Hydrofluorocarbon Emissions Inventory and Mitigation Potential in New York State

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Our Mission:

Advance clean energy innovation and investments to combat climate change, improving the health, resiliency, and prosperity of New Yorkers and delivering benefits equitably to all.

Hydrofluorocarbon Emissions Inventory and Mitigation Potential in New York State

Final Report

Prepared for:

New York State Energy Research and Development Authority

Albany, NY

Macy Testani
Project Manager

James Wilcox
Project Manager

Prepared by:

Guidehouse, Inc.

Burlington, MA

William Goetzler
Jim Young
Timothy Sutherland
Jon Caillouet
Valerie Nubbe
Palak Thakur
Project Managers

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Abstract

Building, transportation, and industrial applications throughout New York State use hydrofluorocarbon (HFC) gases for space cooling, food sales and storage, foam, aerosols, and a variety of other processes. HFCs contribute to the State's greenhouse gas (GHG) emissions both directly through refrigerant emissions to the atmosphere and indirectly through the electricity consumption to operate space conditioning and refrigeration systems. NYS is assessing ways to reduce GHG emissions across a variety of sectors including goals underlying the Clean Leadership and Climate Protection Act (Climate Act).

The purpose of this report is to provide the New York State Energy Research and Development Authority (NYSERDA) with an updated and more detailed inventory for HFC gases in New York State; how statewide HFC usage is expected to change in future years, due to economic growth, appliance electrification, and other trends; and the impacts of potential policies that could be considered to significantly reduce HFC emissions. The Guidehouse project team developed a detailed bottom-up vintaging model to calculate historical, current, and future HFC consumption and emissions for over 40 end-use categories and analyze potential HFC Mitigation Scenarios for the State. Based on these findings, the team then identified and recommended policy actions and research, development, and demonstration (RD&D) activities to further reduce HFC emissions and achieve the Climate Act goals.

Keywords

Hydrofluorocarbon, HFC, refrigerant, global warming potential, GWP, air conditioning, refrigeration, heat pump, HVAC, foam, aerosol, solvent, greenhouse gas emissions, phasedown

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Acronyms and Abbreviations

A2L	Refrigerants Classified with Lower Flammability or Mildly Flammable
A3	Flammable Refrigerants
AC	Air Conditioning
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
AIM	American Innovation and Manufacturing
ALD	Automatic Leak Detection
AR4	IPCC Fourth Assessment Report
AR5	IPCC Fifth Assessment Report
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BEA	U.S. Bureau of Economic Analysis
CA	California
CARB	California Air Resource Board
CBECS	Commercial Building Energy Consumption Survey
CBI	Confidential Business Information
CFC	Chlorofluorocarbons
CLCPA	Climate Leadership and Community Protection Act
CO2e	Carbon Dioxide Equivalent
Com.	Commercial
COP	Coefficient of Performance
DEC	Department of Environmental Conservation
DOE	Department of Energy
DX-GSHP	Ground Source Heat Pump with Direct Ground Exchange
EE	Energy Efficiency
EIA	Energy Information Administration
EOL	End of Life
EPA	Environmental Protection Agency
EU	European Union
FDD	Fault Detection and Diagnostics
F-gas	Fluorinated Greenhouse Gases
GHG	Greenhouse Gas
GSHP	Ground Source Heat Pump
GW	Gigawatt
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbons
HFC	Hydrofluorocarbon
HFO	Hydrofluoro-olefin
HOV	Heat of Vaporization

HP	Heat Pump
HPWH	Heat Pump Water Heater
HVAC	Heating, Ventilation, and Air Conditioning
HVAC&R	Heating, Ventilation, Air Conditioning, and Refrigeration
IPCC	Intergovernmental Panel on Climate Change
MMT	Million Metric Tons
MVAC	Motor Vehicle Air Conditioning
NVC	Non-Vapor Compression
NYS	New York State
NYSERDA	New York State Energy Research & Development Authority
ODS	Ozone Depleting Substances
OEM	Original Equipment Manufacturer
PTAC	Packaged Terminal Air Conditioning
PTHP	Packaged Terminal Heat Pump
RD&D	Research, Development, and Demonstration
RECS	Residential Energy Consumption Survey
Res.	Residential
RMP	Refrigerant Management Program
RTU	Roof Top Unit
SCAQMD	South Coast Air Quality Management District
SEER	Seasonal Energy Efficiency Ratio
SIT	State Inventory Tool
SLCP	Short-Lived Climate Pollutant
SNAP	Significant New Alternatives Policy
TEAP	Technology and Economic Assessment Panel
TRM	Technical Reference Manual
TSD	Technical Support Document
UL	Underwriters Laboratories
UN	United Nations
UNEP	United Nations Environment Programme
UNFCCC	United Nation Framework Convention on Climate Change
VRF	Variable Refrigerant Flow
XPS	Expanded Polystyrene

Summary

The purpose of this report is to provide the New York State Energy Research and Development Authority (NYSERDA) with an updated and more detailed inventory for hydrofluorocarbon (HFC) gases in New York State; how statewide HFC usage is expected to change in future years, due to economic growth, appliance electrification, and other trends; and the impacts of potential policies that could be considered to significantly reduce HFC emissions. This report covers a wide variety of HFC end-use categories, including refrigerants used in space conditioning and refrigeration for residential, commercial, industrial, and transport applications, as well as non-refrigerant HFCs used in foams, aerosol propellants, solvents, and fire protection. Newer HFC applications such as heat pump water heaters and clothes dryers—sales of which are expected to increase as the Climate Leadership and Community Protection Act (Climate Act) drives electrification—are also considered. New York State and federal policies as well as global industry trends present an opportunity to significantly reduce HFC-related greenhouse gas (GHG) emissions and ultimately phase out HFC usage; however, policy strategies and research, development, and demonstration (RD&D) support are necessary to facilitate this transition.

Table S-1 summarizes the contents of each section of the report. Guidehouse first reviewed the assessment of HFC emissions in the NYSERDA 2018 New York State Greenhouse Gas Inventory and supporting documentation for the NYSERDA Pathways to Deep Decarbonization in New York State project.[1] Both of these reports are currently being revised by NYSERDA and the Department of Environmental Conservation (DEC) to meet the requirements of the Climate Act. Guidehouse then conducted a thorough literature review of the latest government and industry research into HFC emissions inventories, refrigerant saturations, low global warming potential (GWP) alternatives, and mitigation strategies. Guidehouse also conducted several interviews with industry organizations. This information was used to develop a detailed bottom-up vintaging model to calculate historical, current, and future HFC consumption and emissions for over 40 end-use categories and analyzed potential HFC Mitigation Scenarios for the State. Based on these findings, Guidehouse then identified and recommended policy actions and RD&D activities to further reduce HFC emissions and achieve the Climate Act goals.

Table S-1. Summary of Each Chapter

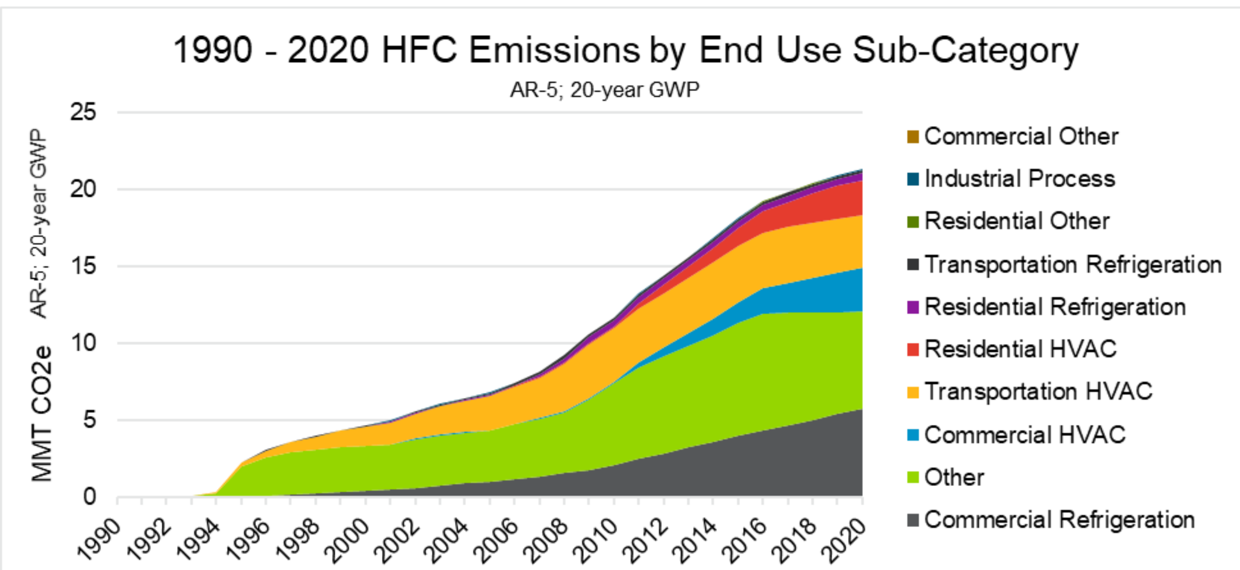
Chapter	Summary
Executive Summary	Brief summary of entire report for wider audience.
1. Introduction	Description of report background, objectives, and technology / market scope.
2. Historical HFC Emissions Inventory	Historical HFC consumption and emissions estimated over 1990-2020 by end-use category, emissions source, and other parameters.
3. Projected Future Reference Cases for HFC Emissions in NYS	Future HFC consumption and emissions projected over 2020-2050 based on expected growth rates, established HFC phasedown policies, and decarbonization pathways to achieve Climate Act goals.
4. Alternatives to High GWP Refrigerants and Leakage Reduction Solutions	Analysis of available low-GWP refrigerants, leakage reduction technologies and policies, and RD&D initiatives to increase their adoption in NYS.
5. Potential HFC Mitigation Scenarios	Analysis of the projected impacts and timelines for several potential mitigation scenarios that could reduce future HFC consumption and emissions in NYS.
6. Conclusions and Recommendations	Summary of key findings, conclusions, and recommendations for NYSERDA, DEC, and other stakeholders to consider when evaluating potential HFC mitigation strategies to achieve Climate Act goals.
7. References	List of references cited throughout the report.
Appendix A. Key Data Inputs and Assumptions	Tables summarizing the Guidehouse model data inputs and assumptions, including sources, GWP values, scenario assumptions, and cost premiums.
Appendix B. HFC Emissions Inventory for NYS	Tables summarizing HFC Emissions Inventory 2005-2020.
Appendix C. Source Documentation for the HFC Emissions Model	Provides details for key data sources and assumptions used in the HFC Emission Model.
Appendix D. Source Documentation for the Scenario Cost Model	Provides details for key data sources and assumptions used in the scenario cost model.
Appendix E. Comparison of HFC Accounting Practices	Explains HFC accounting methodologies and assumptions from various tools and models.
Appendix F. Details for RMP Economic Impact Assessment	Provides details for an earlier cost-benefit analysis performed by the California Air Resources Board on their Refrigerant Management Program.

S-1 Historical Hydrofluorocarbon Emissions Inventory

The foundation for the HFC emissions inventory analysis is an Excel-based vintaging model customized to New York State. For each equipment type, annual HFC consumption and emissions are calculated based on a set of key input assumptions, including refrigerant composition, refrigerant charge size, annual leakage rate, servicing frequency, equipment lifetime, and end-of-life (EOL) loss (i.e., non-recovery) rate. By customizing the input assumptions, a range of business-as-usual growth scenarios, or “reference cases” can be modeled. Against these reference cases, “what-if” scenarios can be modeled to assess the impacts of potential mitigation policies that could be considered to achieve future emissions reduction targets.

Results from the Guidehouse model indicate that HFC emissions in New York State have grown from near zero in 1990 to 21.2 million metric tons (MMT) CO_2e in 2020 (AR-5, 20-year GWP),[2] as shown in Figure S-1. Emissions growth was driven by the use of HFCs to replace chlorofluorocarbons/ hydrochlorofluorocarbons (CFC/HCFC) as they were phased down (primarily) and economic growth in the State (secondarily). In particular, commercial refrigeration, commercial heating, ventilation, and air conditioning (HVAC), and residential HVAC have all shown large increases since 2005. Once all vintage CFC/HCFC equipment has reached an end-of-life condition, future HFC growth will be slower and reflective of economic growth in the State. HVAC and refrigeration (HVAC&R) categories grew most dramatically after 2010, when HFCs became the predominant refrigerant for stationary cooling applications, replacing ozone depleting substances (ODS) refrigerants. HFC use for mobile air conditioning (which began in the 1990s), as well as foams, aerosols, and solvents ("other") has grown only modestly since 2010 and has already begun declining as these categories transition to lower-GWP options. The estimate of 1990 emissions from this analysis was used by DEC to establish certain Climate Act reduction requirements into regulation.[3] All values from this report will be integrated into an updated GHG inventory report, to be issued by DEC in 2021.

Figure S-1. Hydrofluorocarbon Emissions by End-Use Subcategory (1990–2020)



S-2 Projected Future Hydrofluorocarbon Emissions Inventory

Guidehouse developed a series of future reference cases to estimate HFC emissions in New York State during the period 2021–2050, building on the historical HFC inventory (1990–2020) and incorporating the data sources described in section 2.1. Table S-2 highlights the major components of each future reference case, with each reference case building upon the assumptions of the previous reference case. Reference case no. 2 assumes an increased adoption of residential air conditioning systems commensurate with the expectation that climate change will create warmer and more extreme summers. Reference cases no. 3 and 4 are based on the "High Technology Availability Pathway" and the "Limited Non-Energy Pathway," respectively, from the Pathways to Deep Decarbonization in New York State report prepared for NYSERDA by Energy and Environmental Economics, Inc. (E3). These cases assume increasing amounts of building electrification to achieve Climate Act goals, which results in higher projected demand for heat pumps. Reference Case no. 5 includes the aforementioned assumptions from reference cases no. 2 through no. 4, plus the 6 NYCRR Part 494 regulation (2020 NYS SNAP Rule[4]) in effect today. When modeling the potential HFC Mitigation Scenarios in section 5, reference case no. 5 (no. 4 E3's "Limited Non-Energy" Scenario + Implementation of 2020 NYS SNAP Rule) is used as the starting point for evaluating different potential HFC mitigation strategies.[5]

Table S-2. Modeled Reference Cases

Bold highlighted cells denote key change in scenario in relation to previous scenario. Each reference case builds upon the previous reference case.

Key Parameter	Reference Case no. 1	Reference Case no. 2	Reference Case no. 3	Reference Case no. 4	Reference Case no. 5
Description	Business as usual with years 2021–2050 matching year 2020	no.1 + Transition to 100% saturation of Residential AC	no.2 + E3's "High Tech" scenario	no.3 + E3's "Limited Non-Energy" scenario	no.4 + Implementation of 2020 NYS SNAP Rule
Residential AC Saturation	Approx. 90%	**Approx. 100% due to climate change**	Approx. 100% due to climate change	Approx. 100% due to climate change	Approx. 100% due to climate change
HFC Phasedown Policies	None	None	None	None	**2020 NYS SNAP Rule, No further actions**
Low-GWP Leak Rates	None	When new equipment using low-GWP refrigerants enter the market, a 50% reduction in annual leak rate is applied, based on AHRI estimates (Link) for improved design and maintenance practices with flammable and mildly flammable (A2L) refrigerants.			
End-of-Life Recovery	For large systems (e.g., commercial central AC, chillers, warehouse, supermarkets) and transportation, assume relatively high EOL recovery (around 70–80%). For small systems, much lower EOL recovery rates (approximately 0–50%), depending on specific application.				
Building Electrification Policies	None	None	**50% of sales by 2030; 95% by 2050**	**70% of sales by 2030; 100% by 2045**	70% of sales by 2030; 100% by 2045

Figure S-2 highlights the future HFC emissions for New York State under each of the future reference cases (no. 1-5) described in Table S-2. Building electrification is expected to drive a substantial decrease in overall building GHG emissions, but a substantial increase in HFC emissions during the period 2035–2050. Absent mitigation steps, HFC emissions in NYS would increase to approximately 33 MMT CO_2e (AR-5, 20-year GWP, +57% over 2020) due to economic growth, increased residential AC adoption due to climate change (to nearly 100% adoption, up from 91% today), and heating electrification goals (reference case no. 4). The 2020 NYS SNAP Rule restricting the use of high GWP refrigerants for residential and commercial refrigeration, commercial chillers, and other segments is expected to have a significant impact on decreasing future HFC emissions in NYS (reference case no. 5, Green Line) relative to reference case no. 4.

Figure S-2. Hydrofluorocarbon Emissions Across All Reference Cases (1990–2050)

Each reference case builds upon the previous reference case.

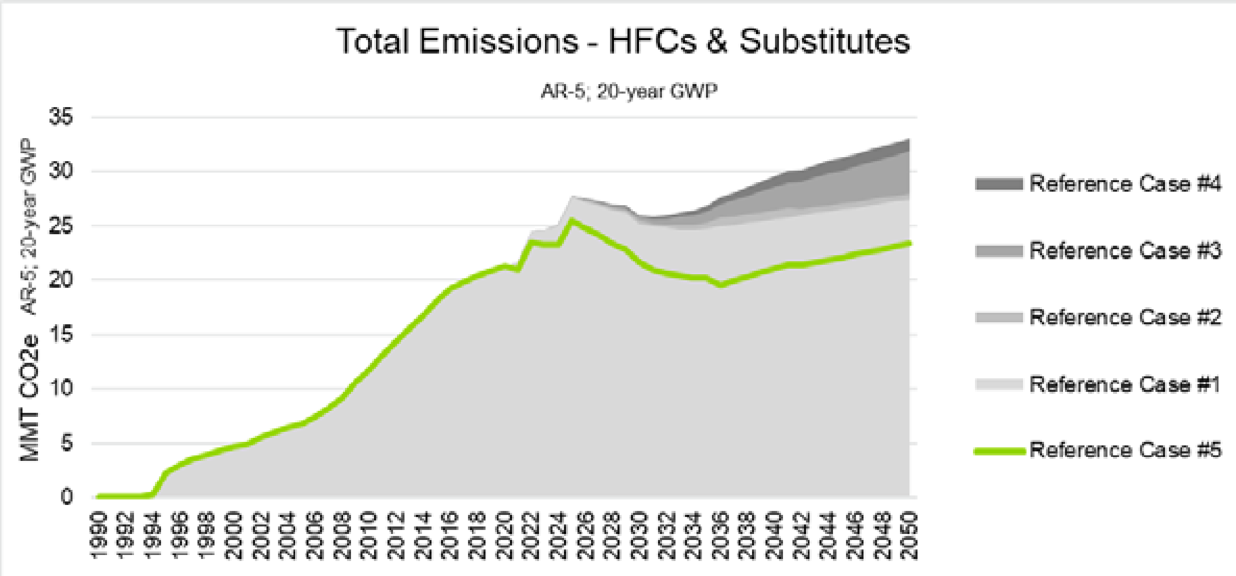
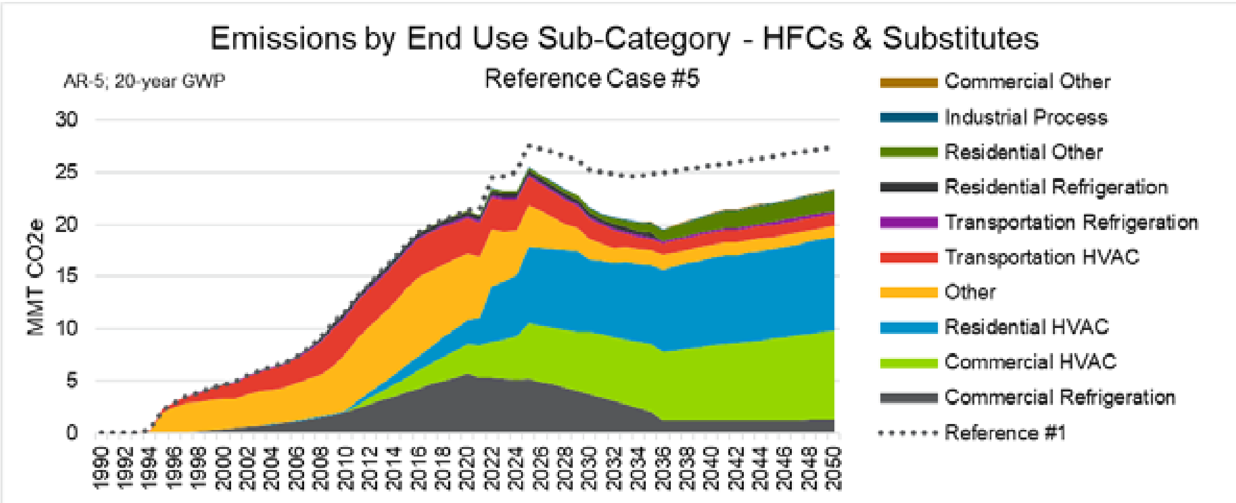


Figure S-3 highlights the HFC emissions by end-use subcategory under reference case no. 5 compared to reference case no. 1. Reference case no. 5 includes maximum adoption of residential AC, space and water heating electrification of 70% by 2030 and 100% by 2045, and the 2020 NYS SNAP Rule. Building electrification strategies are expected to increase HFC emissions for the categories Residential and Commercial HVAC sectors, as well as the Residential Other and Commercial Other, which include Heat Pump Water Heaters (HPWH)s. While building electrification may increase HFC emissions, a building electrification strategy supports overall statewide GHG emission reduction because the technologies help enable a transition away from fossil fuels and overall reductions in statewide emissions.[6] The HFC emissions reduction achieved by the 2020 NYS SNAP Rule is expected to outweigh the impacts of heating electrification (reference cases no. 3–4), resulting in an overall HFC emissions reduction of approximately 30% from reference case no. 1.

Figure S-3. Hydrofluorocarbon Emissions by End-Use Subcategory, Reference No. 5 (1990–2050)

Each reference case builds upon the previous reference case.



S-3 Hydrofluorocarbon Mitigation Scenarios

This section describes Guidehouse's analysis into a range of potential mitigation options that could reduce future HFC consumption and emissions in New York State, including policy and technology approaches. The potential HFC Mitigation Scenarios in this section are compared to a baseline (reference case no. 5) that includes a BAU scenario with electric heat pump adoption of 70% of sales by 2030 and 100% by 2045, as described in the previous section. Table S-3 highlights key attributes of each scenario considered in this section, with additional details provided in appendix A.2. Each scenario considers a collection of potential mitigation options, including the following:

- HFC end-use restrictions or GWP limits.[7]
  - Low-GWP refrigerants have less than 750 GWP (AR4 100-year).
  - Ultra-low-GWP refrigerants have less than 10 GWP (AR4 100-year).[8]
- Charge size reduction for low-GWP refrigerants.
- Leakage reduction for low-GWP refrigerants.
- Greater use of reclaimed refrigerant.
- Greater refrigerant recovery at end-of-life.

Table S-3. Modeled Potential Hydrofluorocarbon Mitigation Scenarios

Bold highlighted cells denote key change in scenario in relation to previous scenario. Each scenario builds upon the previous scenario. Scenarios are compared against reference case no. 5, which assumes maximum residential AC adoption; electric heat pump adoption of 70% of sales by 2030 and 100% by 2045; and the expected impacts of the 2020 NYS SNAP Rule.

