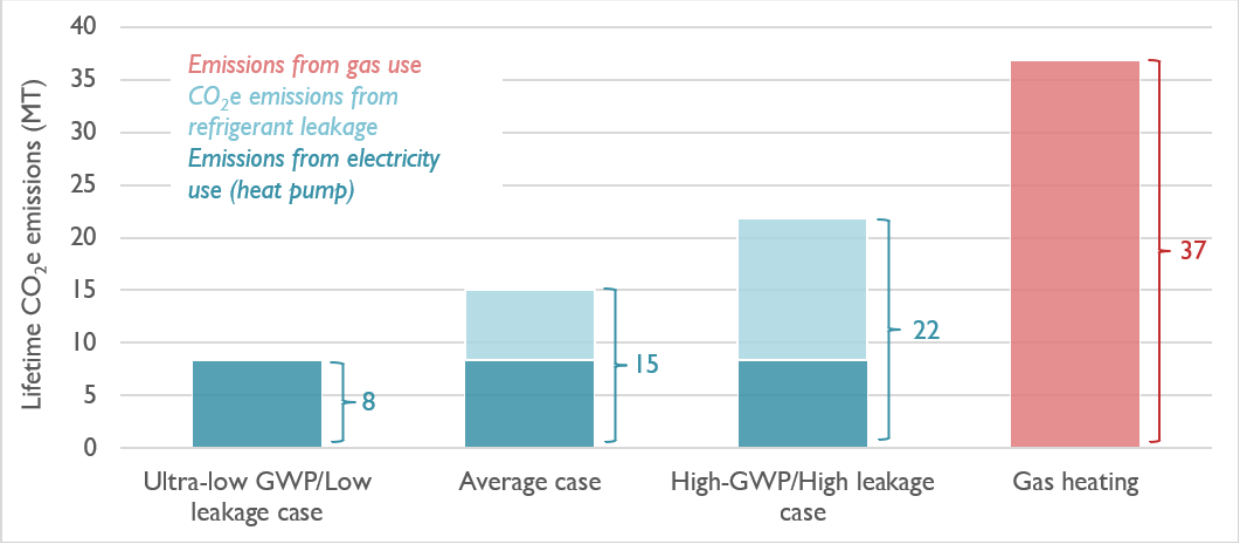
[47] 1 MMBTU of gas combustion produces approximately 117 lbs. of CO_2, or 0.053 metric tons.

[48] The average efficiency of gas heating is about 80 percent per ResStock model results. Thus, the average space heating demand is about 44 MMBtu based on the average gas use of 55 MMBtu (or 12,895 kWh). With the average heat pump efficiency of 285 percent, the annual consumption is 4,525 kWh.

[49] 323 lbs/MWh for New York based on NREL standard scenario for 2024. For detailed discussion on emissions rates, see page 25 of NESCAUM. 2025. *Residential Building Electrification in the Northeast and Mid-Atlantic: Criteria Pollutant and Greenhouse Gas Reduction Potential*. Available at: https://www.nescaum.org/documents/25.03.03-ResStock-Updated-FINAL.pdf.

Figure 9 compares the lifetime emissions of a heat pump under the current grid emissions assumption with the emissions from a residential gas furnace over a 15-year period. The heat pump bars show the breakdown of emissions from electricity use (dark blue segment) and refrigerant leakage (light blue segment). In all refrigerant sensitivity cases, heat pump emissions are well below emissions from gas heating. Overall, even under the high-GWP refrigerant/high-leakage case using 2024 grid emissions, lifetime emissions from a heat pump are nearly 40 percent lower than those from gas heating in New York. It is worth reiterating that this scenario is particularly conservative, because it would not apply to most new equipment installed today due to the phaseout of R-410A in most new equipment. Under the ultra-low GWP refrigerant/low-leakage case, lifetime emissions from a heat pump are nearly 80 percent lower than those from gas heating.