Key Parameter	HFC Mitigation Scenario no. 6A	HFC Mitigation Scenario no. 6B	HFC Mitigation Scenario no. 6C	HFC Mitigation Scenario no. 7	HFC Mitigation Scenario no. 8A	HFC Mitigation Scenario no. 8B
Description	Reference Case no. 5+ New Equipment HFC Restrictions in 2024.	no. 6A + Additional New Equipment HFC Restrictions in 2027–2029.	no. 6B + Additional New Equipment HFC Restrictions Post-2030.	no.6C + Currently Recaptured Refrigerant Used for Maximum Possible Service Reclaim.	no.7 + Increased Recapture for Large Systems to Increase Maximum Possible Service Reclaim.	no.8A + Increased Recapture for Small Systems to Increase Maximum Possible Service Reclaim.
Equipment Restriction Policies	**Phase I (2024)**: Low-GWP for commercial and residential room AC/HP, industrial systems, transport HVAC; and supermarket racks to ultra-low GWP options.	**Phase II (2027-2029)**: Building code updates to allow for low-GWP for commercial central & ductless AC/HP and residential whole-home AC/HP; low-GWP for transport refrigeration; ultra-low-GWP for commercial icemakers and water heating, warehouses, residential water heating and clothes drying.	**Phase III (Post 2030)**: max tech adoption of ultra-low-GWP technologies (<10 GWP) for all residential and commercial AC/HP, chillers (med & small), walk-ins, industrial systems, all residential AC.	Same as no. 6 A, B, C		
Use of Reclaimed Refrigerant	No change in current practice.			**100% of recovered refrigerant at end-of-life is applied to HFC service demand.**	Same as no. 7, but with greater reclaim supplies available due to higher end-of-life recovery rate.	
Low-GWP Leak Rates	When new equipment using low-GWP refrigerants enter the market, a 50% reduction in annual leak rate is applied, based on AHRI estimates for improved design and maintenance practices associated with flammable and mildly flammable (A2L) refrigerants.					
End-of-Life Recovery	Assume same EOL recovery rate as Reference Cases for each end-use.				**Recovery rates increase to 90% for large end-uses starting in 2024 (current loss rates are 20-30%).**	**Recovery rates increase to 90% for large and small end-uses starting in 2024 (current loss rates are 50–80%+ for small end-uses).**

Figure S-4 shows the HFC emissions profile over the period 1990–2050 for each of the potential mitigation scenarios (designated scenario no. 6A, no. 6B, no. 6C, no. 8A, and no. 8B respectively) in comparison to the reference case no. 5, which includes heating electrification. Scenario no. 7 would reduce HFC consumption by using refrigerant currently recovered (and already reflected in the reference cases) for servicing needs but would have no additional impact on HFC emissions and is therefore omitted from the figure. Potential HFC Mitigation Scenarios no. 6A, B, C and no. 8A, B demonstrate successively lower emissions during the period 2030–2050, reflecting that each scenario builds upon the potential mitigation options of the previous scenario. Because the AIM Act and Kigali Amendment target HFC consumption rather than emissions, figures showing HFC emissions do not include the AIM Act phasedown schedule.

Figure S-4. Hydrofluorocarbon Emissions by Potential Mitigation Scenario

Each scenario builds upon the previous scenario. The HFC potential Mitigation Scenarios are quantitatively compared against Reference Case no. 5, and the other Reference Cases are included for qualitative comparison. Scenario no. 7 would provide no additional impact on HFC emissions (only HFC consumption) and is therefore omitted from the figure.

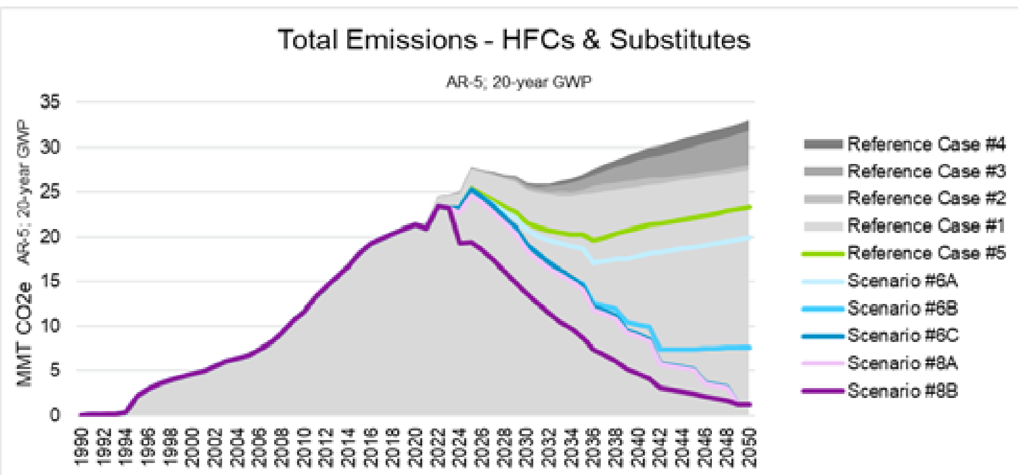
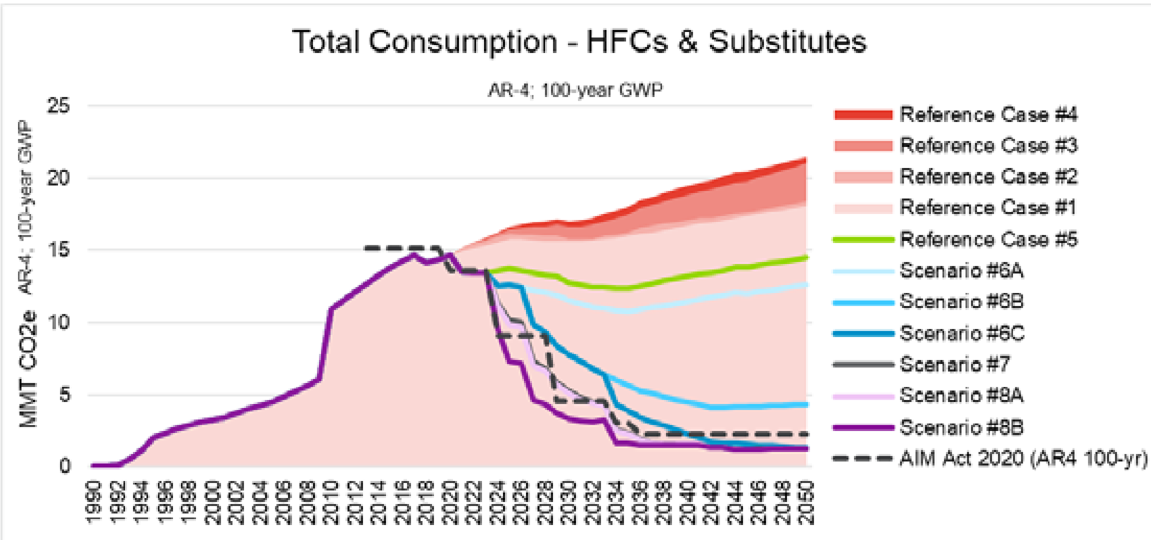


Figure S-5 shows the HFC consumption profile over the period 1990–2050 for each of the mitigation scenarios (designated scenario no. 6A, no. 6B, no. 6C, no. 7, no. 8A, and no. 8B respectively) in comparison to the reference case no. 5, which includes heating electrification. The figure also includes HFC consumption phasedown targets established by AIM Act[9] to align with the Kigali Amendment to the Montreal Protocol (black dotted line).[10] International and United States HFC policies use AR-4 100-year GWP values, whereas NYS uses AR-5 20-year GWP values. As such, all values have been converted to 100-year GWP values when making comparisons to national and international HFC consumption policies, such as Figure S-5.

Figure S-5. Hydrofluorocarbon Consumption by Potential Mitigation Scenario and AIM Act Target

Each scenario builds upon the previous scenario. The potential HFC Mitigation Scenarios are quantitatively compared against Reference Case no. 5, and the other Reference Cases are included for qualitative comparison.



As indicated by the Guidehouse modeling results, implementing several phases of additional HFC policies in New York State in tandem with the availability of technology as barriers to adoption are overcome, would significantly reduce HFC consumption and emissions relative to Reference Case no. 5 (2020 NYS SNAP Rule). Using 2020 as a baseline year (21 MMT CO_2e AR-5, 20-yr), implementing these mitigation actions would reduce HFC emissions by over 85% in 2050 to 1–2 MMT CO_2e. In particular, facilitating updates to State and local building codes in 2027 to allow the use of low-GWP refrigerants in residential and light-commercial HVAC systems would be a major milestone activity for NYS. Post-2030, Guidehouse assumes that virtually all HVAC&R product categories adopt ultra-low-GWP or natural refrigerant options, which would require significant technology advances over the next decade.

Beyond equipment restrictions, the analysis indicates that a rapid growth in the use of reclaimed refrigerant for servicing needs will be a key strategy to reduce HFC consumption, but that current recovery practices, as well as the relatively small number of HFC systems reaching an end-of-life condition between now and 2024, would produce a limited supply of reclaimed refrigerant, especially for R-410a. Furthermore, increasing end-of-life recovery rates for HVAC&R systems (small systems with less than 50 pounds refrigerant charge in particular) would reduce HFC emissions and subsequently reduce HFC consumption by increasing the available supplies of reclaimed refrigerant to be used for servicing needs. Improving reclaimed refrigerant and end-of-life recovery practices will be necessary to meet the phasedown schedule in the AIM Act and would support greater near-term HFC emissions reductions. Scenarios that include improved recovery and reclaim practices achieve the same long-term HFC consumption and emissions impacts as equipment-only scenarios but provide greater near-term HFC emissions reductions than equipment-only scenarios.

The AIM Act will significantly impact the landscape for HFC refrigerants and HVAC&R technologies over the next decade, and its implications will become clearer in the near future due to anticipated Environmental Protection Agency (EPA) regulatory actions in 2021.[11] The AIM Act will require major reductions in HFC consumption through 2050, particularly in 2024 and 2029, but the exact pathways and equipment-specific timelines for achieving these reductions are highly uncertain and very challenging. As noted, federal policies and international agreements target HFC consumption, rather than HFC emissions. Nevertheless, most activities that would reduce future HFC consumption, such as restrictions on new equipment or programs to reduce system leakage, would also directly reduce future HFC emissions. NYS may be able to leverage federal policies enacted to achieve AIM Act HFC consumption targets that would subsequently support HFC emissions reduction in alignment with the Climate Act goals.

For each of the HFC potential Mitigation Scenarios, Guidehouse calculated total emission reductions in the years 2030 and 2050 to allow for easier comparison to the CLPCA GHG reduction mandates for those years. Evaluating the levelized abatement costs of potential HFC mitigation solutions reveals which opportunities may have lower cost and/or higher impact and could be prioritized for adoption in New York State. Levelized abatement cost is the ratio of cumulative abatement cost to cumulative GHG emissions reduction over 2021–2050. Those results are summarized in Table S-4 below, showing that total GHG reductions (AR-5 20-year GWP) of 7.7 and 22.0 MMT CO_2e in 2030 and 2050, respectively, are possible via Scenario no. 8B. Nearly all mitigation strategies considered in this report have relatively low-levelized abatement costs (< $25 per ton CO_2e), except for the residential and commercial water heating sectors, which have relatively minimal potential emissions savings. As such, levelized abatement costs for the potential HFC Mitigation Scenarios are shown with and without low-GWP refrigerant transition for the heat pump water heaters (HPWHs) in future years.

Table S-4. Cumulative Abatement Costs and GHG Impacts and Target Year Greenhouse Gas Impacts by Potential Mitigation Scenario (AR-5, 20-year GWP)

Each scenario builds upon the previous scenario.
Emissions reductions as compared to reference case no. 5 are displayed in parentheses.

Mitigation Scenario	Include GWP Restrictions for HPWH (Yes/No)	Cumulative Abatement Cost 2021-2050 (Billions, $2020)	Cumulative Emissions 2021-2050 (MMT CO_2e)	Levelized Abatement Cost 2021-2050 ($2020 / MMT CO_2e)	2030 Emissions (MMT CO_2e)	2050 Emissions (MMT CO_2e)
Reference Case No. 5	N/A	$0	611	$0	19.4	22.1
No. 6A: Reference Case no. 5+ New Equipment HFC Restrictions in 2024.	Yes	$0.61	555 (56)	$11	18.6 (0.8)	18.8 (3.3)
	No	$0.61	555 (56)	$11	18.6 (0.8)	18.8 (3.3)
No. 6B: Scenario no. 6A + Additional New Equipment HFC Restrictions in 2027–2029.	Yes	$7.03	394 (217)	$32	17 (2.4)	6.5 (15.6)
	No	$3.43	413 (198)	$17	17 (2.4)	8.3 (13.8)
No. 6C: Scenario no. 6B + Additional New Equipment HFC Restrictions Post-2030.	Yes	$7.03	356 (255)	$28	17 (2.4)	0.2 (21.9)
	No	$3.44	375 (236)	$15	17 (2.4)	2 (20.1)
No. 7: Scenario no. 6C + Currently Recaptured Refrigerant Used for Maximum Possible Service Reclaim.	Yes	$7.71	356 (255)	$30	17 (2.4)	0.2 (21.9)
	No	$4.11	375 (236)	$17	17 (2.4)	2 (20.1)
No. 8A: Scenario no. 7 + Increased Recapture for Large Systems to Increase Maximum Possible Service Reclaim.	Yes	$7.75	346 (265)	$29	16.3 (3.1)	0.1 (22.0)
	No	$4.15	365 (246)	$17	16.3 (3.1)	1.9 (20.2)
No. 8B: Scenario no. 8A + Increased Recapture for Small Systems to Increase Maximum Possible Service Reclaim.	Yes	$8.02	244 (367)	$22	11.7 (7.7)	0.1 (22.0)
	No	$4.43	267 (344)	$13	11.7 (7.7)	1.9 (20.2)

S-4 Conclusions

Guidehouse's key conclusions regarding NYS HFC emissions and potential mitigation strategies are summarized below.

- HFC emissions in New York State have grown from near-zero in 1990 to 21.2 MMT CO_2e in 2020 (AR-5, 20-year GWP), driven by the use of HFCs to replace CFCs/HCFCs as they were phased down (primarily) and economic growth in the State (secondarily). Beyond 2020, as all vintage CFC/HCFC equipment reaches end-of-life, business-as-usual growth in HFC emissions will be much slower. Commercial refrigeration is the largest contributor to HFC emissions in 2020, followed by aerosol propellants and light-duty motor vehicle air conditioning (MVAC). For most categories, annual leakage throughout the equipment lifetime is a much greater source of emissions than end-of-life leakage.
- Commercial and residential HVAC&R systems are the fastest-growing sources of emissions historically and are expected to increase further in future years. Heat pump systems have a relatively small contribution to total emissions in 2020 but are expected to grow substantially as heating electrification increases in New York State because heat pump systems, particularly VRF systems, have higher refrigerant charge than comparable AC-only systems. Heat pump water heaters are unlikely to be a significant contributor to HFC emissions, assuming leakage rates are similar to other self-contained systems (i.e., very minor).
- Building electrification is expected to drive a substantial decrease in overall building GHG emissions, but a notable increase in HFC emissions during the period 2035–2050. However, HFC emissions reduction achieved by the 2020 NYS SNAP Rule outweighs the HFC impacts of heating electrification, reflecting a net overall reduction in HFC emissions from the reference case.
- The 2020 NYS SNAP Rule restricting the use of high GWP refrigerants for residential and commercial refrigeration, commercial chillers, and other segments will have a significant impact on decreasing future HFC emissions in NYS, reducing HFC emissions by approximately 30% in 2050 compared to a reference case, which includes heating electrification goals.
- Implementing several phases of additional HFC policies in New York State, as technology becomes available and as barriers to adoption are overcome, would significantly reduce HFC consumption and emissions. Using 2020 as a baseline year (21 MMT CO_2e AR5 20-year), implementing these mitigation actions would reduce HFC emissions by over 85% in 2050 to 1–2 MMT CO_2e. The following bullets describe the HFC policies analyzed in this project and their potential impacts.
- In the near term (i.e., by 2024), HFC prohibitions for new product sales could be implemented on room and window AC/HPs, industrial systems, and transport HVAC; and ultra-low-GWP (< 10) limits could be placed on supermarket systems. These technologies are commercially available, although early products may be more expensive and complex than conventional options.

- Low-GWP alternatives are available for certain applications, but face significant challenges to adoption, most notably with building and safety codes for residential and commercial central HVAC systems. Under the currently projected code cycle, New York State building code updates in 2027 could allow the use of mildly flammable A2L refrigerants for these key applications.
- The use of ultra-low-GWP technologies will be required in the long-term to further reduce HFC emissions beyond what is achievable with current technologies. Significant RD&D is required to support the technological advances that would be required over the next decade to develop ultra-low-GWP options for many key HVAC product categories.
- Although equipment restrictions would significantly reduce HFC emissions in 2050 to 85% below the Reference Case, such restrictions would not provide enough emissions reduction to achieve the consumption phasedown limits established by the AIM Act for 2024 and 2029 (40% and 70% reduction, respectively). Improving reclaimed refrigerant and end-of-life recovery practices will be necessary to meet the consumption phasedown schedule in the AIM Act and would support greater near-term HFC emissions reductions. Scenarios that include improved recovery and reclaim practices achieve the same long-term HFC consumption and emissions impacts as equipment-only scenarios but provide greater near-term HFC emissions reductions than equipment-only scenarios. Costs of increased refrigerant recovery rates are unknown and are not modeled in this report, however the reclamation costs associated with increased volume of recovered refrigerants are modeled in mitigation scenarios no. 7, no. 8A, and no. 8B. Cumulative abatement costs increase from $7 billion in scenario no. 6C (which does not include increased recovery and reclaim practices) to $8 billion in scenario no. 8B (which models the most aggressive recovery and reclaim practices).
- Beyond equipment restrictions, the analysis indicates that a rapid growth in the use of reclaimed refrigerant for servicing needs will be a key strategy to reduce HFC consumption, but that current recovery practices, as well as the relatively small number of HFC systems reaching end-of-life between now and 2024, would produce a limited supply of reclaimed refrigerant, especially for R-410a. Additional supply of reclaimed refrigerant will be required to fulfill servicing needs to achieve the 2024 and 2029 consumption reduction targets.
- Increasing end-of-life recovery rates for small HVAC&R systems (generally less than 50 pounds refrigerant charge), which currently have low end-of-life recovery rates, would substantially reduce HFC emissions and would subsequently reduce HFC consumption by increasing the available supplies of reclaimed refrigerant that can be used for servicing needs. Whereas, increasing end-of-life recovery rates for large systems would have little additional impact, given that large systems already have relatively high end-of-life recovery rates.
- The federal AIM Act will require major reductions in HFC consumption through 2050, particularly in 2024 and 2029, but the exact pathways and equipment-specific timelines for achieving these reductions are highly uncertain and very challenging. NYS may be able to leverage federal policies enacted to achieve AIM Act HFC consumption targets that would subsequently support HFC emissions reduction in alignment with the Climate Act goals.

- Nearly all mitigation strategies considered in this report have relatively low-levelized abatement costs[12] (< $25 per ton CO_2e) with the exception of the residential and commercial water heating sectors, which have relatively minimal emissions savings and would therefore have relatively high-levelized abatement costs ($ per ton CO_2e).

S-5 Recommendations

Based on these conclusions summarized above, Guidehouse recommends the following actions to NYSERDA, DEC, and other stakeholders when evaluating potential HFC mitigation strategies to achieve Climate Act goals.

- Reducing HFC emissions is critical to achieving Climate Act statewide emission reduction goals. Aggressive equipment restrictions are needed in the short-term, mid-term, and long-term to reduce HFC emissions. These strategies have relatively low-levelized abatement costs (< $25 per ton CO_2e), given the findings regarding incremental equipment costs and cumulative emissions savings during the period 2021–2050. These actions would reduce emissions by over 85% by 2050 with specific impacts highlighted in Table S-4:
  - **Phase I (before 2024):** Low-GWP refrigerants for commercial and residential room AC/HP, industrial systems, transport HVAC; and supermarket racks to ultra-low-GWP options.
  - **Phase II (2027–2029):** Building code updates are made by 2027 to allow for low-GWP refrigerants for commercial central and ductless AC/HP and residential whole-home AC/HP; low-GWP refrigerants for transport refrigeration; ultra-low-GWP refrigerants for commercial icemakers and water heating, warehouses, residential water heating and clothes drying.
  - **Phase III (Post-2030):** Ultra-low-GWP refrigerants for all residential and commercial AC/HP, chillers (medium and small), walk-ins, industrial systems, and all residential AC.
- NYS should ensure that local building codes are updated by 2027 to allow for commercial and residential AC/HP systems that use mildly flammable low-GWP refrigerants (i.e., ASHRAE Classification A2L). These HVAC&R segments represent major opportunities for GHG emissions reduction in NYS through the combination of low-GWP refrigerants when replacing HFCs and heating electrification when replacing fossil fuel systems.
- NYSERDA should provide RD&D support over the next decade to develop ultra-low GWP, natural refrigerant, and non-vapor-compression systems (“max tech” technologies) for key end-use sectors such as residential and light commercial HVAC. These sectors do not have a “max tech” option available today. Supporting manufacturer product development, laboratory testing, field demonstrations, and incentive programs can advance these technologies into the U.S. market. In particular, heat pumps for residential and commercial space heating are most critical, whereas heat pump water heaters are less important.

- NYS may be able to leverage federal policies enacted to achieve AIM Act HFC consumption targets that would subsequently support HFC emissions reduction in alignment with the Climate Act goals. NYS should closely follow EPA's development of the policy mechanisms, schedules, and pathways for meeting the AIM Act targets, and work with industry partners to identify how best to guide the State through this transition. NYS should consider voluntary and mandatory strategies to reduce transition cost and complexity in the State (e.g., businesses that prepare early will not be as impacted by the anticipated HFC price spikes in future years). These strategies could consider regulations earlier than EPA timelines, as well as incentives and financial support.
  - If EPA priorities change in future years or do not align with Climate Act goals, NYS should develop its own HFC policies to achieve its goals. The major activities and implementation timelines should align with those envisioned in the potential HFC Mitigation Scenarios.
- Beyond equipment restrictions, a significant increase in recovery/reclaim rates and proper disposal of equipment at its end-of-life state will be needed at a national level to achieve AIM Act targets in 2024 and 2029. In support of this, NYSERDA should do the following:
  - Conduct a market assessment of current HFC recovery and reclaim practices in NYS.
  - Develop an education and outreach strategy for local industry stakeholders.
  - Provide technical, economic, and training support to aid local industry with this transition.
- NYSERDA should conduct further research to address a number of known data gaps and uncertainties that have high sensitivity for these modeling results. For example, further analysis is needed to determine the expected market share of packaged, split, and VRF heat pumps, specifically for commercial sector as well as to determine prototypical leak rates and charge size for VRF systems.
- Table S-5 outlines a series of RD&D activities that NYSERDA could support to advance low-GWP solutions and leakage reduction opportunities in support of Climate Act goals.

Table S-5. RD&D Recommendations for Low-Global Warming Potential and Leak Reduction Solutions

Recommendations	
Research & Development Focus	1. Develop, test, and demonstrate low-charge propane and isobutane equipment that minimizes safety risks. 2. Conduct R&D on CO_2 residential and commercial heat pump systems. 3. Develop, test, and demonstrate building AC/HP systems with low-GWP refrigerants (non-vapor-compression technologies can also be a focus area). 4. Develop and test low-charge ammonia refrigeration equipment that minimizes safety risks. 5. Develop fault detection and diagnostics (FDD) systems to detect leakage from packaged HVAC&R systems. 6. Conduct R&D for VRF charge size and leakage reduction strategies. 7. Conduct R&D on microchannel heat exchangers for heat pumps and leak reduction.
Deployment & Market Support Focus	8. Develop case studies showing the safety, performance, and cost impacts of alternative refrigerants. 9. Develop and conduct large-scale field studies to determine representative leak rates for VRF systems. 10. Provide training for industry technicians, system designers, and other stakeholders on proper use of alternative refrigerants (including transition costs). 11. Support low-GWP awareness campaign for consumer and industry stakeholders. 12. Conduct field studies to evaluate impacts of on-board leak mitigation systems for A3 and A2L refrigerants. 13. Develop NYS case studies showing the safety, performance, and cost impacts of proper refrigerant management practices. 14. Develop NYS case studies showing the benefits of low-charge system design with leak mitigation technologies, such as energy efficiency, initial cost, leakage reduction, GHG emissions, lifecycle maintenance costs, and other attributes. 15. Conduct detailed analysis of charge size differences between AC and heat pump systems using low-GWP refrigerants.

1 Introduction

The purpose of this report is to provide the New York State Energy Research and Development Authority (NYSERDA) with an (1) updated and more detailed inventory for hydrofluorocarbon (HFC) gases in New York State; and (2) explanation of how statewide HFC usage is expected to change in future years, due to economic growth, appliance electrification, and other trends; and an understanding of the impacts potential policies could have in significantly reducing HFC emissions. Building, transportation, and industrial applications throughout New York State use HFCs for comfort space cooling, food sales and storage, foam, aerosols, and a variety of other processes. HFCs contribute to the State's greenhouse gas (GHG) emissions both directly through refrigerant emissions to the atmosphere and indirectly through the electricity consumption to operate space conditioning and refrigeration systems using HFCs. This report addresses direct HFC emissions associated with the use of HVAC&R equipment and foam and aerosol products in the State, rather than emissions associated with chemical production, electronics, or other categories. New York State and federal policies as well as global industry trends present an opportunity to significantly reduce HFC-related GHG emissions and ultimately phase out HFC usage, but policy strategies and research, development, and demonstration (RD&D) support are necessary to facilitate this transition.

This section introduces the underlying drivers of policy action in New York State, report objectives, technology and market scope, and analysis methodology. This project supports NYSERDA's overall Climate Leadership and Community Protection Act (Climate Act) Integration Analysis, which is ongoing.

1.1 Background

In 2019, New York State committed to ambitious climate goals in the Climate Act, including 100% carbon-free electricity by 2040 and 85% GHG emissions reduction by 2050.[13] Table 1-1 includes the three GHG emissions reduction requirements: a reduction in statewide emissions 40% from 1990 levels by 2030, 85% from 1990 levels by 2050, and 100% by 2050 on a net basis. In addition, New York City and other local governments throughout the State have announced their own commitments, including New York City's carbon neutrality goal of 2050. New York State leaders are currently considering potential pathways to reach these goals and are evaluating various economy-wide strategies through the Climate Act Climate Action Council and Advisory Panels.[14]

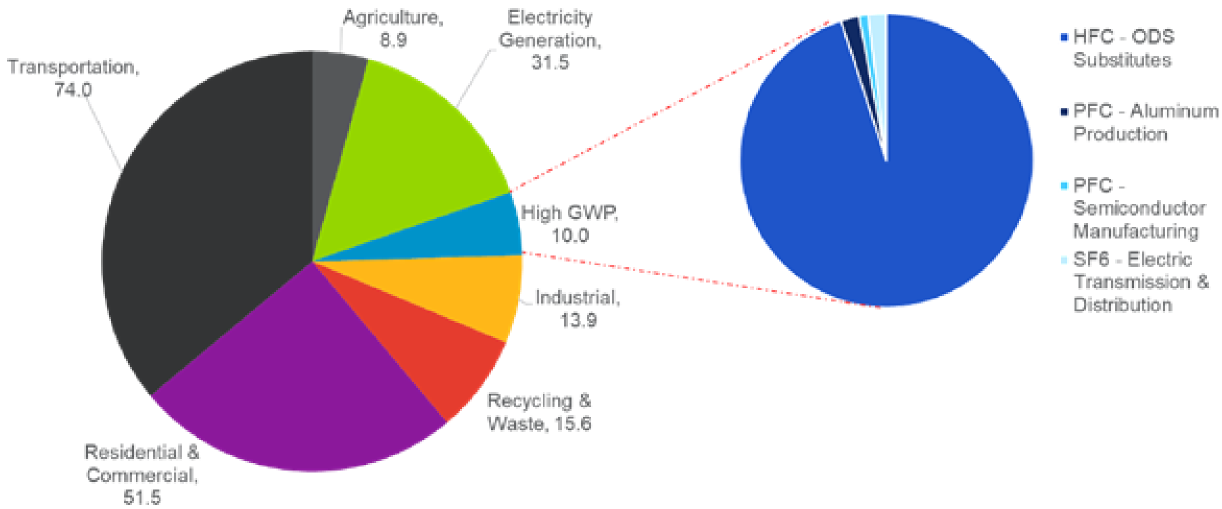
Table 1-1. Climate Act Timeline and Milestones

Climate Act Timeline and Milestones	
2025	• Expand to 6 GW of statewide solar capacity.
2030	• 40% reduction in gross GHG emissions (from 1990). • 70% of electric generation from renewable energy. • Expand to 3 GW of statewide storage capacity.
2035	• Expand to 9 GW of statewide offshore wind capacity.
2040	• 100% of electrical generation as zero emissions.
2050	• 85% reduction in gross GHG emissions (from 1990). • Net zero GHG emissions.

Prior to the Climate Act, New York State GHG emissions inventories estimated emissions of CO_2, methane, nitrous oxide, sulfur hexafluoride, perfluorocarbons, and hydrofluorocarbons from key segments such as transportation, residential and commercial buildings, electricity generation, industrial processes, and other categories. Figure 1-1 highlights estimated 2016 emissions as provided in the NYSERDA (2018) NYS GHG Inventory. The Climate Act encompasses additional emissions, such as those associated with the extraction and transmission of imported fossil fuels, as measured on a 20-year GWP basis. A collection of industrial gases, including HFC refrigerants have relatively small volumetric emissions compared with other sectors but have an outsized impact on statewide emissions due to their significantly higher global warming potentials (GWPs). The GWP values for these gases are typically several thousand times greater impact than the equivalent amount of carbon dioxide (carbon dioxide equivalent or CO_2e). These industrial gases with relatively high GWP values account for approximately 5% of total GHG emissions in NYS today, with the large majority coming from hydrofluorocarbon (HFC) gases used for space conditioning, refrigeration, aerosols, solvents, and other applications. HFCs are the predominant class of refrigerants used today for heating, ventilation, air conditioning, and refrigeration (HVAC&R), typically for building, industrial, and mobile applications. HFCs replaced previous generations of ozone depleting substances (ODS) such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), which had a detrimental impact on the ozone layer. Section 2 discusses this historical transition from CFCs/HCFCs to HFCs and its impacts for the transition to lower-GWP substances.

Figure 1-1. 2016 New York State Greenhouse Gas Emissions (NYSERDA, 2018)

Source: NYSERDA (2018) New York State Greenhouse Gas Inventory Report 1990–2016, 100-year AR4 values



As described above, NYS is assessing ways to reduce GHG emissions per the requirements of the Climate Act. The current pathways being discussed focus on renewable and zero-carbon electricity production as the catalyst for emissions reductions in other sectors through electrification of fossil fuel end-uses, such as building heating and road transportation. To reach the ambitious Climate Act requirements, NYS must address non-energy GHG emissions sources as well, such as from agriculture, wastes, and high-GWP substances, which are challenging to address. While these non-energy emissions sources are relatively small today, they will constitute a more significant portion of emissions as the emissions from other segments are reduced. Furthermore, electrifying space and water heating in buildings with heat pumps is expected to increase HFC refrigerant usage and emissions in the State, partially counteracting the avoided emissions from eliminating fossil fuel usage. Section 3.1 further discusses this topic.

International, federal, and State agencies are currently exploring opportunities to address HFC consumption and emissions through various policies that target different points in the HFC life cycle. Table 1-2 maps the different policies considered and their intended impacts on consumption and emissions across the life cycle of HVAC&R systems. As discussed in section 2.2.8, HFC consumption and emissions occur at different stages of the equipment lifecycle for different HVAC&R categories.

Table 1-2. Potential Hydrofluorocarbon Reduction Policies for a Typical HVAC&R System

Policy Category	Description / Mitigation Option	Mitigation Option Impact on HFC Consumption	Mitigation Option Impact on HFC Emissions
Production	The refrigerant manufacturer produces, stores, and distributes refrigerant to the equipment manufacturer and service technicians. **Mitigation Option**: Prohibit domestic HFC production or imports.	Restricts new HFC supplies and encourages use of alternatives or reclaimed HFCs.	Overall emissions would decrease over the equipment lifetime.
Consumption in New Equipment	The manufacturer fills (*i.e.*, "charges") the product with refrigerant at the factory. Some systems require field charging of refrigerant. **Mitigation Option**: Restriction on manufacture and sales of new equipment using HFCs.	Restricts HFC use, drives adoption for alternatives.	Overall emissions would decrease over the equipment lifetime.
Servicing and Leakage for Existing Equipment	A small amount of refrigerant leaks over time through small cracks in the system piping and subassemblies. If a leak is detected, a service technician will repair the leak and replace the lost refrigerant. **Mitigation Option:** Develop requirements for leak detection, mitigation, and reporting.	Reducing leakage would decrease HFC consumption for service.	Direct reduction of HFC emissions.
End-of-Life Emissions	The full refrigerant charge may be released if the system is damaged or if the system is not properly disposed at the end of its useful life. **Mitigation Option:** Develop requirements for refrigerant recovery and proper disposal.	No direct impact on HFC consumption.	Direct reduction of HFC emissions.
Use of Reclaimed Refrigerant	The service technician may replace refrigerant that has leaked over time with refrigerant that has been recovered from older systems at end-of-life and reclaimed to applicable standards. **Mitigation Option:** Develop requirements for use of reclaimed refrigerant for service use or for new equipment.	Reduces the demand for new HFC production.	No direct impact on HFC emissions but encourages greater end-of-life recovery.

Many of these strategies were first deployed when phasing out the use of CFCs/HCFCs and are familiar to policymakers, manufacturers, and industry organizations. Developing a phasedown schedule for specific HFC end-uses is a common strategy, in which either individual HFCs or refrigerants over a certain GWP limit would no longer be allowed for use in new equipment or applications. This process preserves the use of the HFC refrigerant for servicing existing equipment, and over time achieves HFC reductions as older equipment is replaced with new equipment with lower-GWP refrigerants. New York State's DEC finalized the 6 NYCRR Part 494 regulation (2020 NYS SNAP Rule[15]) in October 2020 that establishes an HFC phasedown schedule for several end-use categories in refrigeration, chiller, aerosol, and foam segments beginning January 1, 2021.[16] These topics are further discussed throughout the report.

1.2 Report Objectives

This report summarizes the key findings of Guidehouse's analysis into HFC consumption and emissions trends for New York State and provides recommended policy actions and RD&D activities to further reduce HFC emissions to achieve the Climate Act goals. The main objectives of this report are the following:

- Provide a detailed inventory of HFC emission sources and quantities by sector in New York State (NYS) over 1990–2020.
- Develop a spreadsheet model to analyze how HFC emissions in NYS are expected to change over 2020–2050 under business-as-usual conditions, already committed HFC regulations, building electrification policies, and future potential mitigation options.
- Evaluate the impacts, cost, and feasibility of potential HFC mitigation opportunities.
- Identify RD&D needs to support HFC alternatives and mitigation solutions, as well as likely policy strategies that could achieve Climate Act goals.

1.3 Technology and Market Scope

This report covers a wide variety of HFC end-use categories including refrigerants used in space conditioning and refrigeration for residential, commercial, industrial, and transport applications, as well as non-refrigerant HFCs used in foams, aerosol propellants, solvents, and fire protection. The report also considers newer HFC applications such as heat pump water heaters and clothes dryers, which are expected to increase in adoption commensurate with Climate Act goals. Table 1-3 highlights the HFC end-use categories and sectors included in this analysis.

Table 1-3. End-Use Sub-Categories and Equipment Types

End Use Sub-Category	Equipment Types
Residential HVAC	Central AC
	Central Heat Pump (HP)
	Window AC
	Ground Source Heat Pump (GSHP)
Residential Refrigeration	Refrigerator/Freezer
	Freezer
Residential Other	Heat Pump Water Heater (HPWH)
	HP Clothes Dryer
	Dehumidifier
Commercial HVAC	Central Split and Package AC, Large
	Central Split and Package AC, Small
	Central Split and Package HP, Large
	Central Split and Package HP, Small
	Room AC/Packaged Terminal AC (PTAC)/Packaged Terminal HP (PTHP)
	GSHP
	Variable Refrigerant Flow (VRF) HP, Large
	VRF HP, Small
	Ductless Split AC
	Ductless Split HP
	Small Chiller
	Medium Chiller
	Large Centrifugal Chiller
Commercial Refrigeration	Refrigerator/Freezer
	Supermarket Racks, Large
	Supermarket Racks, Medium
	Walk-ins/Remote Condensing, Large
	Walk-ins/Remote Condensing, Small
	Self-Contained Display Cases / Reach-ins
	Vending Machines
	Ice Makers
	Refrigerated Warehouse, Medium
	Refrigerated Warehouse, Large
Commercial Other	HPWH
Industrial Process	Industrial Process
Transportation HVAC	Light Duty Vehicles
	Medium Duty Vehicles
	Heavy Duty Vehicles
	Buses
Transportation Refrigeration	Transport Refrigeration
Other	Aerosols, Foams, Solvents, other HFCs

1.4 Project Approach

Table 1-4 summarizes the contents of each section of the report. Guidehouse first reviewed the assessment of HFC emissions in the NYSERDA 2018 NYS GHG Inventory and supporting documentation for the NYSERDA Pathways to Deep Decarbonization in New York State project.[17] Both of these reports are currently being revised by NYSERDA and DEC as part of the Climate Act Integration Analysis project to meet the requirements of the Climate Act.

Guidehouse then conducted a thorough literature review of the latest government and industry research into HFC emissions inventories, refrigerant saturations, low-GWP alternatives, and mitigation strategies. Guidehouse also conducted several interviews with industry organizations. This information was used to develop a detailed bottom-up vintaging model to calculate historical, current, and future HFC consumption and emissions for over 40 end-use categories and analyze potential HFC Mitigation Scenarios for NYS. Based on these findings, Guidehouse identified and recommended policy actions and RD&D activities to further reduce HFC emissions and achieve the Climate Act goals.

Table 1-4. Summary of Each Chapter

Chapter	Summary
Executive Summary	Brief summary of entire report for wider audience.
1. Introduction	Description of report background, objectives, and technology/market scope.
2. Historical HFC Emissions Inventory	Historical HFC consumption and emissions estimated over 1990–2020 by end-use category, emissions source, and other parameters.
3. Projected Future Reference Cases for HFC Emissions in NYS	Future HFC consumption and emissions projected over 2020–2050 based on expected growth rates, established HFC phasedown policies, and decarbonization pathways to achieve Climate Act goals.
4. Alternatives to High GWP Refrigerants and Leakage Reduction Solutions	Analysis of available low-GWP refrigerants, leakage reduction technologies and policies, and RD&D initiatives to increase their adoption in NYS.
5. Potential HFC Mitigation Scenarios	Analysis of the projected impacts and timelines for several potential mitigation scenarios that could reduce future HFC consumption and emissions in NYS.
6. Conclusions and Recommendations	Summary of key findings, conclusions, and recommendations for NYSERDA, DEC, and other stakeholders to consider when evaluating potential HFC mitigation strategies to achieve Climate Act goals.
7. References	List of references cited throughout the report.
Appendix A. Key Data Inputs and Assumptions	Tables summarizing the Guidehouse model data inputs and assumptions, including sources, GWP values, scenario assumptions, and cost premiums.
Appendix B. HFC Emissions Inventory for NYS	Tables summarizing HFC emissions inventory 2005–2020.
Appendix C. Source Documentation for the HFC Emissions Model	Provides details for key data sources and assumptions used in the HFC emission model.
Appendix D. Source Documentation for the Scenario Cost Model	Provides details for key data sources and assumptions used in the scenario cost model.
Appendix E. Comparison of HFC Accounting Practices	Explains HFC accounting methodologies and assumptions from various tools and models.
Appendix F. Details for RMP Economic Impact Assessment	Provides details for an earlier cost-benefit analysis performed by the California Air Resources Board on their Refrigerant Management Program.

2 Historical Hydrofluorocarbon Emissions Inventory

This section describes Guidehouse's analysis of historical HFC consumption and emissions in New York State over the period 1990–2020 based on the results generated by the HFC vintaging model developed for this analysis. The historical emissions inventory serves as the basis for projecting the future HFC emissions inventory in section 3 and evaluating potential HFC mitigation strategies in section 5.

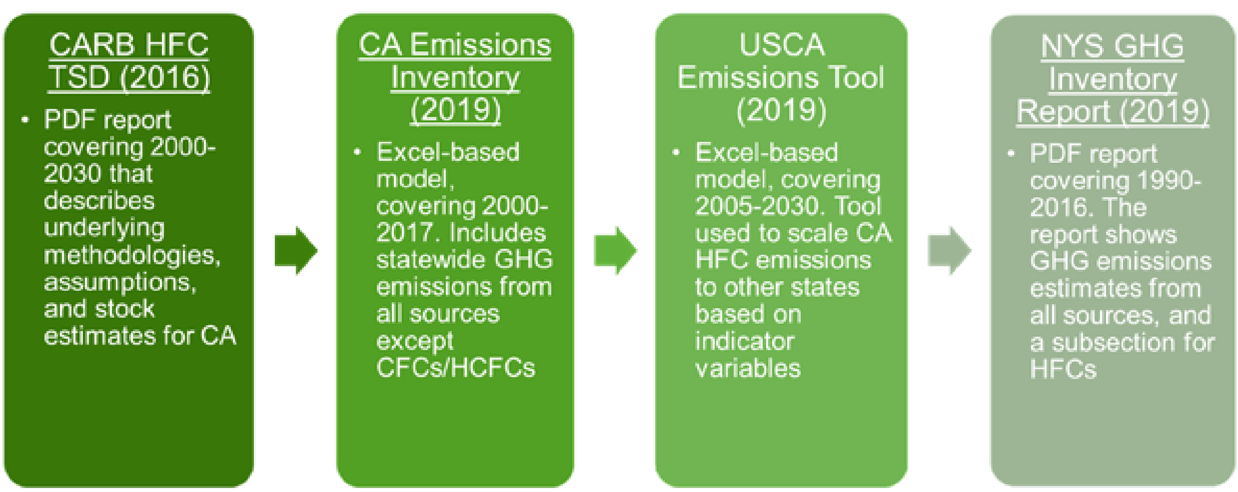
2.1 Methodology and Key Data Sources

The following sections describe the methodology and key data sources used to develop the customized HFC vintaging model for the purpose of updating the emissions inventory for New York State. The goal of this analysis was to review previous methods used for the New York State GHG Inventory, identify assumptions and methodologies, and determine areas for improvement in the updated inventory. The full source documentation for the Guidehouse HFC vintaging model is available in appendix C.

2.1.1 Assessment of New York State Current Hydrofluorocarbon Emissions Inventory

As a first step, Guidehouse reviewed the last NYS GHG Inventory Report 1990–2016, and then reverse-engineered the methods for calculating HFC emissions. At a high level, the previous analysis was generated using a tool provided by the California Air Resource Board (CARB) for tracking HFCs across the United States. A diagram of the modeling process for that tool is shown in Figure 2-1 below.

Figure 2-1. Process Diagram for the NYS GHG Inventory



First, emissions estimates were developed for the State of California using a bottom-up vintaging model, the details of which were presented in the CARB Technical Support Document (TSD). This vintaging model factored in details, such as typical refrigerant charge, equipment lifetime, and emission rates due to leakage and end-of-life, among others. Different emissions methodologies were assigned to major equipment categories, including stationary HVAC&R, mobile HVAC&R, and the “other” categories such as aerosols and foams. Ultimately, many of the underlying assumptions from the CARB vintaging model were used in Guidehouse’s emissions model but updated based on the most recent data. Some key updates to these CARB model assumptions include the following:

- Calculated emissions using a bottom-up approach based on equipment stock estimates in New York State,[18] instead of using a top-down emissions scaling approach (see below).
- Developed differential refrigerant charge size estimates between air-conditioner and heat pump technologies.
- Re-assigned equipment lifetimes based on the NYSERDA Technical Reference Manual.[19]
- Evaluated the historical prevalence of technologies that were not explicitly considered in the CARB inventory (e.g., VRF and ground-source heat pumps)

After emissions estimates were developed for California, the United States Climate Alliance (USCA) tool scaled the California emissions to New York emissions based on key indicator variables such as State population, commercial building square footage, and vehicle registrations. Emissions were also forecast through the year 2030 based on assumed growth rates in New York State of the key indicator variables. The tool then disaggregates those emissions into 14 different categories, which were retained in the NYS GHG Inventory Report. Guidehouse compared the emissions results from 2020 across those same 14 categories, plus two additional categories for “other” and “water heating/appliances” to calibrate the Guidehouse emissions model against the NYS estimates, as shown in Table 2-1. These values are provided for informational purposes only; differences in methodology, product mapping, and data availability make further comparisons challenging.

Table 2-1. Emissions Comparison between New York State Inventory and Guidehouse Inventory (MMT CO_2e)

Note: Emissions values in this table based on IPCC AR-4, 100-year GWP values.

Emissions Category USCA	2020 USCA Estimate	2020 Guidehouse Estimate
Aerosol Propellants	0.75	0.98
Commercial Refrigeration	3.88	3.27
Commercial Stationary AC < 50 pounds	1.31	0.73
Commercial Stationary AC > 50 pounds	0.57	0.65
Foam	0.43	0.90
Industrial Refrigeration	0.16	0.11
Other	--	0.02
Residential (Domestic) Refrigeration	0.10	0.16
Residential Stationary AC Heat Pump	0.23	0.02
Residential Stationary Central AC	1.03	0.87
Residential Stationary Room Unit AC	0.63	0.24
Solvents & Fire Suppressant	0.15	0.28
Transport Heavy-Duty MVAC	0.55	0.11
Transport Light-Duty MVAC	1.46	1.20
Transport Refrigeration	0.30	0.08
Water Heating / Appliances	--	0.03
TOTAL	**11.54**	**9.64**

2.1.2 Modeling Approach—Overview

The foundation for the HFC emissions inventory analysis is an Excel-based vintaging model customized to New York State. The Guidehouse vintaging model estimates the annual installed stock, new shipments, and end-of-life (EOL) retirements of HFC-using equipment. Using a bottom-up accounting methodology, the model calculates annual HFC consumption due to new equipment installations and the servicing of existing equipment to replenish refrigerant leakage; as well as annual HFC emissions to the atmosphere due to equipment leakage and disposition at EOL retirement. The model can be used to project future consumption and emissions over a variety of scenarios defined by the user.

For each equipment type, annual HFC consumption and emissions are calculated based on a set of key input assumptions, including refrigerant composition, refrigerant charge size, annual leakage rate, servicing frequency, equipment lifetime, and EOL loss (i.e., non-recovery) rate. Additional general inputs include projected growth rates of key economic indicators (e.g., number of residential housing units, total commercial square footage, and number of vehicle registrations) and saturation rates of main end-uses (e.g., the portion of residential homes with air conditioning).

By customizing the input assumptions, a range of business-as-usual growth scenarios, or "reference cases" can be modeled. Against these reference cases, "what-if" scenarios can be modeled to assess the impacts of potential mitigation policies that could be considered to achieve future emissions reduction targets. The adaptability of the model also allows for a sensitivity analysis of any of the key input assumptions.

Figure 2-2 shows the key inputs and outputs of the HFC vintaging model.

Figure 2-2. Key Inputs and Outputs of Hydrofluorocarbon Vintaging Model

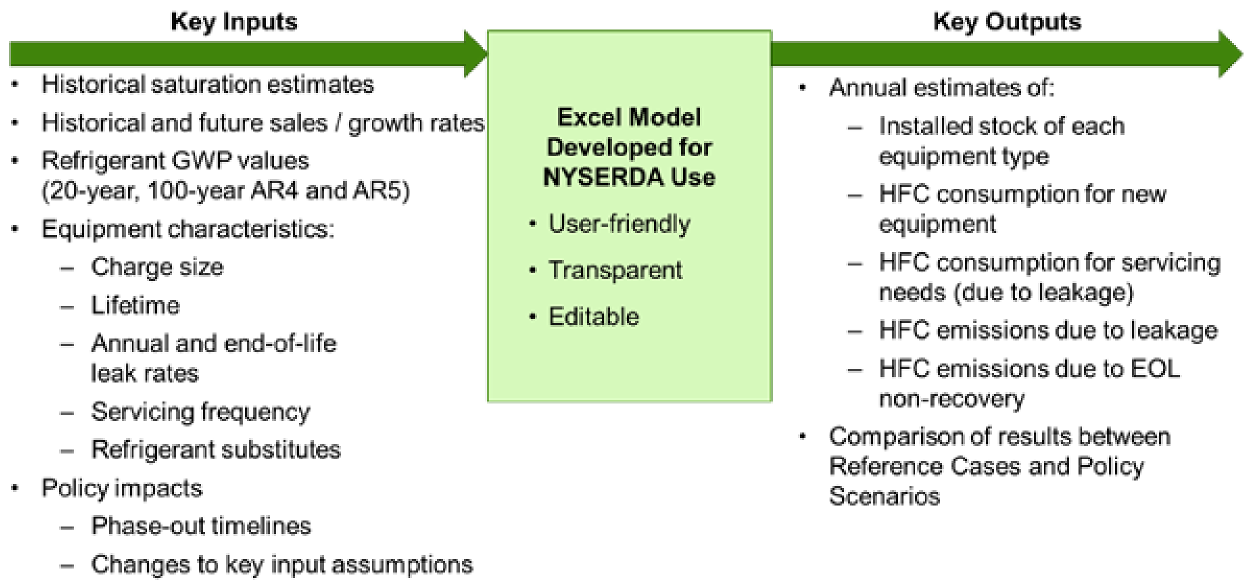
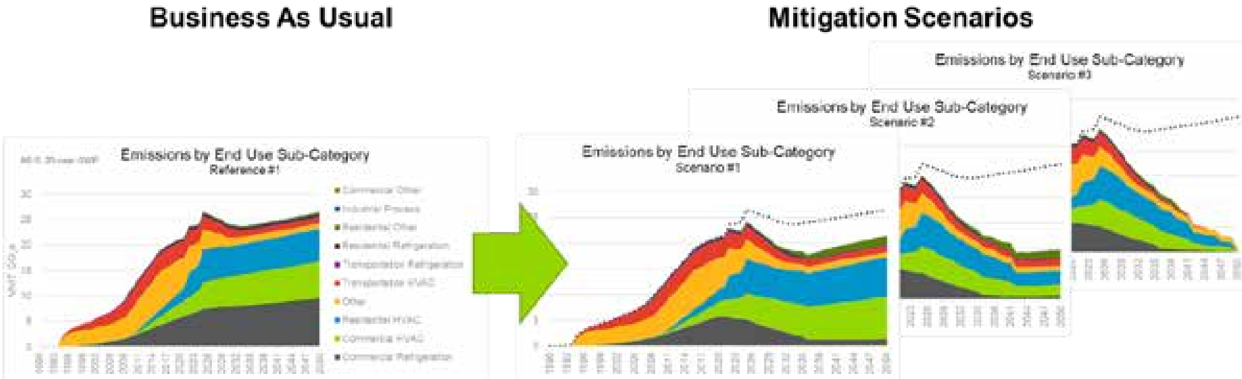


Figure 2-3 provides an illustrative example of using the outputs of the Guidehouse model to compare results between a reference case and various policy scenarios. Appendix C contains a detailed introduction to the modeling spreadsheet.