Figure 9. Lifetime (15-year) GHG emissions from heat pumps and gas heating in New York, including refrigerant leakage sensitivity ranges



These results are based on 2024 grid emissions rates and therefore likely understate the long-term emissions benefits of heat pumps as the electric grid becomes cleaner. As the grid continues to decarbonize and the transition to lower-GWP refrigerants advances, the emissions advantage of heat pumps will widen considerably. New York has committed to achieving 100 percent zero-emission electricity by 2040. Under a fully decarbonized grid, lifetime GHG emissions from an average heat pump would primarily reflect refrigerant emissions, ranging from nearly zero with ultra-low-GWP refrigerants to approximately 13.5 metric tons of CO_2e under an R-410A high-leakage scenario.

6. CONCLUSIONS AND POLICY IMPLICATIONS

This analysis demonstrates that refrigerant leakage modestly reduces the net climate benefits of residential electrification under today's refrigerant mix and would have a substantially smaller impact

under projected transitions to low-GWP refrigerants. Under the Current case, across the OTC region, refrigerant leakage reduces GHG savings from whole-home electrification by approximately 3.3 percent. Under the Future case with lower-GWP refrigerants and a decarbonized grid, this reduction drops to roughly 0.6 percent regionwide. Reductions in GHG savings due to refrigerant leakage range from 1.9 percent to 4.8 percent by OTC jurisdiction under the Current case and from 0.1 percent to 1.2 percent under the Future case.

At the household level, even with high leakage assumptions and high-GWP refrigerants, lifetime GHG emissions from heat pumps are nearly 40 percent lower than those from gas heating. These assumptions correspond to a worst-case scenario of high leakage, including 100 percent leakage at end of life, for heat pumps using R-410A. While R-410A was the most common refrigerant used in residential heat pumps prior to the transition to A2Ls in 2025, it has been largely phased out in new residential HVAC equipment under the AIM Act. As the electric grid decarbonizes, the emissions advantage of electrification will widen considerably. When paired with ultra-low-GWP refrigerants and a zero-emission grid, on-site lifetime heat pump emissions will approach zero.

These findings support several important policy implications:

- **Building electrification is a robust decarbonization strategy**. Even when refrigerant leakage is included, residential building electrification delivers substantial net GHG reductions across all modeled scenarios, driven by the emissions benefits of fuel switching and grid decarbonization.
- **Refrigerant transition policy significantly enhances the climate benefits of electrification**. Both refrigerant choice and lifecycle management practices will be pivotal in ensuring that heat pumps achieve their full decarbonization potential. Accelerating the adoption of low- and ultra-low-GWP refrigerants, including through implementation of the AIM Act and complementary state policies, can substantially reduce lifetime refrigerant-related emissions from heat pumps.
- **Improved refrigerant management can substantially reduce near-term emissions**. Reducing operational leakage and end-of-life releases, strengthening refrigerant recovery and disposal requirements, and improving technician training can meaningfully reduce emissions. These measures are particularly important for the existing stock of air conditioners and heat pumps using higher-GWP refrigerants such as R-410A.
- **Refrigerant emissions should be incorporated into climate planning and policy design**. Although refrigerant leakage does not materially undermine the climate benefits of electrification, accounting for these emissions reinforces the importance of managing refrigerant transitions alongside building decarbonization so that heat pumps achieve their full, long-term climate potential.

Appendix A. REFRIGERANT LEAK RATES LITERATURE REVIEW

We conducted a literature review of the studies below to collect annual refrigerant leak rates and end-of-life leak rates in the residential and commercial air conditioning and heat pump systems:

- **Pistochini et al. 2022. Greenhouse Gas Emission Forecasts for Electrification of Space Heating in Residential Homes in the U.S.:** This study, conducted by researchers at the University of California, Davis, and supported by the Natural Resources Defense Council (NRDC), evaluates the GHG impacts of replacing natural gas furnaces with electric heat pumps in residential homes. To assess refrigerant-related impacts, the study estimates GWP effects from refrigerant leakage, assuming rates of 0.5 percent at installation, 5.8 percent annually, and 25 percent at end of life, based on emissions factors from the U.S. Environmental Protection Agency's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2018*.[50]
- **EPA Vintaging Model, Annexes to the Inventory of U.S. GHG Emissions and Sinks:** The EPA Vintaging Model is a tool that estimates the consumption and emissions of HFCs and PFCs and the decline of ozone-depleting substance (ODS) consumption and emissions. The Vintaging Model estimates the use and emissions of ODS alternatives from refrigeration, air conditioning, foams, aerosols, solvents, and fire extinguishing by combining historical data with simulations of how new, non-ODS technologies replace older systems over time. It calculates total emissions as the sum of first-fill, annual leakage and servicing, and disposal emissions for each equipment type, while accounting for gradual improvements in leak and disposal rates as newer technologies enter the market.[51]
- **California Public Utilities Commission (CPUC) Refrigerant Avoided Cost Calculator (RACC) and California Air Resources Board:** The RACC is a tool developed by the CPUC to estimate the monetary value of avoided GHG emissions resulting from reducing refrigerant leaks or transitioning to lower-GWP refrigerants.[52] It converts avoided refrigerant emissions into cost savings based on the GHG impacts. It was created to support California's climate and energy efficiency goals and to provide policymakers, utilities, and program administrators with a consistent framework for evaluating the cost-effectiveness of fuel-substitution measures. The RACC uses equipment-specific annual refrigerant leak rates and EOL leak rates derived from