Figure 2-3. Illustrative Example of Model Outputs



2.1.3 Equipment Category Mapping

Guidehouse defined an initial list of equipment categories to match the level of granularity from E3's building stock tool for the Climate Act Integration Analysis. Additional categories were created as needed, for example to align with differentiation in refrigerant charge quantities (e.g., commercial VRF systems) or with specific market segments of interest (e.g., ductless heat pumps). Each equipment category was mapped to existing USCA end-use categories and E3 building stock categories for use in the Climate Act Integration Analysis. As a result, all equipment categories can be "rolled up" into the existing categories from either USCA or E3. Table 2-2 shows the mapping between each equipment category in the Guidehouse model and the corresponding category from USCA.

Table 2-2. Mapping of End-Use Sub-Categories and Equipment Types to USCA Categories

Guidehouse End-Use Sub-Category	Equipment Types	USCA Category
Residential HVAC	Residential Central AC	Residential Stationary Central AC
	Residential Central HP	
	Residential GSHP	Residential Stationary AC Heat Pump
	Residential Window AC	Residential Stationary Room Unit AC
Residential Refrigeration	Residential Refrigerator / Freezer	Residential (Domestic) Refrigeration
	Residential Freezer	
Residential Other	Residential HP Clothes Dryer	(Not Defined)
	Residential Dehumidifier	
	Residential HP Water Heater	
Commercial HVAC	Commercial Central Split & Package AC, Large	Commercial Stationary AC > 50 pounds
	Commercial Central Split & Package HP, Large	
	Commercial VRF HP, Large	
	Commercial Chiller, Large Centrifugal	
	Commercial Chiller, Medium	
	Commercial Chiller, Small	
	Commercial Central Split & Package AC, Small	Commercial Stationary AC < 50 pounds
	Commercial Central Split & Package HP, Small	
	Commercial GSHP	
	Commercial VRF HP, Small	
	Commercial Ductless Split AC	
	Commercial Ductless Split HP	
	Commercial Room AC/PTAC/PTHP	
Commercial Refrigeration	Commercial Ice Makers	Commercial Refrigeration
	Commercial Refrigerator/Freezer	
	Com. Self-Contained Display Cases/Reach-ins	
	Commercial Supermarket Racks, Large	
	Commercial Supermarket Racks, Medium	
	Commercial Vending Machines	
	Com. Walk-ins/Remote Condensing, Large	
	Com. Walk-ins/Remote Condensing, Small	
	Commercial Refrigerated Warehouse, Large	Industrial Refrigeration
	Commercial Refrigerated Warehouse, Medium	
Commercial Other	Commercial HP Water Heater	(Not Defined)
Industrial Process	Industrial Process	(Not Defined)
Transportation HVAC	Buses	Transport Heavy-Duty MVAC
	Heavy Duty Vehicles	
	Light Duty Vehicles	Transport Light-Duty MVAC
	Medium Duty Vehicles	
Transportation Refrigeration	Transportation Refrigeration	Transportation Refrigeration
Other	Aerosol Propellants	Aerosol Propellants
	Foams	Foam
	Solvents & Fire Suppressants	Solvents & Fire Suppressant

2.1.4 Key Modeling Assumptions, Limitations, and Data Sources

The Guidehouse vintaging model incorporates a number of key assumptions and inherent modeling limitations, as summarized in Table 2-3. Based on the research findings in Task 1.1, Guidehouse updated assumptions and data sources from New York State to develop the more detailed estimates for the vintaging model. Table 2-3 also describes the data sources and process followed to update each model assumption.

Table 2-3. Key Model Assumptions, Limitations, and Data Sources

Model Parameter	Key Model Assumptions/Limitations	Data Sources and Methodology
Equipment Stock	· Calculated as saturation rate multiplied by key economic indicator (e.g., number of residential housing units, total commercial square footage). · Saturation rate determined for "base" year using most recent available data (e.g., 2018). · Years prior to base year extrapolated using historical growth rate of economic indicator; assumes constant growth rate over that period. · Future years extrapolated using user-defined annual growth rate of an economic indicator.	· Compared NYSERDA residential and commercial baseline studies with data from CARB, U.S. DOE, and the Energy Information Administration (EIA). · Based on these comparisons, developed stock saturation estimates for "base" year. · Extrapolated historical and future stock growth estimates based on projections of key economic indicators.
Equipment Lifetime	· Single lifetime value applied to each equipment type. · Products are assumed to retire at exactly the assigned lifetime (e.g., no distribution of survival time assumed). · Early "catastrophic" loss not considered in the model. · Equipment types that are considered substitutes within the same "main application" must be assigned the same lifetime.	· Assigned equipment lifetimes based on NYSERDA Technical Reference Manual (TRM). · Conducted literature review to assign lifetimes for any equipment categories not considered in the TRM. · Verified equipment lifetimes with other sources such as U.S. DOE rulemakings.
Equipment Charge Size	· Reported in pounds of refrigerant per piece of equipment. · Single representative charge size defined for each type of HFC-using equipment. · "Charge size multiplier" can be applied to alternative refrigerant designs if known to have a smaller or larger charge size.	· Reviewed charge size for existing product categories in CARB TSD. · Conducted literature review to verify certain charge size assumptions from CARB TSD. · Consulted product specification sheets and internal product experts for equipment categories not covered by CARB (e.g., VRF systems in Section 2.1.5).
Annual Leak Rate	· Constant leak rate assumed across lifetime of equipment. · Users can vary the assumed leak rate of the installed stock each year post-2020.	· Used CARB TSD as primary source · Conducted literature review and consulted with internal equipment experts for any categories not covered by CARB.

Table 2-3 continued

Model Parameter	Key Model Assumptions/Limitations	Data Sources and Methodology
End-of-Life Loss Rate	· EOL emissions reflect equipment placed into service one "lifetime" ago, all retiring simultaneously. · Loss rate reflects the fraction of units reaching EOL whose refrigerant is emitted into the atmosphere	· Used CARB TSD as primary source. · Conducted literature review and consulted with internal equipment experts for any categories not covered by CARB.
Service Frequency	· Service interval (in years) defined for each product category	· Used CARB TSD as primary source · Conducted literature review and consulted with internal equipment experts for any categories not covered by CARB.
Refrigerant Allocations	· For each equipment type, refrigerant allocations represent the portion of shipments each year containing each refrigerant.	· Used CARB F-Gas ODS-to-HFC Transition Timeline to apportion refrigerant types by equipment category for the period 1990–2020. · Verified HFC apportionment for certain equipment categories through literature review and consultation with internal product experts.
Refrigerant GWP Values	· Four different GWP methodologies are available to evaluate results (AR4 vs. AR5; 100-year vs. 20-year) · CFC and HCFCs assigned GWP value of 0 for HFC inventory purposes.[20]	· GWP values obtained from AR reports · Where unavailable, GWP values for HFC blends determined by calculating weighted average of pure components.

Sections 2.1.6 and 2.1.7 describe differences in the overall modeling approach used for the Transportation HVAC&R and "Other" categories, due to the unique nature of these categories in comparison to the building HVACR equipment categories.

2.1.5 Charge Size Differences by Equipment Type and Efficiency

Most HFC inventories consider all packaged central residential and commercial HVAC equipment with the same refrigerant charge size regardless of equipment category or efficiency level. Guidehouse reviewed manufacturer product literature to understand whether there are key differences in charge size for heat pump versus cooling-only products and different equipment types (e.g., central split, roof top unit [RTU], variable refrigerant flow [VRF], ground source heat pump [GSHP]). The analysis suggests significant charge size differences between equipment categories, as well as by efficiency level within each category for some manufacturers.

Table 2-4 highlights key differences between comparable residential central split-system products. Charge size typically increases with efficiency level due to the use of larger heat exchangers. Heat pumps have higher charge size in comparison to AC-only products due to the addition of components that provide reversible heating functions. There is significant variation by manufacturer based on individual product design decisions.

Table 2-4. Charge Size Differences between Residential Central Split-System Products

Manufacturer (3 ton central split-systems)*	Standard Efficiency (SEER 13–14) Charge Size (pounds)			Medium Efficiency (SEER 16–17) Charge Size (pounds)			High Efficiency (SEER >20) Charge Size (pounds)		
	AC	HP	% Increase HP vs. AC	AC	HP	% Increase	AC	HP	% Increase HP vs. AC
Carrier	4.9	7.7	57%	9.3	13.7	48%	12.7	13.1	3%
Daikin	5.0	7.2	44%	7.1	10.6	49%	9.6	17.0	77%
York	6.0	12.0	100%	**	**	**	7.0	11.0	57%
Average	**5.3**	**9.0**	**69%**	**8.2**	**12.2**	**49%**	**9.8**	**13.7**	**40%**

* Detailed model data for Trane and Lennox products is not publicly available.

** York's medium efficiency models showed the opposite effect, in which the heat pump had a smaller charge size than the AC-only product, and charge size was smaller than standard and high efficiency models. These products have been excluded from the table because they incorporate different compressor platforms and other significant design changes compared to the other models listed in the table. This highlights how manufacturer design decisions can significantly impact charge size.

2.1.5.1 Charge Size Differences: Commercial Rooftop Units and Variable Refrigerant Flow

Similar to central spit-systems, commercial rooftop units (RTUs) with heat pump function have higher charge than AC-only models, and high-efficiency models have higher charge than standard efficiency models. Variable refrigerant flow (VRF) heat pumps have significantly higher charge than RTUs, assuming typical refrigerant line lengths. VRF models assume 300 feet of refrigerant lines. Total line length can vary significantly by installation.

Table 2-5. Charge Size Differences Between Commercial Rooftop Unit Heat Pumps

Manufacturer (8-ton models)	Standard Efficiency (SEER 13–14) Charge Size pounds)		Medium Efficiency (SEER 16–17) Charge Size pounds)		High Efficiency (SEER >20) Charge Size (pounds)				
	AC-Only RTU	HP RTU	AC-Only RTU	HP RTU	AC-Only RTU	HP RTU	VRF HP*	VRF w/ Heat Recovery*	VRF w/ HR and Low Ambient*
Average Across Carrier, Daikin, and Mitsubishi	14	21	19	24	22	26	58	61	64

*VRF models assume 300 ft of refrigerant lines. Total line length can vary significantly by installation.

Ground source heat pumps (GSHP) with water/glycol loops have comparable charge size as split-systems (4–6 pounds). GSHP with direct ground exchange (DX-GSHP) with refrigerant have much higher charge sizes, likely similar in magnitude to VRF systems. This type of GSHP is much less common than water/glycol loop systems. E3 has indicated that they do not intend to break-out the different types of GSHPs. Without additional data suggesting that adoption of DX-GSHPs in New York State will significantly rise, these systems were not modeled separately from water/glycol GSHPs.

2.1.5.2 Approach for Modeling Charge Size Differences

The analysis suggests significant charge size differences between equipment categories, as well as efficiency levels within each category. The model incorporates separate stock and charge size differences between AC-only versus heat pump products and key equipment categories (central, GSHP, RTU, VRF) to better align with the E3 pathways modeling. The increasing adoption rate of some of these categories (e.g., GSHP, VRF), and the magnitude of difference in charge size, warrants tracking these separately.

The model does not separately model charge size differences by efficiency level due to (1) uncertainty of future sales estimates for standard, medium, and high-efficiency products in NYS; (2) inconsistent differences in charge size across different manufacturers; and (3) the likelihood of future manufacturer design changes to accommodate low-GWP A2L refrigerants. Guidehouse could consider performing a sensitivity analysis of efficiency level differences based on E3's pathway modeling on the need for high-efficiency products to meet Climate Act targets.

2.1.6 Transportation HVAC and Refrigeration

Stock estimates for the Transportation HVAC and Transportation Refrigeration categories were determined using a different method than for the building HVACR equipment categories. Whereas building HVACR equipment stock is calculated as a saturation rate multiplied by a key economic indicator (e.g., number of residential housing units), the stock of vehicles is set equal to the number of vehicle registrations as determined by the sources shown in Table 2-6.

Table 2-6. Vehicle Stock Assumptions and Data Sources for Transportation HVAC and Refrigeration Categories

Model Parameter	Key Model Assumptions	Data Sources
Vehicle Stock	· Set equal to number of vehicle registrations. · Vehicle registrations determined for "base" year using most readily available data (e.g., 2015 for Transportation HVAC; 2018 for Transportation Refrigeration). · Years prior to base year extrapolated using historical growth rate of vehicle registrations; assumes constant growth rate over that period. · Future years extrapolated using user-defined annual growth rate of vehicle registrations.	· Total vehicle registrations for Transportation HVAC based on E3's estimate of total vehicle stock in 2015. · Vehicle registrations for Transportation Refrigeration based on data from CARB for 2018, scaled to NYS based on population ratio.

Aside from the determination of vehicle stock, the same general modeling assumptions and methodology as described in section 2.1.4 were used for the Transportation HVAC and Refrigeration categories. In particular, a 15-year average lifetime was assumed across all vehicle categories. As with the building HVAC&R equipment categories, vehicles are assumed to retire at exactly the assigned lifetime (e.g., no distribution of survival time was assumed). Early "catastrophic" loss is not considered in the model. Existing stocks of vehicles with high-GWP refrigerants will continue to emit as long as they remain in service.

The Reference Cases assume that the large majority of light-duty and medium-duty vehicles have already transitioned to low-GWP alternative refrigerants (e.g., R-1234yf) by 2020, driven in part by corporate average fuel economy "credits" granted to vehicles using R-1234yf instead of the traditional HFC refrigerant beginning in 2010.[21]

2.1.7 Aerosols, Foams, Solvents, and Fire Suppressants

Aerosols, foams, solvents, and fire suppressants collectively comprise the "other" category in the emissions model. Because of the unique characteristics of each of these categories, they are considered individually and modeled separately from the bottom-up stock-based analysis that is used for the HVACR sectors. For the aerosols, solvents, and fire suppressants sectors, the products are generally assumed to be dispensed within the same year of manufacture, such that there is no stock buildup or rollover to account for, and emissions and consumption are equivalent in each year. The foams sector introduces significant complication because of the wide variety of foam products in which ODS substitutes are used (e.g., spray foam, expanded polystyrene (XPS) foam, flexible polyurethane, etc.). Each of these foam products have a different emissions profile, lifetime, and HFC composition, which would make developing a bottom-up stock analysis significantly more challenging than the residential and commercial equipment categories. Developing a stock estimate for foams also poses a challenge in terms of how they would be quantified (e.g., by volume, by mass, etc.).

To estimate historical emissions for these sectors, Guidehouse used a top-down scaling approach instead of a bottom-up vintaging approach. Guidehouse first used the Environmental Protection Agency (EPA) State Inventory Tool to estimate total national emissions for each of the categories. The national emission numbers were then scaled to New York State using the ratio of State population to national population, which varied in each of the years 1990–2020. This simple scaling process yielded a top-level estimate of emissions for each of the years 1990–2020. The next step was converting the top-level emission estimates from an AR4 100-year GWP methodology to each of the other three GWP methodologies. Information from the 2020 EPA GHG inventory report[22] and the CARB fluorinated greenhouse gases (F-Gas) to ODS Transition tool was used to disaggregate each sector into an assumed distribution of refrigerants used for each sector in each year. Finally, a "weighted GWP ratio" was calculated for each end-use and year in order to convert between AR4 100-year GWP and other methods (e.g., AR5 20-year). This ratio was applied as a multiplier to the top-line emissions estimates in each year.

Unlike the equipment categories, for the "other" categories Guidehouse assumed significant reductions in HFC emissions as part of the business-as-usual Reference Case no. 1 (and all subsequent reference cases and potential mitigation scenarios). According to Guidehouse discussions with industry representatives, the aerosol and foam industries have already begun transitioning from HFCs to other low-GWP substitutes, and the use of HFCs in these sectors is expected to phase out nearly completely by around 2030. Data from the EPA State Inventory Tool confirms that nationwide HFC emissions from aerosols peaked in 2015 and has steadily declined since then. Accordingly, Guidehouse modeled emissions from the aerosols category as continuing the same rate of decline until reaching zero emissions in 2032. EPA data also shows that HFC emissions from foams appears to have reached a plateau in 2018. Guidehouse modeled emissions from foams as peaking in 2018 and following a downward trajectory that mirrors the upward trajectory leading to the 2018 peak. In contrast to aerosols (in which emissions are assumed to occur in the same year as production/consumption), foams are used as building insulation and other applications with a 30- to 50-year lifetime and emit gases over the lifetime of the foam as well as at building end-of-life (for example, when a building is renovated or demolished). To account for this, the model limits the assumed reduction of HFC emissions from foam to 50% of the 2018 peak value, which is reached in 2028. This reflects an expectation that even after phasing out the use of HFCs by around 2028, the installed "stock" of foam products will continue to emit for another 30–50 years.[23]

2.2 Historical Inventory for Major End-Uses

The following sections summarize the key results of the updated historical HFC inventory.

2.2.1 NYS HFC Emissions 2005–2020 by End-Use Category

HFC emissions in New York State have grown from near-zero in 1990 to 21.2 MMT in 2020 (AR-5, 20-year GWP), as shown in Figure 2-4, driven by the use of HFCs to replace CFCs/HCFCs as they were phased down (primarily) and economic growth in the State (secondarily). In particular, commercial refrigeration, commercial HVAC, and residential HVAC have all shown large increases since 2005. Once all vintage CFC/HCFC equipment has reached end of life, future HFC growth will be slower and reflective of economic growth in the State. HVAC&R categories grew most dramatically after 2010, when HFCs became the predominant refrigerant for stationary cooling applications, replacing ODS refrigerants. HFC use for mobile air conditioning (which began in the 1990s), as well as foams, aerosols, and solvents ("other") has grown only modestly since 2010 and has already begun declining as these categories transition to lower-GWP options. The estimate of 1990 emissions from this analysis was used by DEC to establish certain Climate Act reduction requirements into regulation.[24] All values from this report will be integrated into an updated GHG inventory report, to be issued by DEC in 2021.

Figure 2-4. Hydrofluorocarbon Emissions by End-Use Subcategory (1990–2020)

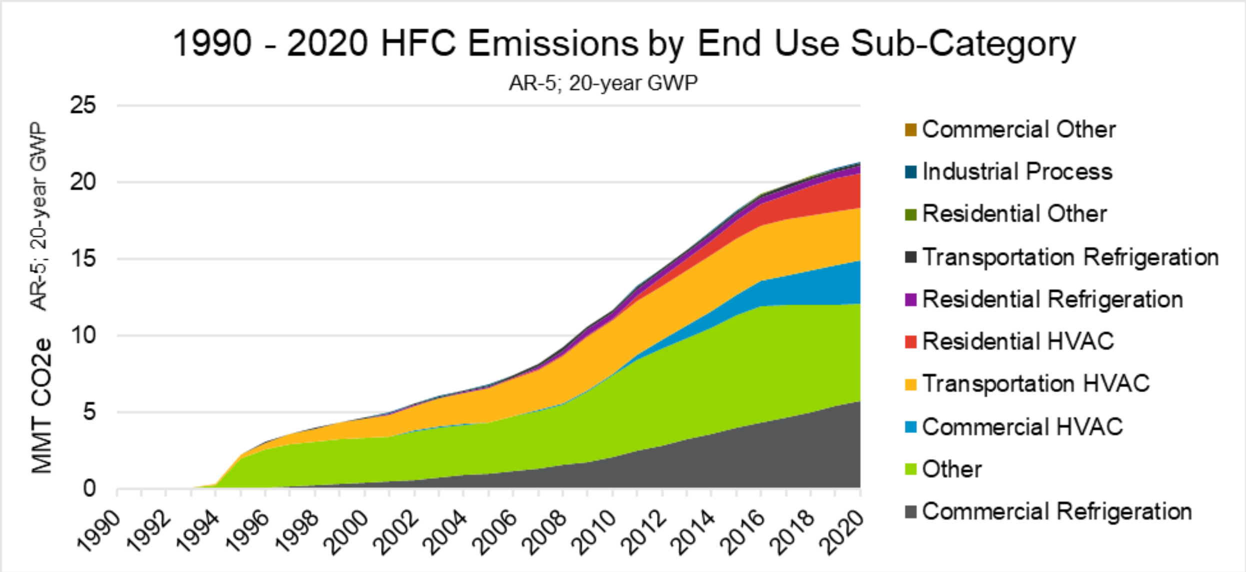


Table 2-7 summarizes the estimated HFC emissions by category in five-year increments during the period 2005 to 2020.

Table 2-7. New York State Hydrofluorocarbon Emissions 2005–2020 by End-Use Category, in MMT CO_2e (AR-5 20-year)

End-Use Sub-Category	2005	2010	2015	2020	2020 % of Total	Notes
Residential HVAC	0.03	0.14	1.16	2.32	10.9%	Includes AC, HP, GSHP, and room products.
Residential Refrigeration	0.05	0.40	0.41	0.42	2.0%	Includes refrigerators and freezers.
Residential Other	0.00	0.00	0.02	0.06	0.3%	Includes HPWHs, dehumidifiers.
Commercial HVAC	0.02	0.05	1.40	2.84	13.3%	Includes AC, HP, PTAC, VRF, ductless, GSHP, and chiller products.
Commercial Refrigeration	1.03	2.06	3.98	5.71	26.8%	Includes supermarket, walk-ins, reach-ins, vending machines, icemakers.
Commercial Other	0.00	0.00	0.00	0.00	0.0%	Includes HPWHs
Industrial Process	0.01	0.02	0.03	0.04	0.2%	
Transportation HVAC	2.23	3.51	3.62	3.39	15.9%	Light-, medium-, heavy-duty, and buses.
Transportation Refrigeration	0.13	0.17	0.18	0.19	0.9%	
Other	3.29	5.35	7.32	6.34	29.8%	Aerosols, Foams, Solvents.
Total	**6.79**	**11.70**	**18.12**	**21.31**	**100%**	

2.2.1.1 Building HVAC Hydrofluorocarbon Emissions Subcategories

Residential and commercial central AC-only systems account for the majority of building HVAC emissions today, but heat pump/VRF systems are expected to increase in future years due to heating electrification. As described in section 2.1.5, the analysis suggests significant charge size differences between equipment categories: heat pumps have 33% greater charge than AC-only products, and VRF systems have at least two times greater charge than other heat pump products. Packaged terminal air conditioning (PTACs), chillers, room ACs, and other self-contained systems have low-HFC emissions due to relatively low-leak rates. Many of these end-uses are already transitioning to low- and ultra-low-GWP options, including R-32, R-513A, and R-1234yf.

Table 2-8 summarizes the 2020 HFC emissions for HVAC applications by equipment type.

Table 2-8. 2020 Hydrofluorocarbon Emissions for HVAC by Equipment Type (AR-5, 20-year GWP)

Category	2020 Emissions MMT CO_2e (AR-5 20-year GWP)	% of 2020 HVAC Total
Commercial Central Split & Package AC, Large	0.78	15.1%
Commercial Central Split & Package AC, Small	0.68	13.1%
Commercial Central Split & Package HP, Large	0.15	2.9%
Commercial Central Split & Package HP, Small	0.22	4.4%
Commercial Chiller, Large Centrifugal	0.05	0.9%
Commercial Chiller, Medium	0.02	0.4%
Commercial Chiller, Small	0.33	6.4%
Commercial Ductless Split AC	0.23	4.4%
Commercial Ductless Split HP	0.11	2.1%
Commercial GSHP	0.00	0.1%
Commercial Room AC / PTAC / PTHP	0.03	0.6%
Commercial VRF HP, Large	0.02	0.4%
Commercial VRF HP, Small	0.22	4.3%
Residential Central AC	1.68	32.6%
Residential Central HP	0.10	1.9%
Residential Ductless Split AC (Placeholder)	0.00	0.0%
Residential Ductless Split HP (Placeholder)	0.00	0.0%
Residential GSHP	0.04	0.7%
Residential Window AC	0.50	9.8%
Grand Total	**5.16**	**100.0%**

2.2.1.2 Building Refrigeration Hydrofluorocarbon Emissions Subcategories

Refrigeration systems for supermarkets, cold storage, and food service account for approximately 90% of building refrigeration emissions today (approximately 50% of total building HFC emissions), even though other refrigeration segments have a much larger installed base. Supermarket racks, refrigerated warehouse, and walk-in refrigeration systems have high-leak rates and use high-GWP refrigerants. Most HFC phasedown policies have targeted these segments as high priority for refrigerant phasedown and leakage management. Residential-style refrigerators, freezers, ice makers, vending machines, and other self-contained systems have low-HFC emissions due to low-leak rates. Many of these technologies are already transitioning to isobutane (R-600a) or other natural refrigerants with ultra-low-GWP.

Table 2-9 summarizes the 2020 HFC emissions for refrigeration applications by end-use category.

Table 2-9. 2020 Hydrofluorocarbon Emissions for Refrigeration by Equipment Type (AR-5, 20-year GWP)

Equipment Type	2020 Emission MMT CO_2e (AR-5 20-year GWP)	% of 2020 Refrigeration Total
Commercial Ice Makers	0.01	0.1%
Commercial Refrigerated Warehouse, Large	0.15	2.4%
Commercial Refrigerated Warehouse, Medium	0.03	0.5%
Commercial Refrigerator/Freezer	0.01	0.2%
Commercial Self-Contained Display Cases/Reach-ins	0.07	1.1%
Commercial Supermarket Racks, Large	0.51	8.3%
Commercial Supermarket Racks, Medium	3.08	50.2%
Commercial Vending Machines	0.01	0.1%
Commercial Walk-ins/Remote Condensing, Large	0.66	10.8%
Commercial Walk-ins/Remote Condensing, Small	1.18	19.3%
Residential Freezer	0.06	1.0%
Residential Refrigerator/Freezer	0.36	5.9%
Grand Total	**6.13**	**100.0%**

2.2.1.3 Transportation and Other Hydrofluorocarbon Emissions Subcategories

HFC emissions across transportation and other subsectors have remained relatively flat since 2010, whereas emissions from heat pump water heaters and clothes dryers may increase slightly in future years with building electrification trends. Nevertheless, heat pump water heaters (HPWH) are unlikely to be a significant contributor to HFC emissions if the leakage rates are similar to other self-contained systems (1–2%/yr). Transportation cooling is currently transitioning from the HFC refrigerant R-134a to the ultra-low-GWP refrigerant R-1234yf.

Table 2-10 summarizes the 2020 HFC emissions for transportation and “other” applications by end-use equipment.

Table 2-10. 2020 Hydrofluorocarbon Emissions for Transportation and Other Equipment by End-Use Equipment (AR-5, 20-year GWP)

Equipment Type	2020 Emissions MMT CO_2e (AR-5 20-year GWP)	% of 2020 Total for Listed Equipment Types
Aerosol Propellants	3.34	33.7%
Commercial Water Heater HP	0.00	0.0%
Foams	2.42	24.4%
Industrial Process	0.04	0.4%
Residential Clothes Dryer HP	0.00	0.0%
Residential Dehumidifier	0.03	0.3%
Residential Water Heater HP	0.02	0.3%
Solvents and Fire Suppressant	0.59	5.9%
Transportation Buses	0.19	1.9%
Transportation Light Duty Vehicles	2.85	28.8%
Transportation Medium Duty Vehicles	0.25	2.5%
Transportation Refrigeration	0.19	1.9%
Grand Total	**9.92**	**100.0%**

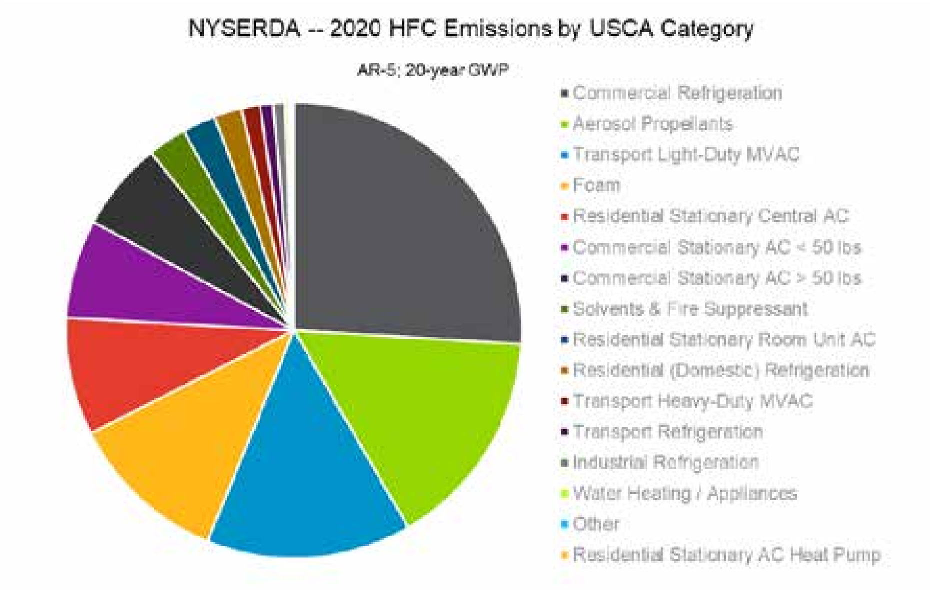
2.2.1.4 Comparison of Hydrofluorocarbon Emissions Categories

Commercial refrigeration and space cooling systems for residential, commercial, and mobile applications account for approximately 70% of statewide HFC emissions. Commercial refrigeration includes supermarket and walk-in systems, which have high-leak rates and high-GWP refrigerants today. Light-duty vehicle emissions should decrease in the future based on current industry transition to R-1234yf. Building AC systems have large installed bases using R-410a and will be challenging to transition to alternatives. Aerosols, foams, and other non-HVAC&R end-uses account for approximately 15% of HFC emissions.

Figure 2-5 shows the relative breakdown of 2020 HFC emissions by category according to the categories defined by USCA.

Figure 2-5. Relative Breakdown of 2020 Hydrofluorocarbon Emissions by United States Climate Alliance Category (20-year GWP AR-5)

Listed in clockwise order from largest to smallest.



2.2.2 Hydrofluorocarbon Emissions by Annual and End-of-Life Leakage

Leakage over equipment lifetime is the greatest source of emissions for most categories. Completely sealed, self-contained systems like residential refrigeration and heat pump water heaters (categorized as "residential other") have very low leakage, resulting in a greater share of end-of-life emissions. Mitigation options can be designed to best address the most prevalent leakage source in each category. For example, California's Refrigerant Management Program (RMP) targets annual leakage in supermarkets and cold storage, whereas a utility recycling program for refrigerators, freezers, room ACs, and HPWHs would target end-of-life leakage.

Figure 2-6 and Figure 2-7 show HFC emissions by cause (annual leakage versus end of life) and end-use category in terms of MMT CO_2e and percent of total, respectively.

Figure 2-6. Hydrofluorocarbon Emissions by Cause and End-Use Category, 2020 (MMT CO_2e AR-5 20-year GWP)

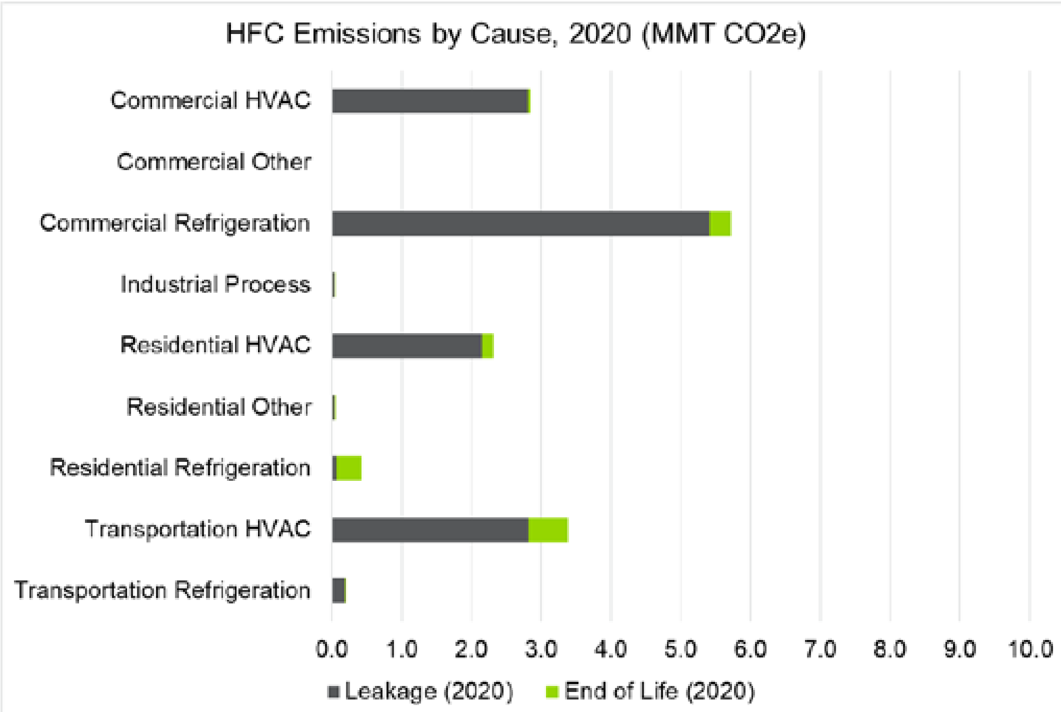
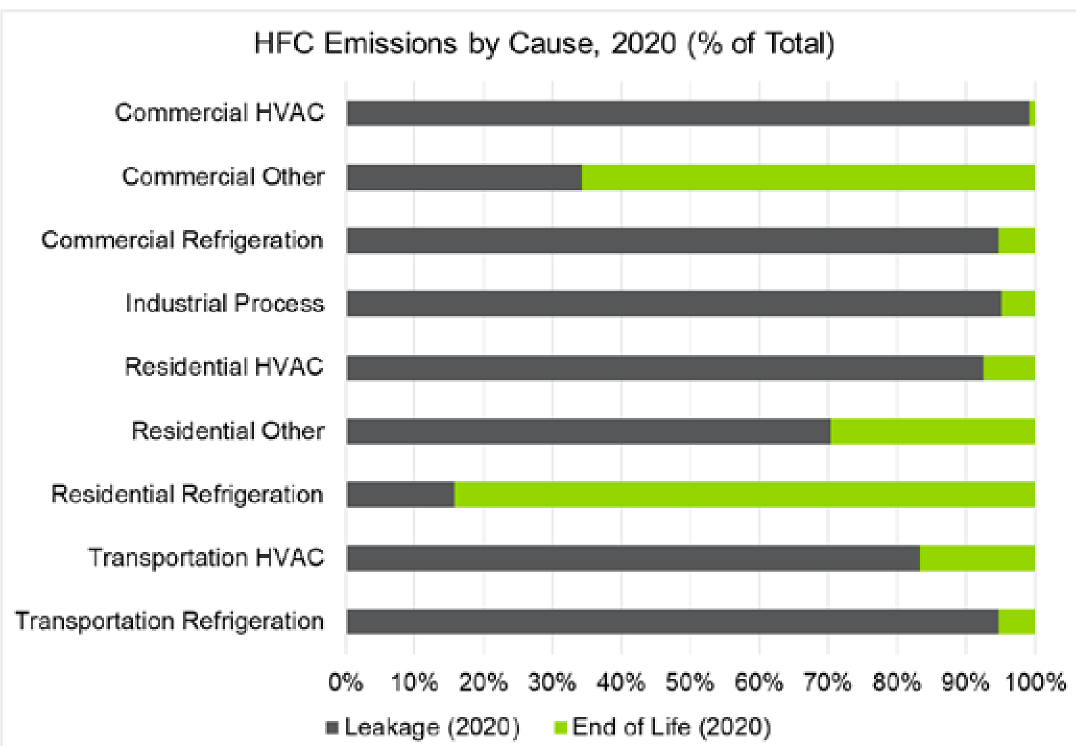


Figure 2-7. Hydrofluorocarbon Emissions by Cause and End-Use Category, 2020 (% of total) (AR5 20-year GWP)



2.2.3 Comparison of AR4 100-Year and AR5 20-Year Inventories

Climate Act analysis requires 20-year GWP values, whereas 100-year GWP values are important for historical tracking and discussions with industry stakeholders. Historically, AR4 100-year GWP values have been used in GHG inventories. The Guidehouse model provides the ability to view results using any of the four GWP methodologies listed in Table 2-10, in order to assist DEC in meeting the Climate Act requirement to publish the Inventory Report in AR5 20-year GWP. In this report, future projections of HFC consumption/emissions are based on AR5 20-year GWP. Table 2-11 compares 2020 HFC emissions by subcategory across 100-year and 20-year GWP values for AR4 and AR5.

Table 2-11. 2020 Hydrofluorocarbon Emissions by Subcategory MMT CO_2e

Category	AR4-100	AR5-100	AR4-20	AR5-20
Commercial Refrigeration	3.38	3.36	5.40	5.71
Other	2.15	2.04	6.34	6.34
Commercial HVAC	1.38	1.28	2.90	2.84
Transportation HVAC	1.31	1.19	3.50	3.39
Residential HVAC	1.13	1.04	2.36	2.32
Residential Refrigeration	0.16	0.15	0.43	0.42
Transportation Refrigeration	0.08	0.08	0.19	0.19
Residential Other	0.02	0.02	0.06	0.06
Industrial Process	0.02	0.02	0.04	0.04
Commercial Other	0.00	0.00	0.00	0.00
TOTAL	**9.63**	**9.19**	**21.22**	**21.31**

AR5 20-year GWP values results in significantly higher emissions than AR4 100-year values. There are only minor changes in GWP values for individual gases between Intergovernmental Panel on Climate Change (IPCC) AR4 and AR5.

2.3 Summary of Key Findings

Based on the analysis, the key findings regarding the historical HFC emissions inventory for New York State include the following:

- Charge size typically increases with efficiency level; and heat pumps typically have higher charge size in comparison to AC-only products. The Guidehouse model incorporates separate stock and charge size differences between AC-only versus heat pump products and key equipment categories but does not separately model charge size differences by efficiency level.

- Due to the unique characteristics of aerosols, foams, solvents, and fire suppressants, these categories were modeled using a top-down scaling approach instead of a bottom-up vintaging approach.
- HFC emissions in New York State have grown from near-zero in 1990 to 21.2 MMT in 2020 (AR-5, 20-year GWP), driven by CFC/HCFC phasedowns (primarily) and economic growth in the State (secondarily). Beyond 2020—as all vintage CFC/HCFC equipment reaches end-of-life—business-as-usual growth in HFC emissions will be much slower.
- Commercial refrigeration is the largest contributor to HFC emissions in 2020, followed by aerosol propellants and light-duty MVAC.
- Commercial and Residential HVAC and refrigeration are the fastest-growing sources of emissions, while Transportation and "Other" categories are steady or declining.
- For most categories, annual leakage throughout equipment lifetime is a much greater source of emissions than end-of-life leakage.
- Heat pump systems have a relatively small contribution to total emissions in 2020 but are expected to grow substantially as heating electrification increases in New York State. This trend is further discussed in section 3.
- Heat pump water heaters are unlikely to be a significant contributor to HFC emissions, assuming leakage rates are similar to other self-contained systems (i.e., very minor).

3 Projected Future Reference Cases for Hydrofluorocarbon Carbon Emissions in New York State

This section describes Guidehouse's analysis into future HFC consumption and emissions in New York State based on expected growth rates, established HFC phasedown policies, and decarbonization pathways to achieve Climate Act goals. These projections serve as the reference cases for the evaluation of additional potential HFC mitigation strategies in section 5.

3.1 Future Reference Cases

Guidehouse developed a series of future Reference Cases to estimate HFC emissions in New York State during the period 2021–2050, building on the historical HFC inventory (1990–2020) and incorporating the data sources described in section 2.1. Table 3-1 highlights the major components of each future Reference Case, with each reference case building upon the assumptions of the previous reference case. These future reference cases are referred to by number (i.e., Reference Case no. 2) throughout the discussion in this section. Reference Case no. 1 represents "business as usual," in which growth of HFCs follows natural economic growth. Reference Case no. 2 assumes an increased adoption of residential air conditioning systems commensurate with the expectation that climate change will create warmer and more extreme summers (up for approximately 90% today). Reference Cases no. 1–2 do not include necessary energy-related solutions to meet Climate Act goals (e.g., building heating electrification). Reference Cases no. 3–5 represent a more realistic baseline for the future of New York State since these projections include the building electrification strategies to meet Climate Act goals. Reference Cases no. 3–4 are based on the High Technology Availability Pathway and the Limited Non-Energy Pathway, respectively, from the Pathways to Deep Decarbonization in New York State report prepared for NYSERDA by E3. Reference Case no. 5 includes the aforementioned assumptions from Reference Cases no. 2–4, plus the 6 NYCRR Part 494 regulation (2020 NYS SNAP Rule[25]) in effect today. When modeling the potential HFC Mitigation Scenarios in section 5, Reference Case no. 5 (no. 4 E3's Limited Non-Energy Scenario plus Implementation of 2020 NYS SNAP Rule) is used as the starting point for evaluating different potential HFC mitigation strategies.[26]

Table 3-1. Modeled References Cases

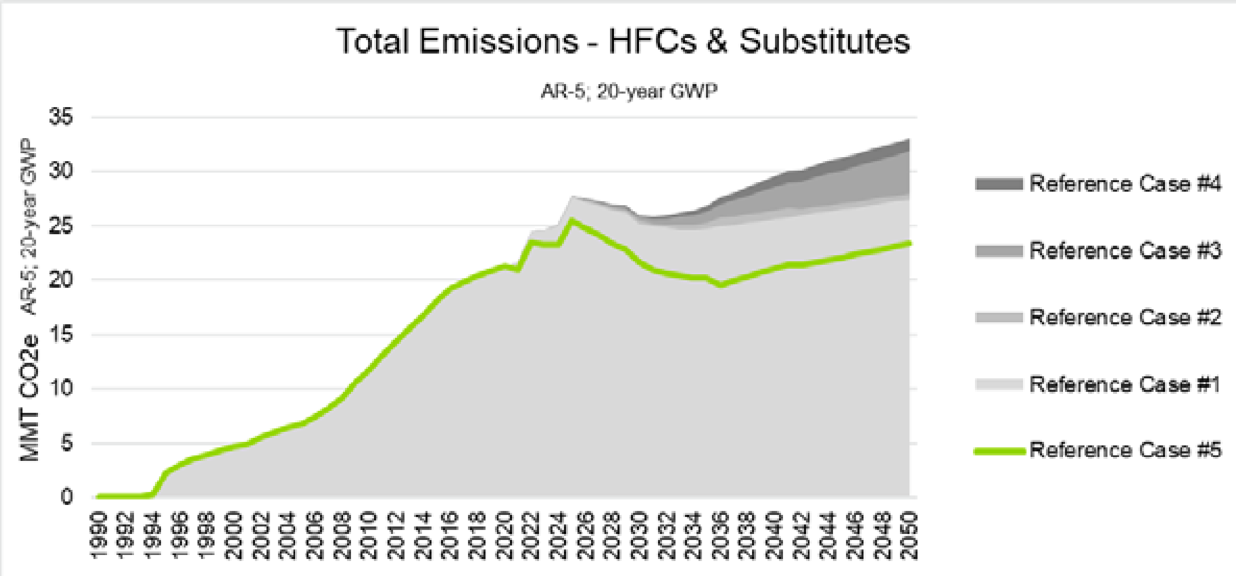
Bold highlighted cells denote key change in scenario in relation to previous scenario. Each reference case builds upon the previous reference case.

Key Parameter	Reference Case no. 1	Reference Case no. 2	Reference Case no. 3	Reference Case no. 4	Reference Case no. 5
Description	Business as usual with years 2021–2050 matching year 2020	No. 1 + Transition to 100% saturation of Residential AC	No. 2 + E3's "High Tech" scenario	No. 3 + E3's "Limited Non-Energy" scenario	No. 4 + Implementation of 2020 NYS SNAP Rule
Residential AC Saturation	Approx. 90%	**Approx. 100% due to climate change**	Approx. 100% due to climate change	Approx. 100% due to climate change	Approx. 100% due to climate change
HFC Phasedown Policies	None	None	None	None	**2020 NYS SNAP Rule, No further actions**
Low-GWP Leak Rates	None	When new equipment using low-GWP refrigerants enter the market, a 50% reduction in annual leak rate is applied, based on AHRI estimates (Link) for improved design and maintenance practices with flammable and mildly flammable (A2L) refrigerants.			
End-of-Life Recovery	For large systems (e.g., commercial central AC, chillers, warehouse, supermarkets) and transportation, assume relatively high EOL recovery (around 70–80%). For small systems, much lower EOL recovery rates (approximately 0–50%), depending on specific application.				
Building Electrification Policies	None	None	**50% of sales by 2030; 95% by 2050**	**70% of sales by 2030; 100% by 2045**	70% of sales by 2030; 100% by 2045

Figure 3-1 highlights the future HFC emissions for New York State under each of the future Reference Cases (no. 1-5) described in Table 3-1.

Figure 3-1. Hydrofluorocarbon Emissions Across All Reference Cases (1990–2050)

Each reference case builds upon the previous reference case.



The following general trends are apparent in each of the future Reference Cases:

- **Reference Case no. 1: Business-as-usual:** Without considering climate change, heating electrification, or the 2020 NYS SNAP Rule, HFC emissions are expected to continue to grow over time in New York State due to continued economic and building growth. The more rapid growth occurs over 2020–2025 due to continued retirements of the HVAC&R products using CFC/HCFC refrigerants. These refrigerants are replaced with new equipment using HFC refrigerants and combined with retirements from the first generation of products that adopted HFCs in the early 2010s when HFCs became the predominant refrigerant. With lifetimes between 10–20 years, these first systems reach end-of-life during this time and consequently we see a significant spike in end-of-life refrigerant emissions. HFC emissions decrease during the period 2030–2035 due to the voluntary adoption of low-GWP refrigerants in some sectors (e.g., mobile AC, other end-uses including foams, aerosols, and solvents). However, after 2035 emissions begin to increase again due to economic and building growth.
- **Reference Case no. 2: Reference Case no. 1 plus transition to 100% saturation of Residential AC:** Residential AC systems would experience greater emissions in the future as more NYS residents install air conditioning to maintain comfort in future summers that are expected to experience more extreme temperatures due to climate change. This Reference Case shows the impact of increasing from approximately 90% residential AC adoption to nearly 100% over the period of 2021–2030. Because New York State already has a high penetration of residential AC systems, the magnitude of this impact is modest. A similar projection for states with lower AC saturation (e.g., Washington, California) would see a more significant increase.

- **Reference Case no. 3: Reference Case no. 2 plus E3's "High Tech” Scenario:** This Reference Case includes building electrification strategies necessary to meet the energy-related Climate Act goals, with Reference Case #3 having an adoption timeline of 50% of sales by 2030, and 95% by 2050. As described in Section 2.1.5, most heat pump systems, particularly VRF systems, have higher charge size than comparable AC-only systems, which causes HFC consumption and emissions to increase as more buildings replace AC-only systems with heat pumps. Furthermore, conventional fuel-fired or electric resistance water heaters do not use refrigerants, so a heat pump model introduces refrigerant where previously none existed. Under this scenario, by 2050, the majority of the residential and commercial building market in New York State would be using heat pump systems, which further contributes to the increase in overall HFC emissions in the state.
- **Reference Case no. 4: Reference Case no. 3 plus E3's Limited Non-Energy scenario:** This Reference Case builds upon Reference Case no. 3 by considering a more rapid adoption of heat pumps for residential and commercial buildings (70% of sales by 2030, 100% by 2045). The greater number of heat pumps would increase HFC emissions beyond the increases associated with Reference Case no. 3.
- **Reference Case no. 5: Reference Case no. 4 plus Implementation of 2020 NYS SNAP Rule (Green Line):** The 2020 NYS SNAP Rule restricting the use of high GWP refrigerants for residential and commercial refrigeration, commercial chillers, and other segments is expected to have a significant impact on decreasing future HFC emissions in the State. HFC emissions will decrease over time as older HFC units reach end-of-life and the installed base of low- and ultra-low-GWP options increases. The restrictions take effect during the period 2021–2024 and reach 100% of the market approximately 10–20 years later, depending on the end-use. HFC growth in other segments from economic development contributes to returning growth in the years 2036–2050. The HFC emissions reductions achieved by the 2020 NYS SNAP Rule outweighs the impacts of heating electrification (Reference Cases no. 3–4), reflecting an overall HFC emissions reduction for NYS.