[50] Pistochini et al. 2022. "Greenhouse Gas Emission Forecasts for Electrification of Space Heating in Residential Homes in the U.S." Energy Policy, 163, 112813. Available at: https://www.sciencedirect.com/science/article/pii/S0301421522000386.

[51] EPA. 2019. *Annexes to the Inventory of U.S GHG Emissions and Sinks*. Available at: https://www.epa.gov/sites/default/files/2019-04/documents/us-ghg-inventory-2019-annexes.pdf.

[52] DNV. 2024. *Refrigerant Avoided Cost Calculator and Fuel-Sub Calculator Technical Guidance*. Prepared for the California Public Utilities Commission. Available at: https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/building-decarb/deer_supporting_files_racc-fsc-technical-guidance-document_2024419_racc-fsc_technical_guidance.pdf?.

California Air Resource Board's (CARB) estimates, which are based on CARB's fluorinated gas (F-gas) Inventory. A detailed breakdown of CARB's refrigerant leak estimates is provided in Figure 3. CARB used stationary refrigeration and AC equipment refrigerant usage and loss data provided by the South Coast Air Quality Management District (SCAQMD) and CARB Refrigerant Management Program. The average loss of refrigerant at equipment end of life was based on estimates informed by multiple sources, including a CARB-contracted study by the Armines Center for Energy and Processes, U.S. EPA Vintaging Model estimates, and studies of ozone-depleting substances by the United Nations Environment Programme.[53]

- **Efficiency Maine Refrigerant Leakage Assessment:** Efficiency Maine Trust (EMT) prepared this study at the request of the Maine State Legislature's Joint Standing Committee on Environment and Natural Resources (ENR). ENR asked EMT to review refrigerant leakage issues and identify potential mitigation options. EMT retained Cadmus Group (Cadmus) to evaluate refrigerant leakage rates and associated GHG impacts in Maine's residential and commercial buildings following the passage of LD 226, which phases out high-GWP HFCs. Cadmus quantified statewide refrigerant volumes and refrigerant annual leakage by applying leakage rates based on the Intergovernmental Panel on Climate Change's 2019 estimates and findings from EMT's residential heat pump survey, which reported that refrigerant leakage–related repairs occurred in approximately 2 percent of installations.[54]

[53] California Air Resources Board. 2016. *California's High Global Warming Potential Gases Emission Inventory*. p. 15. Available at: https://ww2.arb.ca.gov/sites/default/files/classic/cc/inventory/slcp/doc/hfc_inventory_tsd_20160411.pdf.

[54] Efficiency Maine Trust. 2022. *Refrigerant Leak Assessment*. pp. 1-3. Available at: https://www.efficiencymaine.com/docs/EMT_Refrigerants_Report_FINAL_2022-3-14.pdf.