Figure 3-2 highlights the HFC emissions by end-use subcategory under Reference Case no. 1. Without considering climate change, heating electrification, or the 2020 NYS SNAP Rule, most HFC end-use categories will continue to increase over time due to economic development in the State. In addition, during the period 2020–2025, some HVAC&R equipment categories will not yet have experienced end-of-life emissions. After 2025, every HVAC&R end-use category will have turned over one complete cycle of HFC equipment, such that end-of-life emissions contributions will be reflected in more steady-state growth rates. Categories Transportation HVAC and Other show decreases over 2020–2030 since these sectors are undergoing an industry-lead voluntary transition to lower-GWP options.

Figure 3-2. Hydrofluorocarbon Emissions by End-Use Subcategory, Reference No. 1 (1990–2050)

Each reference case builds upon the previous reference case.

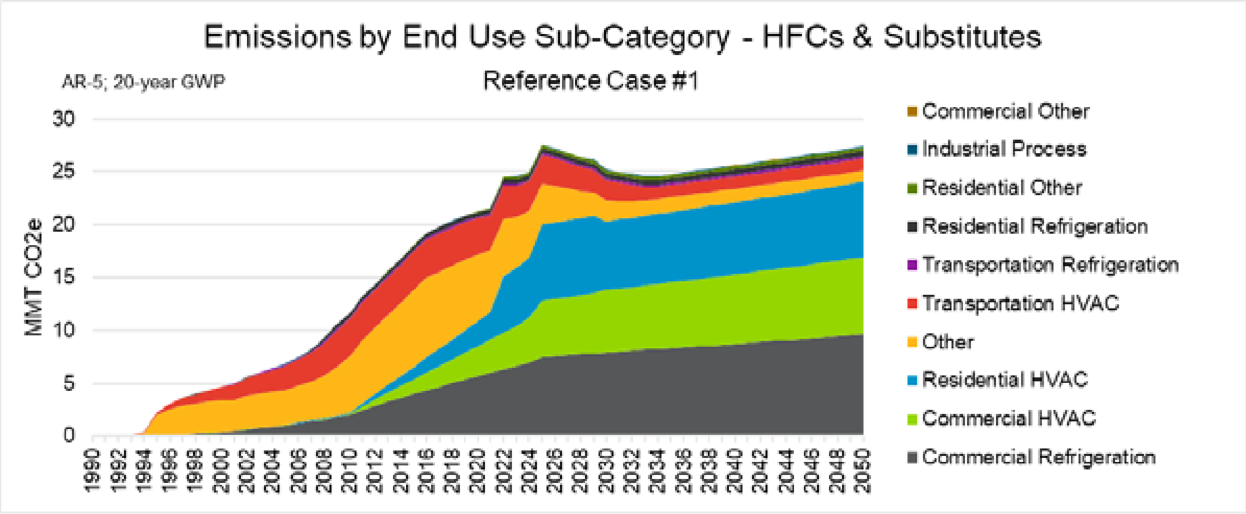


Figure 3-3 highlights the HFC emissions by end-use subcategory under Reference Case no. 4, which includes near-100% of residential AC adoption and space and water heating electrification of 70% by 2030 and 100% by 2045. Building electrification strategies will increase HFC emissions for the Residential and Commercial HVAC sectors, as well as the categories Residential and Commercial Other, which include HPWHs. While building electrification may increase HFC emissions, the strategy supports overall statewide GHG emissions reductions because the technologies help enable a transition away from fossil fuels and overall reductions in statewide emissions.[27] In the absence of mitigation steps, HFC emissions in NYS would increase further to 33 MMT CO_2e by 2050 (AR-5, 20-year GWP, +57% over 2020) due to economic growth, increased AC adoption due to climate change, and heating electrification goals.

Figure 3-3. Hydrofluorocarbon Emissions by End-Use Subcategory, Reference No. 4 (1990–2050)

Each reference case builds upon the previous reference case.

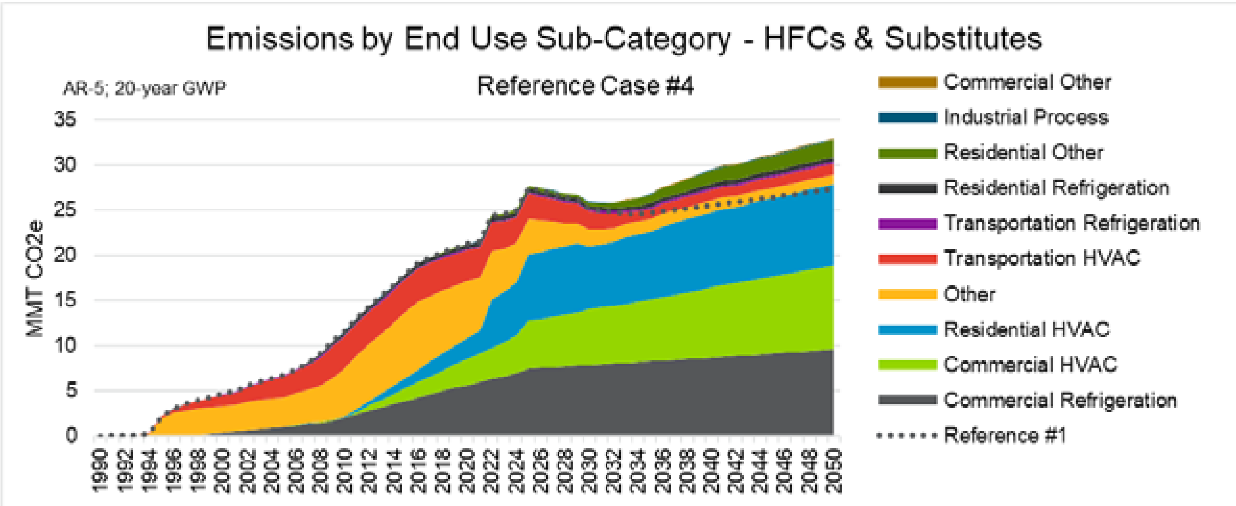
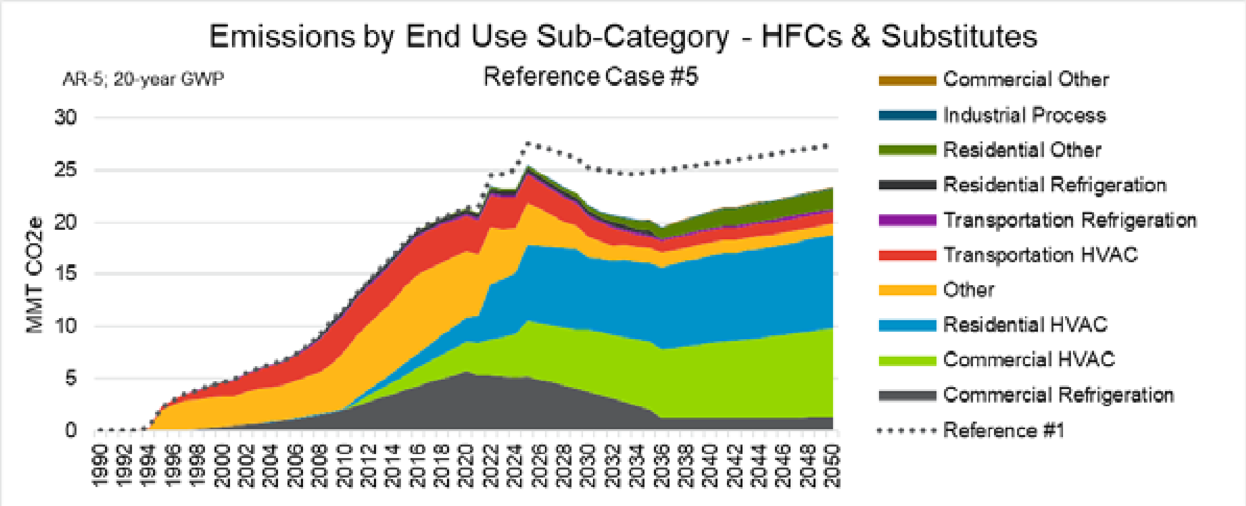


Figure 3-4 highlights the HFC emissions by end-use subcategory under Reference Case no. 5. The 2020 NYS SNAP Rule is expected to result in a significant reduction in future HFC emissions, most notably for the commercial refrigeration segment. Supermarket refrigeration systems have both high charge and leak rates, so the restrictions on high GWP refrigerants for this sector will have a major impact in future years. The rule targets new refrigeration systems, so the effects are realized over the roughly 15-year timeframe of 2021–2036 as the installed stock of HFC systems is replaced by new systems using low-GWP options. Commercial chillers are also impacted by the 2020 NYS SNAP Rule; however, they are less significant contributors to HFC emissions due to their lower leak rates. The Guidehouse model results indicate that HFC emissions reduction achieved by the 2020 NYS SNAP Rule will outweigh the impacts of heating electrification (Reference Cases no. 3–4), resulting in an overall HFC emissions reduction of approximately 30% from Reference Case no. 1.

Figure 3-4. Hydrofluorocarbon Emissions by End-Use Subcategory, Reference No. 5 (1990–2050)

Each reference case builds upon the previous reference case.



3.2 Key Trends Impacting Future Reference Cases

Guidehouse incorporated the following technology trends and policy actions in the future Reference Cases described above. In general, the trends for charge size differences and reduced leak rates for flammable refrigerants will further increase the HFC emissions savings when transitioning from high GWP HFCs to lower-GWP alternatives. Low-GWP refrigerants have less than 750 GWP (AR4 100-year), and ultra-low-GWP refrigerants have less than 10 GWP (AR4 100-year). As described in Reference Case no. 5, the 2020 NYS SNAP Rule will have a significant impact on statewide HFC emissions. The following topics are further discussed in the report:

- Charge size differences for alternative refrigerants
- Reduced leak rates for alternative refrigerants
- New York State HFC phasedown policies

3.2.1 Charge Size Differences for Alternative Refrigerants

Manufacturers must consider a range of thermodynamic and chemical properties of refrigerant gases in addition to their GWP values during the system design and selection process. Available alternatives to high GWP refrigerants may have higher or lower charge size depending on the baseline HFC refrigerant (e.g., R-134a, R-404A, R-410a), candidate refrigerant (e.g., R-32, R-454B, R-466A, R-1234yf), and typical evaporating temperature per application (e.g., 25°C for air conditioning, 0 °C for refrigeration, or –30 °C for freezing). While manufacturers can optimize the system design around a given refrigerant to adjust charge size, some alternative refrigerants would inherently offer charge size reductions or increases based on their thermodynamic properties. If low-GWP refrigerants have lower charge size than today's HFCs, the emissions reduction potential of that refrigerant would be compounded since a lower amount of refrigerant would be leaked annually and at end-of-life.

To account for impact of changes in charge size in the modeling, Guidehouse developed a methodology to estimate charge size differences for alternative refrigerants based on heat of vaporization (HOV). HOV is the amount of energy required to transform a unit amount of liquid into the same amount of vapor (typically measured in units of kJ/kg). Through discussion with internal subject matter experts, Guidehouse identified HOV as the key driver for heat exchanger design, and thus overall system charge size. The higher the HOV of a refrigerant, the more energy it can absorb during evaporation, and the smaller the heat exchanger needs to be, assuming the charge ratio below:

$$Charge\ Ratio = \frac{Charge_{Substitute}}{Charge_{Base}} = \frac{HOV_{Base}}{HOV_{Substitute}}$$

Guidehouse validated this estimation method by comparing these charge size estimates with information available in public literature. Table 3-2 shows estimated charge size reductions between two common baseline refrigerants (R-410A and R-134A) and their likely low-GWP alternatives. Multiple estimates are shown to represent the HOV-ratio approach as compared to publicly available literature.

Table 3-2. Charge Size Ratio Estimates from Multiple Sources

Sources: AHRI-AREP-047,[28] *Cold Hard Facts,*[29] *Pardo,*[30] *AHR News.*[31]

Refrigerant Name	Designation	Charge Ratio from HOV Estimation	Charge Ratio from Publicly Available Literature
R-410A	Baseline	-	-
R-32	Substitute for R-410A	71%	76%–78%
R-454B	Substitute for R-410A	75%	85%
R-466A	Substitute for R-410A	118%	110%–115%
R-134A	Baseline	-	-
R-513A	Substitute for R-134A	111%	100%
R-1234yf	Substitute for R-134A	122%	92%–122%

Table 3-3 provides a comparison of charge size differences for HFC and low-GWP options for the use-cases analyzed in this report. Since HOV is a function of temperature, Guidehouse selected HOV values that were most appropriate for the equipment application (e.g., HOV @ 77°F for HVAC, HOV @ 32°F for refrigeration, HOV @ -22°F for freezing). Most low-GWP alternatives show a charge size reduction, including R-32, R-452B, R-454B, R-450A, R-513A, and hydrocarbons. Guidehouse did not consider charge size changes for ammonia as an alternative refrigerant because the GWP value of ammonia is zero, and therefore charge size has no impact on calculated emissions (which are zero, accordingly). Charge size increases will have negligible impact on ultra-low-GWP refrigerants (e.g., R-1234yf with GWP of 4). The relative charge size for low-GWP options does impact the attractiveness of individual refrigerants on overall emissions reduction. For example, R-32a appears to be a more attractive substitute than R-466a when replacing R-410a due to its lower-GWP and lower charge size.

Table 3-3. Charge Size Differences between Hydrofluorocarbon and Low-Global Warming Potential Alternatives

Charge Ratio is a ratio of the mass of alternative refrigerant required to properly charge a given system versus the mass of traditional HFC refrigerant required to properly charge an otherwise identical system.

Baseline Refrigerant [AR4 100-year GWP]	Equipment Types	Low-GWP Substitutes [AR4 100-year GWP]	Charge Ratio
R-134A [1430]	Commercial refrigerant, mobile/transport HVAC, Chillers, fridge/freezers, vending machines, industrial process refrigeration.	R-513A [631]	100%
		R-1234yf [4]	110%
		R-600a (isobutane) [3]	60%
		R-290 (propane) [3]	55%
R-404A [3922]	Supermarket racks, cold storage, some chillers, ice makers.	R-407A[2107]	85%
		R-448A/R-449A [1387/1397]	80%
		R-744 (CO_2) [1]	70%
R-407A [2107]	Supermarket racks, cold storage, some chillers, ice makers.	R-448A / R-449A [1387/1397]	95%
R-407C [1774]	Chillers	R-32 [675]	70%
R-410A [2088]	Residential and Commercial HVAC, chillers	R-32 [675]	75%
		R-452B [698]	85%
		R-454B [466]	80%
		R-466A [733]	115%
		R-1234ze [7]	120%
R-507 [3985]	Chillers, commercial refrigerant, commercial HVAC.	R-448A/R-449A [1387/1397]	80%
		R-450A [604]	85%
		R-513A [631]	90%

3.2.2 Reduced Leak Rates for Alternative Refrigerants

Described in greater detail in section 4.1, many low-GWP options are classified as “flammable (A3)” or “mildly flammable (A2L)” under ASHRAE Standard 34, whereas most HFCs and other refrigerants today are non-flammable (A1).[32] To address these fire and safety risks, applicable industry standards have established requirements for safety measures relating to system design, installation, and operation. The safety risk associated with leaks with flammable refrigerants is higher than that of conventional HFCs and creates an incentive for manufacturers and installers to minimize leaks, particularly when considering the perceived risks impacting market acceptance. Furthermore, several low-GWP options may have higher costs than HFC refrigerants, particularly in early years of market introduction, which incentivizes reduced leak rates to reduce lifetime maintenance costs.

To account for the anticipated industry improvements in leak rate for systems using flammable or mildly flammable refrigerants (those classified as A3 and A2L under ASHRAE Standard 34), a 50% reduction in annual leak rate has been applied for new equipment entering the market in each end-use category (e.g., domestic refrigerators change from 1.0% to 0.5% when adopting R-600a; commercial rooftop units change from 11.3% to 5.7% when adopting R-32). This assumption is based on a 2018 Air-Conditioning, Heating, and Refrigeration Institute (AHRI)-sponsored study into the consumer cost impacts of the Kigali Amendment:[33]

> The industry has an ongoing trend toward reduced refrigerant leak rate in residential and commercial air conditioning and refrigeration products. Leaks and recharging over the lifetime of air conditioning equipment without Kigali are estimated for this study to be equivalent to a leak rate of 10% per year. There is additional incentive to significantly lower the leak rate of flammable and low flammability low-GWP refrigerants, with the improvements applied to all equipment. The average leak rate is assumed here to be approximately 5% with Kigali [50% less than today], reducing consumer recharging costs.

Guidehouse discussed these assumptions with AHRI representatives, who confirmed that manufacturers anticipate significant leak rate reductions in future years and that these may be conservative estimates (i.e., actual leak rates may be even lower). Determining accurate leak rate information for HVAC&R systems using low-GWP refrigerants will require further laboratory and field research once products are introduced in the U.S. market. At such time, these assumptions can be adjusted.

3.2.3 New York State Hydrofluorocarbon Phasedown Policies

As discussed, in 2020, New York State DEC established regulations for the phasedown or prohibition of HFCs for specific end-use applications beginning January 1, 2021. Table 3-4 summarizes the impacts of these regulations for the HFC end-uses analyzed in this project. As described in the next section, the impacts of the 2020 NYS SNAP Rule are included in Reference Case no. 5. End-use categories not covered by the 2020 NYS SNAP Rule include: residential and commercial AC, HP, water heaters, and appliances (except chillers), industrial process cooling, mobile AC and refrigeration.

Table 3-4. New York State HFC Phasedown Policies by End-Use Sector

End-Use Sector (Equipment Type)	2020 NYS SNAP Rule Transition Timeline
Res Refrigerator/Freezer	High GWP prohibited Jan 1, 2022 (built-ins are 2023)
Res Freezers	High GWP prohibited Jan 1, 2022 (built-ins are 2023)
Small Chiller	High GWP prohibited Jan 1, 2024 (410a, 134a, others)
Medium Chiller	High GWP prohibited Jan 1, 2024 (410a, 134a, others)
Large Centrifugal Chiller	High GWP prohibited Jan 1, 2024 (410a, 134a, others)
Com Refrigerator / Freezer	High GWP prohibited Jan 1, 2022
Supermarket Racks, Large	High GWP prohibited Jan 1, 2021 (R404, R407, R507, others)
Supermarket Racks, Medium	High GWP prohibited Jan 1, 2021 (R404, R407, R507, others)
Walk-ins/Remote Condensing, Large	High GWP prohibited Jan 1, 2021 (R404, R407, R507, but not R410a or R134)
Walk-ins/Remote Condensing, Small	High GWP prohibited Jan 1, 2021 (R404, R407, R507, but not R410a or R134)
Self-Contained Display Cases / Reach-ins	High GWP prohibited Jan 1, 2021 depending on design (medium-R134a, R410a, R404, R407, R507, low-temp does not restrict 134a)
Vending Machines	High GWP prohibited, new Jan 1, 2022 (R134a, R410a), retrofits are 2021 (404, 507)
Refrigerated Warehouse, Medium	High GWP prohibited Jan 1, 2023 (410, 404, 407, 507, others)
Refrigerated Warehouse, Large	High GWP prohibited Jan 1, 2023 (410, 404, 407, 507, others)
Aerosols, Foams, Solvents, other HFCs	High GWP prohibited Jan 1, 2021 (134a, 227, and others)

3.3 Summary of Key Findings

The key findings regarding projected future Reference Cases include the following:

- Because New York State already has a high penetration of residential AC systems, increasing residential AC adoption to 100% has only a modest impact on overall emissions.
- Building electrification will cause a notable increase in HFC emissions during the period 2035–2050. Absent mitigation steps, HFC emissions in NYS would increase further to 33 MMT CO_2e (AR-5, 20-year GWP, +57% over 2020) due to economic growth, increased residential AC adoption due to climate change (to nearly 100% adoption, up from 91% today), and heating electrification goals.

- The 2020 NYS SNAP Rule restricting the use of high GWP refrigerants for residential and commercial refrigeration, commercial chillers, and other segments is expected to have a significant impact on decreasing future HFC emissions in the State, reducing HFC emissions by approximately 30% in 2050 compared to Reference Case no. 4, which includes heating electrification goals.
- In future HVAC&R systems, charge size reductions for many equipment types and reduced leak rates for flammable refrigerants will provide even greater HFC emissions reductions when transitioning from high GWP HFCs to lower-GWP alternatives.

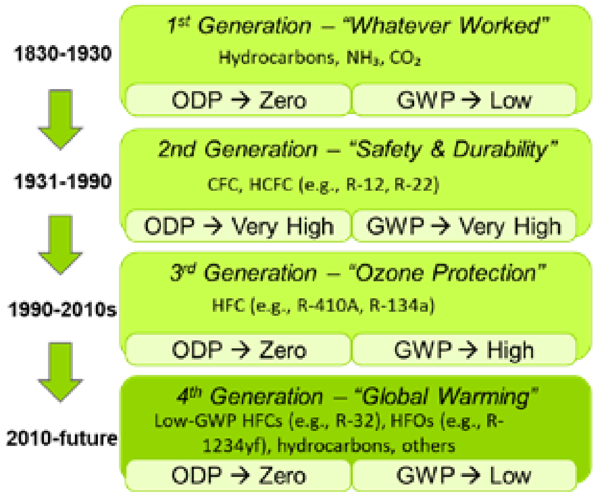
4 Alternatives to High-Global Warming Potential Refrigerants and Leakage Reduction Solutions

This section describes Guidehouse's analysis into available low-GWP refrigerants, leakage reduction technologies and policies, and RD&D initiatives to increase their adoption in NYS. The topics discussed in this section are included in the future Reference Cases (section 3.1) and potential HFC Mitigation Scenarios (section 5) analyzed in this report.

4.1 Technology, Market, and Policy Drivers Affecting Refrigerant Selection

The HVAC&R industry is transitioning to the fourth generation of refrigerants, shown in Figure 4-1 below, which substantially reduce GHG emissions and help mitigate the environmental impact of increased demand globally for comfort cooling and refrigeration. Similar transitions have occurred for other HFC-consuming segments including foams, aerosols, and solvents. Government entities, OEMs, and trade associations are continuing to work toward alleviating the barriers to deploy these next-generation refrigerants. The Montreal Protocol committed countries to phasing out second generation refrigerants, though some HCFCs are still in use. Many countries use third generation refrigerants today, and transitioning to low-GWP refrigerants will include revisiting some previously explored options, like CO_2 and hydrocarbons (R-290, R-600a). The transforming refrigerant landscape has resulted in risk assessments and mitigation measures that have allowed the use of some flammable refrigerants in certain applications.

Figure 4-1. Refrigerant Transitions Over Time[34]



Manufacturers and design engineers must consider many factors when selecting low-GWP refrigerants for new HVAC&R equipment and systems, as well as gases for foams, aerosols, and other applications. Specific refrigerant selection criteria include operating temperatures, system charge size, efficiency impacts, GWP, flammability, toxicity, and other thermodynamic and chemical properties. System designers must balance these characteristics and will typically favor a small number of refrigerants for any given application to reduce manufacturing and servicing complexity. Low-GWP options under consideration will typically share similar characteristics to the high GWP refrigerant targeted for replacement, except for potentially flammability and toxicity properties. While many options are promising, there are several barriers restricting the wide use of low-GWP refrigerants in some or all applications using HFCs today:

- Building, fire, and safety codes
- EPA SNAP approval
- Lack of federal low-GWP regulation specific to many applications
- Technician training
- Potentially higher costs of gases or systems
- Lack of awareness for industry professionals and end-users
- Equipment sell-through dates and neighboring states
- Availability of materials and supplies

On a national level, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 34–2016 classifies new refrigerants based on flammability and toxicity refrigerants are often referred to by their ASHRAE Standard 34 classification (e.g., A2L for refrigerants classified with lower flammability, i.e., mildly flammable):

- Toxicity Groups
    - A–Nontoxic: most candidate refrigerants
    - B–Toxic: R-717 ammonia
- Flammability Classes
    - 1–No flame propagation (i.e., non-flammable): R-134a, R-410a, R-744, R-466
    - 2L–Lower flammability: R-32, R-1234yf, many low-GWP alternatives
    - 2–Flammable: few candidate refrigerants
    - 3–Higher flammability: hydrocarbons including R-290, R-600a

In addition, ASHRAE Standard 15–2016 serves as the industry benchmark for safe use of HVAC&R refrigerants; UL covers safe use for specific HVAC&R equipment; and EPA SNAP specifies acceptable and unacceptable refrigerants for specific end-use applications.

A variety of low-GWP refrigerants, alternate low-charge-system designs, and leakage detection and reduction measures are being explored and implemented to reduce GHG emissions with today's HFC refrigerants. Implementation of these alternatives is expected to grow as global, national, and State policies advance toward HFC phasedowns, restrictions, and other emissions reduction initiatives. The HVAC&R industry is undergoing regulatory and technological transitions, including manufacturing, installation, operation, and disposal of systems with flammable refrigerants, so safety training and education for contractors, distributors, and other stakeholders is crucial to safely advance the newer technologies.

4.2 Projected Low-Global Warming Potential Alternatives for Major End-Uses

Table 4-1 summarizes low-GWP alternatives under consideration for major end-use sectors. All major HFC end-uses have promising low-GWP alternatives, although refrigerant approval and product availability may still be under development. Some low-GWP options are readily available in global markets, but are waiting for EPA SNAP approval before adoption in new systems in the U.S. Other low-GWP refrigerants are subject to EPA SNAP charge limits, which prevents their use in higher capacity applications. Very few alternative refrigerants are direct drop-in replacements for HVAC&R and other end-use sectors, which can pose challenges to adoption because the only alternative is a full-system replacement. Even in instances where an alternate refrigerants' properties are similar, systems may require some redesign and component upgrades to manage flammability.

Table 4-1. Low-Global Warming Potential Alternatives for Major End-Use Sectors

Sources: AR4 100-year GWP values from IPCC, EPA SNAP.

Category	Current HFC (AR4 100-year GWP)	Promising Low-GWP Alternative	U.S. Approval Status
Residential HVAC	R-410A (2,088)	R-32 (675) R-290 (3) R-466A (733) R-454B (466) R-452B (698)	· No alternative refrigerants are approved for use in residential central split-system, ductless split-system, or geothermal AC/HP systems in the U.S. today. · EPA SNAP Rule 23 (2020) proposes to list several new alternatives subject to use restrictions. · State and local building code updates would be necessary for flammable refrigerants. · Currently, R-32 and R-290 are the only alternative refrigerants approved for use in room/window AC/HP systems in the U.S.
Commercial HVAC	R-410A (2,088) R-134a (1,430)	R-32 (675) R-290 (3) R-600a (3) R-466A (733) R-454B (466) R-452B (698) R-450A (604) R-513A (631)	· Similar to residential, no alternative refrigerants are approved for use in commercial rooftop unit, split-system, VRF, or geothermal systems in the U.S. today. · EPA SNAP Rule 23 (2020) proposes to list several options subject to use restrictions. · State and local building code updates would be necessary for flammable refrigerants. · Currently, R-32 and R-290 are the only alternative refrigerants approved for use in PTAC/PTHP systems in the U.S.
Residential Refrigeration	R-134a (1,430)	R-600a (3) R-290 (3)	· Manufacturers have started offering domestic refrigerators using R-600a to replace the R-134a with full adoption in the next few years. · UL raised the charge limits for residential refrigerators from 57g to 150g in April 2017 to align with the latest IEC guidelines (60335-2-24). EPA SNAP adopted this standard in August 2018.
Commercial Refrigeration	R-134a (1,430) R-507 (3,985) R-404A (3,922)	R-744 (1) R-717 (0) R-448A (1,387) R-449A (1,397) R-32 (675) R-290 (3)	· Alternatives available today include R-600a, R-290, R-717, and R-744. In some cases, the refrigerants are subject to use restrictions (e.g., cascade R-717 systems, self-contained R-290). · EPA SNAP allows the use of R-600a and R-290 up to 150g for commercial refrigerators and use of CO_2 in BVMs with no limitations.
Chillers (small to medium)	R-410A (2,088)	R-32 (675) R-466A (733) R-454B (466) R-450A (604) R-513A (631) R-717 (0)	· Alternative refrigerants that are approved for use in the U.S. are R-744 (A1), R-717, R-450A (A1), R-513A (A1), and R-1234ze (A2L).
Chillers (large)	R-134a (1,430)	R-1234yf (4) R-1234ze (7)	
Water Heating	R-134a (1,430)	R-1234yf (4) R-1234ze (7) R-744 (1)	· High-efficiency HVAC&R systems using R-744 are commercially available today in heat pump water heating applications.

Category	Current HFC (AR4 100-year GWP)	Promising Low-GWP Alternative	U.S. Approval Status
Industrial	R-507 (3,985) R-404A (3,922) R-407A (2,107) R-410A (2,088) R-134a (1,430)	R-717 (0) R-744 (1) R-290 (3) R-450A (604) R-513A (631) R-448A/R-449A (1387/1397)	· Cold storage and industrial facilities commonly use R-717 refrigeration systems for the improved energy efficiency and performance at low temperatures and maintain the required safety systems and personal. Manufacturers now offer R-744 systems as replacement for the toxic and mildly flammable R-717 (B2L).
Transportation	R-134a (1,430)	R-1234yf (4) R-744 (1)	· Under SNAP, EPA recently listed three low-GWP passenger vehicle AC refrigerants as acceptable subject to use conditions: HFO-1234yf, R-744, and HFC-152a. · Many OEMs have already transitioned to HFC alternatives.
Aerosol	R-134a (1,430)	R-1234ze(E) (7) R-152a (124) HFO-1336mzz(Z) (2)	· R-134a is unacceptable, except for certain use conditions, starting July 2016, but EPA will not apply these listings in the near-term based on 2018 guidance.[35] · The three alternative refrigerants listed are EPA SNAP approved.
Foam	R-134a (1,430) R-245fa (1,030) R-365mfc (794)	HFO-1234ze (7) HFO-1336mzz(Z) (2) R-152a (124)	· The three alternatives listed are EPA SNAP approved alternatives.

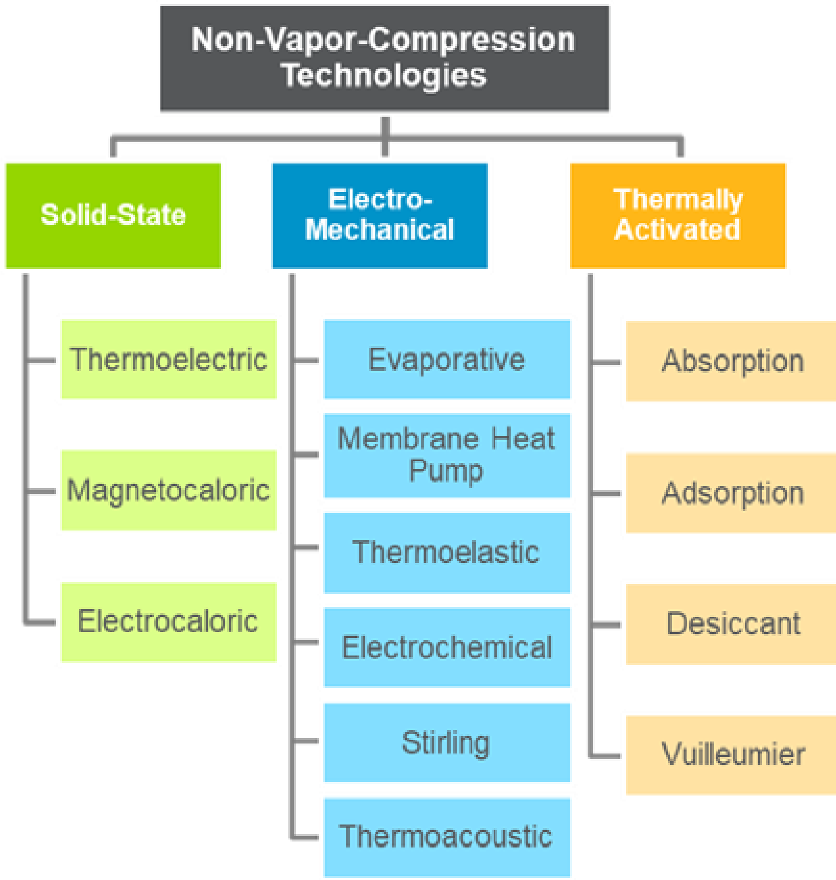
In addition to lower-GWP refrigerants, researchers are investigating a series of space conditioning and refrigeration systems that use unique properties of specialized materials or alternative system designs that do not use the traditional vapor-compression cycle. These non-vapor-compression (NVC) or not-in-kind technologies can transfer thermal and mechanical energy without the use of HFC refrigerants. Many of these NVC technologies are available today for specialized or niche applications, and further research and development is necessary to adapt the core technology to wider building applications. These NVC systems have the potential for lower direct and indirect GHG emissions by using working fluids with low- or no GWP (e.g., helium, salts, water) and offering lower energy consumption compared to conventional HVAC&R systems.

Figure 4-2 highlights available NVC technologies under development today. While each technology is unique, this list is broadly classified into the following categories:

- **Solid-State** NVC technologies produce useful temperature differences based on the intrinsic material properties of their core solid-state substance when activated through electrical input. In addition to a centralized cooling system, these technologies could enable alternative system designs such as wearable or localized cooling. Examples include thermoelectric, magnetocaloric, and electrocaloric.

- **Electro-Mechanical** NVC technologies use electrical input to alter the phase or other properties of a working fluid or material to pump heat. Examples include evaporative, membrane, thermoelastic, electrochemical, Stirling, and thermoacoustic.
- **Thermally Activated** NVC technologies use thermal energy as the primary input to drive a mechanical or chemical heat pump cycle. Thermal energy may be supplied by waste heat or solar thermal resources. Examples include absorption, adsorption, desiccant, and Vuilleumier.

Figure 4-2. Non-Vapor-Compression Technologies Under Development



4.2.1 Switching Costs for Low/Ultra-Low Global Warming Potential Technologies and Energy Efficiency Impacts

For most technologies, the cost impact of switching to low-GWP refrigerants is still uncertain. During the transition from ODS, U.S. manufacturers made an estimate one-time investment of $20–$50 million each to develop and test new products and reengineer production facilities.[36] These costs were then passed to consumers through short-term increases in prices for the new technologies. Table 4-2 shows estimated cost and efficiency impacts of switching to low-GWP refrigerants based on available data, primarily from CARB's Proposed Amendment Staff Report,[37] or other assumptions as described below.

CARB's cost premium estimates are derived from stakeholder meetings and interviews, though it is unclear what assumptions are made on future policy adoption. There are still significant data gaps for transportation, chillers, ice makers, vending machines, dehumidifiers, room AC, heat pump water heaters, and heat pump clothes dryers. In cases with no available data, cost premiums were assumed to be 10% or the same as similar technologies categories that had cost premium estimates (marked with asterisks in Table 4-2). The estimated 10% equipment and installation cost premium assumption is based on the AHRI *Consumer Cost Impacts of the US Ratification of the Kigali Amendment Report* (2018).[38] These cost premium estimates are also likely based on national incremental costs, and they have not been adjusted to reflect costs that would occur if only a portion of the U.S. market (e.g., New York and California) adopted HFC phasedown policies. National incremental costs reflect shared transitions costs across the entire U.S. market, whereas state-by-state transitions could allocate costs over a smaller number of units and increase the cost premiums further. The full list of baseline costs and estimated cost premiums are available in appendix A.3.

Certain technologies were assumed to have no additional cost premium for switching to low-GWP refrigerants because of the low cost of propane/isobutane (e.g., residential-style refrigerators/freezers and refrigerated vending machines) and/or because the manufacturers have already made transitions to low-GWP refrigerants in the U.S. (e.g., mobile AC with some manufacturers). Some technologies are projected to undergo a two-tiered refrigerant transition under certain mitigation scenarios—first to a "low-GWP" option (generally characterized by GWP < 750) and then to an "ultra-low-GWP" option (generally characterized by GWP < 10). For example, residential and commercial HVAC technologies that are currently using R-410a are expected to transition to a low-GWP refrigerant such as R-32 within the next decade, and then transition again to an ultra-low-GWP refrigerant such as HFO-1234ze(E) as further GWP restrictions come into effect. Due to the uncertainty of marginal cost impacts for a second transition to ultra-low-GWP refrigerants, Guidehouse assumed no additional incremental transition costs between low-GWP and ultra-low-GWP equipment. This assumption should be researched further once viable design options with ultra-low-GWP refrigerants are identified in applicable end-use sectors.

Beyond refrigerant regulations, many HVAC&R equipment types are subject to federal appliance energy efficiency standards, State appliance and building standards, and other applicable codes (e.g., ASHRAE 90.1). Manufacturers will need to ensure that their products meet both energy efficiency and low-GWP refrigerant standards in future years. Fortunately, most alternative refrigerants under consideration project similar or improved efficiency in initial testing, typically on the order of 10% improvement but will vary by system design. Even for technologies that have estimated efficiency impacts, there is significant variation. The increased cost of refrigerants may also have impacts on annual maintenance costs to refill refrigerant that has leaked. However, annual maintenance and refrigerant cost impacts were not included in this analysis because there is little data available, as many proposed refrigerants are not on the market today; in addition, the cost of refrigerants is likely to change over time as markets mature. Cost premiums for handling refrigerants with increased flammability or toxicity were also not considered in this analysis.

Table 4-2. Low-Global Warming Potential Refrigerant Cost Impacts

Sources: CARB's Proposed Amendment Staff Report,[39] EU's Possible Bans for Aerosols and Foams Factsheet,[40] AHRI's Consumer Cost Impacts of U.S. Ratification of the Kigali Amendment,[41] DC Engineering's Refrigeration System Study,[42] Emerson's The Case for R-290 in U.S. Commercial Foodservice,[43] and The News' Refrigerant Choices for Chillers Remain Complex.[44]

Category	Subcategory	Estimated Equipment Cost Premium	Installation Cost Premium	Efficiency Impact
Residential HVAC	Room AC/HP	5%*	3%*	N/A
	Central AC/HP	5%	3%	N/A
	Dehumidifiers	5%*	5%*	N/A
Residential Refrigeration	Refrigerator/ Freezers	0%	0%	0%
Residential Appliances	Heat Pump Water Heaters	10%*	10%*	N/A
	Heat Pump Clothes Dryers	10%*	10%*	N/A
Commercial HVAC	Large	6%	6%	N/A
	Small	10%	10%	N/A
	Variable Refrigerant Flow	5–10%	5–10%	N/A
Commercial Chillers	Large	10%*	10%*	-0.1 to -0.04 COP
	Medium/Small	10%*	10%*	-0.34 to + 0.17 COP
Commercial Water Heating	Heat Pump Water Heaters	10%*	10%*	N/A
Commercial Refrigeration	Refrigerated Warehouses	20%	20%	-10%
	Supermarket Racks	15–20%	10%	-14% to 0%
	Self-Contained Display Cases/Reach-Ins	20%	10%	0 to +20%
	Refrigerated Vending Machines	0%	0%	0%
Aerosols	Non-medical	$4/pounds refrigerant	N/A	N/A
Foams	XPS	$4/pounds refrigerant	N/A	N/A
	Spray PU	$4/pounds refrigerant	N/A	N/A
Industrial Process	-	20%	20%	-10%
Transportation	Buses and Vehicles	0%	0%	0%
	Refrigeration	10%*	0%	N/A

* Guidehouse estimate based on available data for similar categories

4.2.2 End-of-Life Recovery and Refrigerant Management Costs

In addition to the primary costs associated with switching to low-GWP and ultra-low-GWP refrigerants, additional costs may occur as a result of mitigation efforts aimed at managing refrigerants in equipment that has reached end-of-life. End-of-life costs occur in three main areas:

1. **During recovery.** The service technician must spend labor hours to properly capture any refrigerant that may be remaining in the system and transfer it to a refrigerant tank. Success is measured by "EOL recovery rate," defined as the mass of refrigerant successfully recovered as a proportion of total refrigerant remaining in the system at end-of-life. EPA Section 608 rules prohibit the known venting of any refrigerant to the atmosphere, but venting is believed to be common and difficult to track or enforce. Increasing EOL recovery rates, particularly for smaller systems, is one of the mitigation options with the greatest potential in the near term for reducing refrigerant emissions for HFC systems, but costs for doing so are not analyzed in this report.
2. **Between recovery and reclaim/disposal.** During this stage, the tanks of recovered refrigerant may be passed between multiple parties as they are transported from the job site, potentially stored and/or aggregated at a refrigerant wholesaler warehouse and transported to the ultimate destination of the disposal or reclaim site. Costs in this stage are highly variable, as systems that are widely dispersed will incur greater transportation costs per unit of recovered refrigerant. A robust chain-of-custody process should be enacted during the transportation and storage phase.
3. **At reclaim or disposal.** At this stage, the recovered refrigerant must undergo one of two industrial processes—reclaim or disposal. Refrigerant disposal typically consists of an incineration process that removes the ozone-depleting and global-warming potential of the gas. Refrigerant reclaim consists of purifying the recovered refrigerant until it meets AHRI Standard 700 purity specification and can effectively be used as for new equipment or service use. This analysis does not include any differential cost of reclaim versus disposal, but it is likely that reclaim is a more expensive process due to the requirement for careful tracking, labeling, and re-storage of the purified refrigerant. Refrigerant reclaim strategies can offset some demand for consumption of new refrigerant but will have no impact on refrigerant emissions. Both reclaim and new refrigerant would be emitted to the atmosphere during annual leakage or end-of-life.

Using reports from the Environmental Investigation Agency (EIA)[45] and UNEP Technology and Economic Assessment Panel (TEAP),[46] Guidehouse estimated the incremental cost of EOL management policies as a part of NYS mitigation strategies. These reports offer a two-step hierarchy for estimating EOL management costs. First, differential abatement costs were assigned at the equipment subcategory level, which assumes that certain applications would require more or less time to recover and transport refrigerant. These costs were further characterized as "low effort" or "medium effort" based on geographic spread, reflecting the increased transportation and storage costs associated with highly dispersed systems. For example, the EIA and UNEP TEAP reports estimate that EOL management costs are more than six times higher for a commercial refrigeration system under a "medium effort" scenario versus a mobile air conditioning system in a "low effort" scenario. Guidehouse then applied additional steps to arrive at a simplified EOL cost analysis. First, wherever costs were presented as a range for a given sector and effort level (e.g., “low-effort” stationary AC), the lower end of the range was assigned to commercial equipment while the upper end of the range was assigned to residential equipment. This assumes that recovering refrigerant in a residential setting would likely be more time- and cost-intensive than in a commercial setting. Finally, Guidehouse averaged the “low-effort” and “medium-effort” costs across each end-use subcategory to develop a representative value. End-of-life abatement costs are summarized in Table 4-3 below.

Table 4-3. Representative End-of-Life Abatement Costs by End Use Sub-Category

End Use Sub-Category	Representative EOL Abatement Cost ($2020 per pound)
Commercial HVAC	$8.81
Commercial Refrigeration	$40.34
Commercial Other	$40.34
Industrial Process	$9.09
Residential HVAC	$13.92
Residential Other	$13.92
Residential Refrigeration	$13.92
Transportation HVAC	$11.36
Transportation Refrigeration	$9.38

In order to calculate total abatement costs for EOL abatement, Guidehouse first considered the total mass of refrigerant in each year that would go through the EOL abatement processes (i.e., reclaim). The amount of refrigerant reclaim was estimated through a multi-step process. First, the mass of recovered refrigerant was calculated based on the number of systems reaching end-of-life in any given year, the assumed charge contained in each system. and the EOL recovery rate for each system. Then, a mass-balance was performed independently for each refrigerant to determine whether enough recovered refrigerant was available to be reclaimed and subsequently used in service consumption in the same year. In many cases, not enough reclaim refrigerant exists to cover the demand for service consumption. In these cases, the Guidehouse model assumes that all possible reclaim refrigerant is utilized and the balance of consumption must be made up through new refrigerant. Finally, Guidehouse calculated total EOL abatement costs by multiplying the mass of refrigerant used for reclaim in each end use sub-category by the incremental abatement cost associated with that subcategory.

4.3 Current Refrigerant Policy Landscape

Numerous policies and regulations focused on reducing emissions from refrigerants have been enacted at the global, federal, and state level. Over the last several years, HFC phasedown efforts in the U.S. have been relatively fragmented, as individual states have taken action to reduce HFC usage beyond federal regulation. With the passage of the federal AIM Act in December 2020, it is expected that the U.S. EPA will take action in the near future to enact new HFC restrictions, approve additional low-GWP refrigerants, and encourage the development of improved recovery and reclaim practices. With the development of low-GWP refrigerants with flammable properties, multiple organizations are evaluating updates to codes and standards to permit the use of A3 and A2L refrigerants.

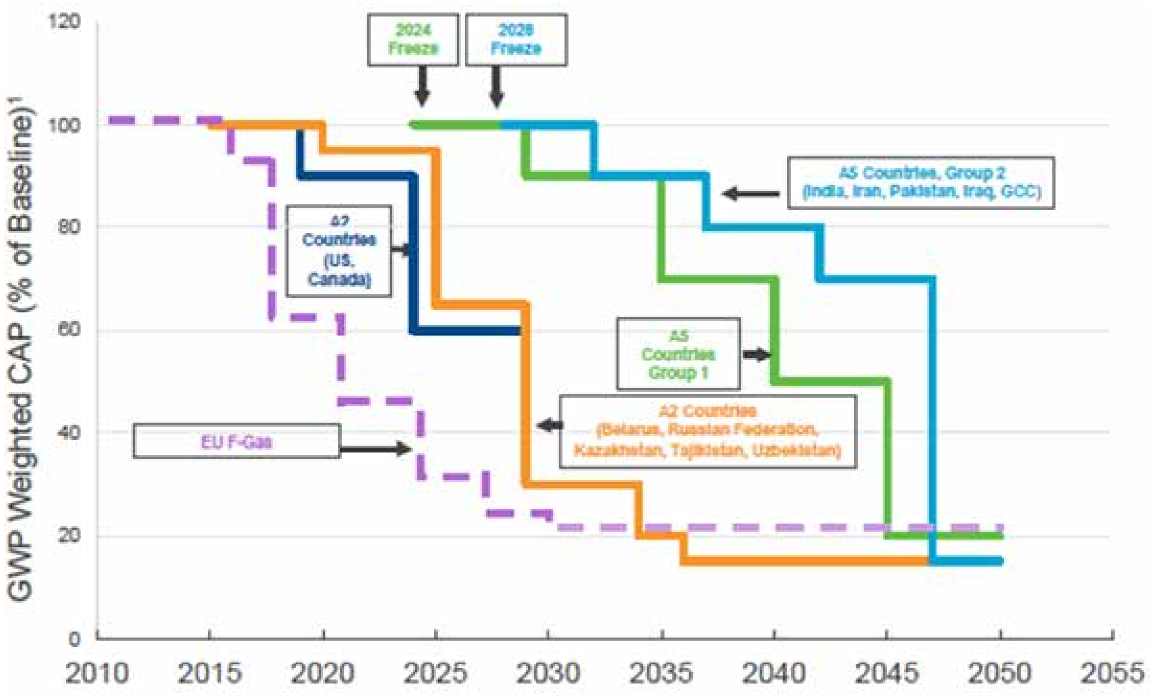
4.3.1 International Policies

The global transition towards refrigerants and technologies with lower GHG emissions is largely driven by the Kigali Amendment to the Montreal Protocol and the Paris Agreement on climate change. While the U.S. Congress has not ratified either treaty to date, several other technology, market, and policy drivers impact the transition for HVAC&R systems in the U.S. and NYS. Global markets have predominantly adopted the HFC production and consumption phasedown schedules in the 2016 Kigali Agreement, and individual countries have enacted GWP thresholds for specific end-use systems. Figure 4-3 shows the HFC phasedown schedules under the Kigali Amendment, including a 70% decrease by 2029 and 85% decrease by 2036 for the U.S. The Kigali Amendment to the Montreal Protocol is effective since January 2019 where ratified. Europe’s 2015 F-Gas Regulations and Canada’s 2018 HFC Ruling establishes GWP thresholds for key HVAC&R segments, such as residential refrigerators, chillers, commercial refrigeration, and split-system AC (EU only).

It is important to note that the Kigali Amendment and many international policies focus on HFC production and consumption rather than HFC emissions, which is the primary focus of New York State’s Climate Act goals. For HVAC&R categories, HFC emissions occur over a delayed period from annual and end-of-life leakage. The majority of HFC emissions for aerosols and solvents occurs during initial use, typically within a year of manufacturer, whereas foams can have both immediate and delayed HFC emissions depending on their use. The Guidehouse model analyzes consumption as end-use refrigerant demand for new and service applications whereas national and international agreements often define consumption as national production, import, and export.