Appendix B. State-by-State Net Lifetime GHG Savings for Space Heating and Water Heating Electrification Scenarios

Table 7. Current Case: state-by-state lifetime (15-year) GHG savings for the Space Heating Electrification scenario

State	CO_2 savings before refrigerant leakage (MMT CO_2)	GHG emissions increase from refrigerant leakage (MMT CO_2e)	GHG emissions savings after refrigerant leakage (MMT CO_2e)	Reduction in GHG savings due to refrigerant leakage (%)
CT	92.7	2.1	90.7	2.2%
DC	9.9	0.1	9.8	1.0%
DE	20.2	0.0	20.1	0.1%
MA	168.2	4.8	163.4	2.9%
MD	107.4	0.1	107.3	0.1%
ME	55.4	2.3	53.1	4.1%
NH	48.5	1.5	47.1	3.1%
NJ	190.6	2.7	187.9	1.4%
NY	483.5	12.4	471.1	2.6%
PA	276.0	6.5	269.5	2.3%
RI	32.2	0.8	31.4	2.5%
VA	122.4	-0.5	123.0	-0.4%
VT	27.3	1.1	26.2	4.0%
Region Wide	**1,634.2**	**33.8**	**1,600.5**	**2.1%**

Table 8. Future Case: state-by-state lifetime (15-year) CO_2e savings for the Space Heating Electrification scenario

State	CO_2 savings before refrigerant leakage (MMT CO_2)	GHG emissions increase from refrigerant leakage (MMT CO_2e)	GHG emissions savings after refrigerant leakage (MMT CO_2e)	Reduction in GHG savings due to refrigerant leakage (%)
CT	95.3	0.4	95.0	0.4%
DC	9.2	0.0	9.2	-0.1%
DE	17.7	-0.1	17.8	-0.4%
MA	184.9	0.9	184.0	0.5%
MD	95.8	-0.4	96.2	-0.4%
ME	51.1	0.5	50.6	1.0%
NH	49.0	0.3	48.7	0.6%
NJ	204.7	0.2	204.6	0.1%
NY	558.8	2.2	556.6	0.4%
PA	292.9	1.0	291.9	0.3%
RI	31.8	0.2	31.6	0.5%
VA	89.4	-0.8	90.2	-0.9%
VT	27.9	0.2	27.6	0.9%
Region Wide	**1,709.5**	**4.6**	**1,703.9**	**0.3%**

Table 9. Current Case: state-by-state lifetime (15-year) GHG savings for the Water Heating Electrification scenario

State	CO_2 savings before refrigerant leakage (MMT CO_2)	GHG emissions increase from refrigerant leakage (MMT CO_2e)	GHG emissions savings after refrigerant leakage (MMT CO_2e)	Reduction in GHG savings due to refrigerant leakage (%)
CT	9.6	1.5	8.1	15.3%
DC	1.4	0.3	1.1	20.7%
DE	2.9	0.4	2.5	13.9%
MA	18.3	2.7	15.5	15.0%
MD	13.0	2.3	10.6	18.0%
ME	3.9	0.8	3.1	19.6%
NH	3.8	0.6	3.2	16.2%
NJ	22.9	3.3	19.7	14.3%
NY	51.7	7.9	43.8	15.3%
PA	35.6	5.5	30.2	15.4%
RI	3.1	0.5	2.7	14.4%
VA	18.2	3.3	14.9	18.3%
VT	1.9	0.4	1.6	19.3%
Region Wide	**186.4**	**29.4**	**156.9**	**15.8%**

Note: Refrigerant leakage has a greater proportional impact on net CO_2e savings for water heating compared to space heating because heat pump water heaters deliver smaller energy and emissions savings relative to system capacity.

Table 10. Future Case: state-by-state lifetime (15-year) GHG savings for the Water Heating Electrification scenario

State	CO_2 savings before refrigerant leakage (MMT CO_2)	GHG emissions increase from refrigerant leakage (MMT CO_2e)	GHG emissions savings after refrigerant leakage (MMT CO_2e)	Reduction in GHG savings due to refrigerant leakage (%)
CT	9.6	0.2	9.4	2.2%
DC	1.3	0.0	1.2	2.8%
DE	1.5	0.0	1.5	1.6%
MA	18.7	0.4	18.3	2.2%
MD	10.1	0.1	9.9	1.4%
ME	3.9	0.1	3.8	3.8%
NH	3.8	0.1	3.7	2.5%
NJ	24.2	0.3	23.9	1.3%
NY	54.6	1.2	53.5	2.1%
PA	35.4	0.7	34.7	2.0%
RI	3.1	0.1	3.0	2.3%
VA	12.4	0.1	12.3	1.2%
VT	1.9	0.1	1.9	3.8%
Region Wide	**180.6**	**3.5**	**177.1**	**2.0%**