Figure 4-3. Hydrofluorocarbon Phasedown Schedule in Kigali Amendment to the Montreal Protocol

Source: Emerson March 2020 webinar.[47]



4.3.2 United States Federal and State Policies

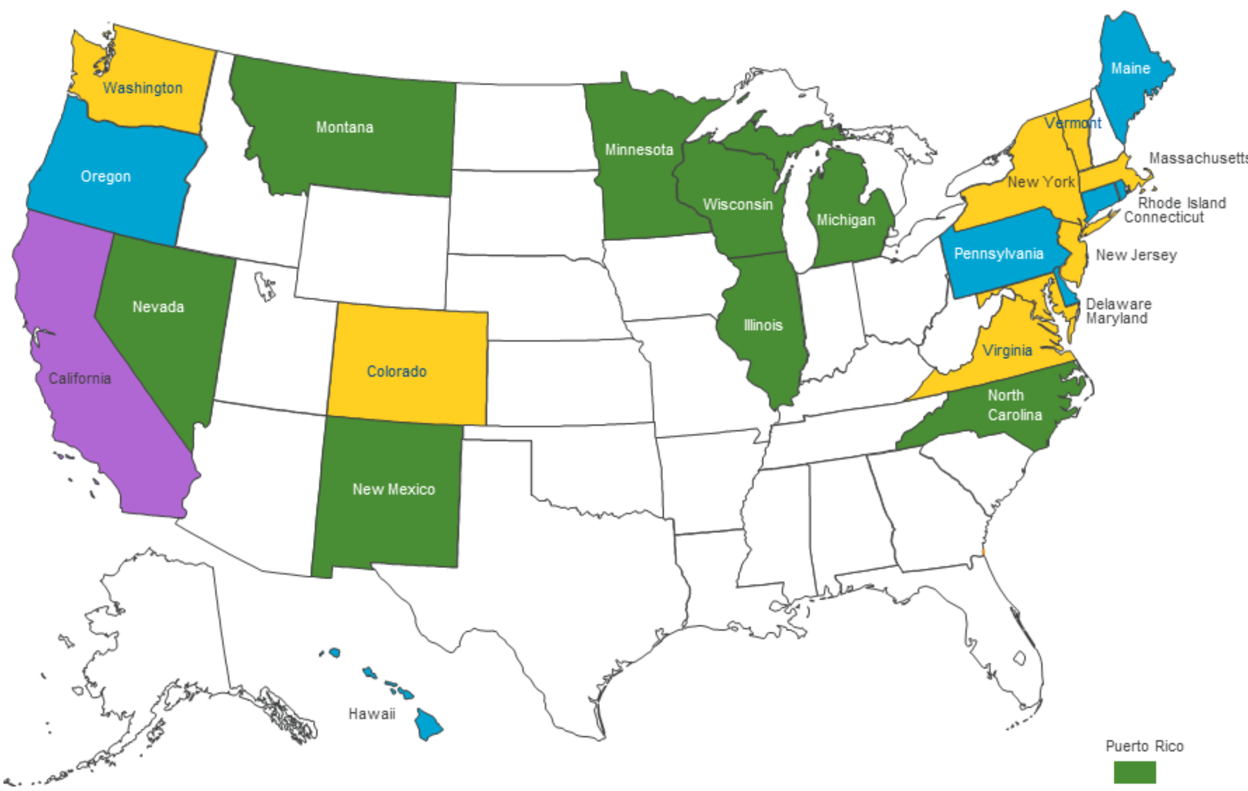
On the federal level, the U.S. EPA SNAP Program evaluates and lists acceptable substitutes for ODS based on characteristics such as ozone depleting potential, GWP, toxicity, flammability, consumer health, and more. SNAP Rules 20/21 prohibited the use of certain high-GWP HFCs and provide new listings of safer substitutes but were vacated at the federal level due to a court challenge. Proposed SNAP Rule 23 provides new listing of 12 substitutes for refrigeration and air conditioning and foams. Section 608 of the Clean Air Act established leak repair, inspection, and record keeping requirements for large HVAC&R systems with over 50 pounds of ODS refrigerants, such as supermarket rack systems. The 2016 updated rule expanded the requirements to include both ODS and HFCs, which lowered the leak rate threshold in supermarket refrigeration systems with HFCs from 35% to 20% as well as other HFC management requirements. In 2020, EPA rescinded the 2016 expansion to cover HFCs, which reestablished Section 608 requirements applying only to systems using ODS refrigerants.[48]

Without federal ratification of the Kigali Amendment, individual state policies have driven the refrigerant transition for HVAC&R systems in the U.S. over the last several years. The U.S. Climate Alliance is a group of 24 states and Puerto Rico that pledged to implement policies advancing the goals of the Paris Climate Agreement.[49] Several states in the Climate Alliance have adopted HFC restrictions covering several commercial refrigeration and chiller applications that were previously subject to EPA SNAP 20/21 proposals. California, Washington, Vermont, New Jersey, Colorado, Massachusetts, Maryland, and New York State have adopted U.S. EPA SNAP 20/21. Section 3.2.3 describes the recent New York State HFC regulations in detail.

Figure 4-4. United States Climate Alliance States and Status of Low Global Warming Potential Policies as of April 2020[50]

Green: Not Proposed, Blue: Proposed, Yellow: Final, Purple: Beyond SNAP 20/21

Source: Emerson February 2021 webinar.[51]



Of the Climate Alliance states, California has adopted the most aggressive regulations of HFC refrigerants, aligning with its commitment to reduce GHG emissions from HFCs by 40% by 2030. In 2017, California Legislature adopted the California Cooling Act (SB1013), which incorporated SNAP Rules 20/21 into state law and combined it with the existing HFC Regulation to cover all end-uses. The requirements of the combined regulation, Prohibitions on Use of Certain Hydrofluorocarbons in Stationary Refrigeration, Chillers, Aerosols-Propellants, and Foam End-Uses Regulation, took effect on January 1, 2019.[52]

In its most recent proposal, CARB has delayed the limit of 750 GWP for refrigerants in new residential and light-commercial AC/HP systems from January 1, 2023 until January 1, 2025. The 750 GWP limit for VRF systems is delayed from January 1, 2023 until January. 1, 2026; and there is no change in January 1, 2023, effective date for smaller equipment, such as window ACs and dehumidifiers that do not need building code updates. Section 5.4 describes the HFC emissions reduction impacts for NYS should it adopt similar HFC regulations with a delayed timeline in potential HFC Mitigation Scenarios no., 6A and 6B.

CARB's latest proposal for stationary refrigeration includes the following:

- For new systems in new facilities containing more than 50 pounds refrigerant, CARB is proposing 150 GWP limit in 2022 and 2024 for ice rinks.
- For new systems in existing facilities:
  - Retail food regulation includes company-wide reduction targets for systems greater than 50 pounds of less than 1,400 GWP weighted average, or a 55% or greater reduction in their GHG potential below 2019 levels by 2030.
  - Non-retail regulation includes 1,500–2,200 GWP limit in 2022 for industrial refrigeration and 750 GWP limit in 2024 for ice rinks.

The Refrigerant Recycle, Recovery, and Reuse (R4) Program requires that new equipment entering the California market in 2023 and 2024 must use at least 10% certified reclaimed R-410A. The program also offers an early action credit for low-GWP refrigerant use. Manufacturers selling AC and VRF equipment in California in 2023 and 2024 must certify that reclaimed refrigerant constitutes at least 10% of initial equipment operating charge. In 2025 this value rises to 30%.

AHRI supported the reclaim requirements in recognition that California building code updates would not be ready until 2025. AHRI developed a proposal suggesting how industry would implement reclaim requirements in a document titled "Air Conditioning, Heating and Refrigeration Institute (AHRI) Air Conditioning Proposal Background Document and Proposed Regulatory Text."[53] CARB plans to further develop the idea in the near future. In its analysis, AHRI highlighted the opportunity for HFC emissions reductions through reclaim. A limited supply of R-410A is available in the near term, which limits the total amount that could be reclaimed due to the timing of equipment nearing end-of-life. For example, if California contractors reclaimed 10% of the total R-410A reclaimed nationally, then California would have reclaimed approximately 118 tons of R-410A last year.[53] As per AHRI's refrigerant use calculations using three different approaches, approximately 2,700–3,100 metric tons of R-410A are used for servicing existing equipment in California each year, and approximately 3,800–4,300 metric tons of R-410A are used for charging new units entering service in California each year. Furthermore, not all refrigerant can or will be recovered, and an estimated 0.5 to 30% of refrigerant is lost during the reclamation process in part due to recovery practices.[53]

At the federal level, the AIM Act was signed into law on December 27, 2020, requiring a 40% reduction in HFC consumption by 2024, 70% reduction in 2029, 80% reduction by 2034, and 85% reduction by 2036. For comparison, the maximum HFC reduction from SNAP Rules 20/21 is estimated as 20%. The AIM Act directs the EPA to establish production and consumption phasedown limits consistent with the Kigali Amendment within nine months (i.e., late 2021) and authorizes the EPA to establish standards for HFC management such as servicing, repair, recovery, recycle, and reclaim.[54] AHRI and other trade organizations have supported the AIM Act in Congress to enable the EPA to regulate refrigerants based on GWP. Overall, the AIM Act enables a phasedown of HFC usage at the national level, which could minimize the complexity of varying state regulations for manufacturers, distributors, contractors, and other industry stakeholders.

Even if states adopt HFC phasedowns for HVAC&R systems, state and local building codes may not allow flammable or mildly flammable refrigerants for certain applications, most notably residential and commercial HVAC. Further, even if building model codes adopt flammable refrigerant provisions, there will be a delay in adoption by state and local jurisdictions. For example, R-32 (675 GWP) would meet the CARB 750 GWP limit for 2023 but would face challenges on a state and local level relating to building, mechanical, fire, and other codes due to its A2L ASHRAE 34 classification.

Industry organizations are working to update these model codes on a national level to ensure the safe transportation, handling, servicing, and installation of mildly flammable refrigerants. Figure 4-5 highlights the process to update necessary industry and building safety codes to accommodate flammable (A3) and mildly flammable (A2L) refrigerants. There is uncertainty whether the 2021 updates will allow A2L refrigerants for all classes and capacities of HVAC and refrigeration systems. Even if the model codes adopt A2L provisions, there will be a delay in adoption by state and local jurisdictions.

Figure 4-5. Process for Updating Industry and Building Safety Codes to Accommodate Flammable Refrigerants

Table 4-4 summarizes the current outlook for building code updates in New York State that could incorporate A2L refrigerants for major HVAC applications under the current code adoption cycle. Based on this timeline, the likely first date by which NYS could consider a phasedown of high GWP HFCs for residential and commercial AC and HP application would be January 1, 2027. This timeline has been modeled in the potential HFC Mitigation Strategies in Section 5. New York State Department of State and other building code stakeholders may decide to adjust the code adoption cycle to address the A2L refrigerant issue.

Table 4-4. Building Code Update Modeling Assumptions in New York State

Year	Building Code Update Modeling Assumptions
2020	NYS adopts 2020 version of Uniform Code (based on 2018 ICC codes), went into effect May 12, 2020.
2021	ICC codes finalized, although *does not include* the necessary allowances for A2L and A3 refrigerants for packaged HVAC.
2023	NYS finalizes review of the 2021 ICC codes, any amendments to the Uniform Code could go into effect by 2024 if adopted by the NYS Code Council.
2024	ICC codes finalized, *could potentially include* the necessary allowances for A2L and A3 refrigerants for packaged HVAC.
2026	NYS finalizes the review of the 2024 ICC codes, any amendments to the Uniform Code could go into effect by 2026 if adopted by the NYS Code Council.
2027	NYS DEC could consider a 750 GWP Limit for Packaged HVAC.

4.4 Refrigerant Leakage Causes and Solutions

Leakage over lifetime equipment is the greatest source of HFC emissions for most end-use categories. Refrigerant leaks can also cause adverse energy efficiency, performance, financial, and operational impacts. Understanding how leakage occurs in HVAC&R systems and finding ways to address leakage rapidly and effectively are critical to reducing HFC emissions.

The first step in system leak repair is detection. Many different leak test methods and technologies are available today for HVAC&R end-uses, including direct and indirect methods. For direct leak detection, the concentration of refrigerants in the air is directly monitored through devices that can either be stationary or portable, as highlighted in Table 4-5. Stationary leak detection systems can be connected to a facility's energy management system, enabling remote monitoring and notifications. Indirect leak detection monitors and assesses the status and operation of the refrigeration system by analyzing metrics such as temperatures, pressures, liquid levels, and ambient conditions against historical system data. This method would typically use existing sensors and hardware and does not require additional leak detection hardware to be installed on site. Both direct and indirect leak technologies are options to comply with automatic leak detection (ALD) requirements, as described later in the report, but the applicability will vary by the specific situation.

Table 4-5. Example Leak Detection Methods

Leak Detection Method	End-Use	Costs	Lifetime & Detection System Response
Infrared Sensor Technology	All types	Handheld: $300–$400 Stationary: $1,000–$12,000	· Lifetime: 5 years (handheld); 10–15 years (stationary) · Produces either a 4–20 mA or HART signal; Connects to alarm system
Metal Oxide Semiconductor	CFC, HFCs, HCFCs, HFOs	Stationary: $500–$1,300 Sensing element: $3–$100	· Lifetime: 3–5 years (stationary) · Sensor lifetime decreases with continued exposure to poisoning/false-triggering gases; connects to alarm system

In order to minimize refrigerant losses, HVAC&R manufacturers and design engineers attempt to reduce the opportunities for potential leakage in system design. Refrigerant leaks are caused by system wear and tear, poor design, improper installation, servicing, and maintenances practices. These include improperly brazed refrigerant piping, improperly tightened fittings, material incompatibilities, vibration, and corrosion, among others. Leak reduction measures can be implemented based on the opportunities listed in Table 4-6.

Table 4-6. Leak Reduction Opportunities

Leakage Reduction Opportunity	Expected Impact	Key Challenges
On-Board Leak Mitigation Systems for Flammable Refrigerants	Many HVAC&R end-use categories are transitioning to A2L or A3 refrigerants, which will require leak detection sensors, controls, and alerts to meet industry standards and building codes. AHRI estimates a 50% decrease in AC leakage rate due to the additional sensors and mitigation steps for flammable/toxic substances.[55]	Limited data on servicing practices for systems with refrigerant leakage detection/ mitigation, as well as the leakage reduction that could be achieved.
Brazing and Joining Technologies	Advanced joint verification technologies can identify small leaks that would normally go undetected through pressure or visual inspection. Verifying joints in factory and field applications would help adapt the verification techniques and processes to the requirements of the HVAC&R industry, including factory and field installation techniques, technician expertise, cost and time requirements, and other considerations.	Creating reliable, consistent, and cost-effective brazing connections in factory and field settings.
Component and Material Initiatives	One way to reduce the amount of refrigerant released to the atmosphere during a total loss event is by incorporating advanced system designs that require less refrigerant charge. Additionally, manufacturers could add valves and sensors throughout the refrigerant system that would shut off the flow of refrigerant if any of the sensors detect a sudden loss in refrigerant pressure.	Sudden damaging events are not a major concern for manufacturers, contractors, etc., and uncertain cost and value to building owner. While the practice of copper-to-aluminum joining is increasing, few options exist to join other dissimilar, alternative materials.
Installation, Operations, Maintenance Initiatives	Fault detection and diagnostics (FDD) systems could help prevent refrigerant leakage in catastrophic events by activating shutoff valves by sensing a loss in refrigerant pressure. The next generation of refrigerant leakage FDD can incorporate lower-cost sensor networks and algorithms that reduce hardware costs for each HVAC&R unit.	Overcoming industry aversion to developing and employing new joining technologies, and uncertain payback and benefits to customer from costly installation of embedded/ add-on systems.

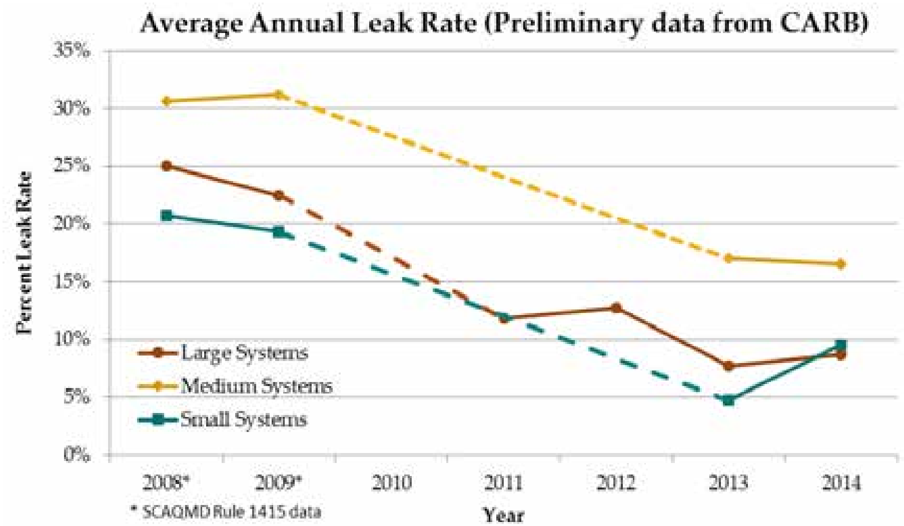
Effective program design for leak detection and implementation of reduction measures across all end-uses is key for wide HFC reduction impact. Best practices include following proper maintenance procedures, quantifying cost savings of refrigerant management, and education for end-users. Mitigation options can be designed to best address the most prevalent leakage source in each category, including focusing efforts on annual leakage versus end-of-life leakage, depending on which is a more prevalent source of refrigerant leakage in the specified end-use. For example, completely sealed, self-contained systems like residential refrigeration and heat pump water heaters have very low leakage, resulting in a greater share of end-of-life emissions. In such cases, a utility recycling program for refrigerators, freezers, room ACs, and HPWHs would be more impactful than annual refrigeration leakage inspections.

Depending on the jurisdiction, government regulations may require leak detection systems for HVAC&R applications, particularly larger commercial refrigeration systems. For example, CARB has identified certain large facilities that are subject to ALD requirements and must install an ALD system which must be audited and calibrated annually. Medium-sized systems must undergo leak inspections once every three months, while smaller systems are required once a year. However, both medium and small systems do not require a leak inspection if a CARB compliant ALD is installed. CARB RMP regulations require that leak inspections must be conducted using a calibrated refrigerant leak detection device, a bubble test, or observation of oil residue.[56] Installing ALD devices may be more beneficial over time, as ALD devices allow building owners to continuously monitor their systems, satisfy reporting requirements, and reduce the need for manual inspections.

CARB's RMP program builds on EPA's Section 608 regulation (currently rescinded for HFCs) around leak repair, inspection, and record keeping requirements and introduces new measures to promote effective management of refrigerants and minimize leaks. RMP uses system classifications based on refrigerant charge (large, medium, small) and requires periodic leak inspections and follow-up actions. CARB's system classification for RMP includes retail food refrigeration, industrial process refrigeration, and cold storage warehouses. Annual reports on refrigerant purchase and use and following best leak management practices is required for compliance. The robust reporting requirements of RMP enables CARB to estimate the annual leak rates of facilities covered in the program. By pairing South Coast Air Quality Management District (SCAQMD) Rule 1415 leak data with RMP leak data, CARB developed the historical leak rate plot in Figure 4-6. The plot indicates a roughly 50% decline in annual leak rate due to implementation of the RMP.

Figure 4-6. Average Annual Leakage Rate by System Size

Source: AHRI



For facility owners, the cost of compliance with the RMP is largely offset by the cost savings from the avoided leakage. Over time, the cost to replace the refrigerant that would have been leaked without the RMP requirements in place is often greater than the RMP compliance costs. However, this cost analysis does not include any one-time or periodic investments to reduce system leakage. The recurring costs experienced by end-users of regulated refrigeration systems, shown in Table 4-6, include costs associated with replenishment of leaked refrigerant and compliance with CARB's RMP regulation. The estimated pre-RMP refrigerant replenishment costs are based on a 20% annual leak rate. It is estimated there is roughly a 50% reduction in annual leak rate due to RMP implementation (i.e., 10% annual leak rate), such that the refrigerant replenishment savings through RMP are roughly 50% of pre-RMP costs. The baseline ongoing costs per system are listed in Table 4-7. To the extent that implementation of the AIM Act may increase the cost of legacy HFC refrigerants, RMP requirements would experience even greater cost savings.

Table 4-7. Refrigerant Management Program Leakage Reduction and Associated Costs

Source: *CARB 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.*

End-Use Sector	System Size	Estimated Pre-RMP Refrigerant Replenishment Cost (~20% annual leak rate)	Refrigerant Replenishment Savings through RMP (~50% of pre-RMP)	Cost of Regulatory Compliance with RMP	Net Annual Cost Impacts from RMP (% Change from Pre-RMP Cost)
Retail Food Refrigeration	Large	$11,400	$5,700	($3,100)	$2,600 (23%) savings
	Medium	$2,200	$1,100	($650)	$450 (20%) savings
	Small	$220	$110	($150)	$40 (18%) increase
Other Commercial Refrigeration	Large	$11,400	$5,700	($3,100)	$2,600 (23%) savings
	Medium	$2,200	$1,100	($650)	$450 (20%) savings
	Small	$220	$110	($150)	$40 (18%) increase
Industrial Process Cooling	Large	$10,200	$5,100	($3,100)	$2,000 (20%) savings
	Medium	$1,160	$580	($650)	$70 (6%) increase
	Small	$140	$70	($150)	$80 (57%) increase
Cold Storage	Large	$15,000	$7,500	($3,100)	$4,400 (29%) savings
	Medium	$800	$400	($650)	$250 (31%) increase
	Small	$58	$29	($150)	$121 (209%) increase

* **Baseline cost for refrigerant replenishment per year** = Average full charge of system (pounds) x Average Annual Leak Rate x Average baseline cost of refrigerant (i.e., $7 per pound). This is the estimated amount of money spent each year for replenishing leaked refrigerant from each system (rounded to two significant figures).

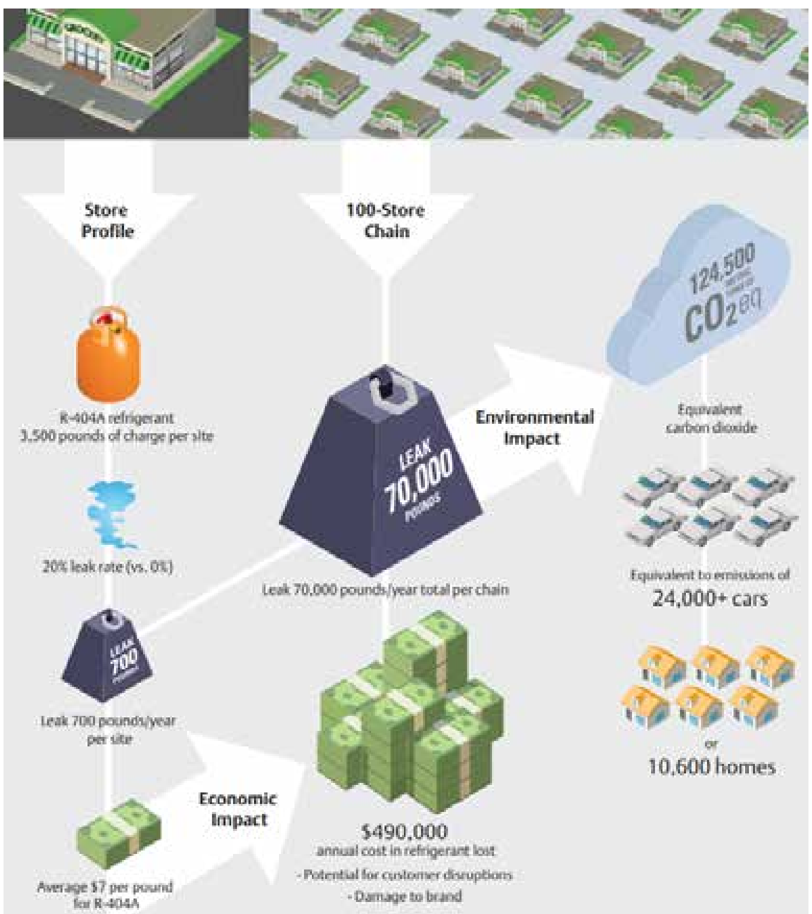
Based on the analysis above, leakage reduction measures for medium and large systems are generally more cost effective than for small systems. This suggests that additional incentives to implement leak reduction measures in smaller systems may be required.

CARB conducted a detailed economic impact analysis for the Refrigerant Management Program from both a facility's perspective and enforcement agency's perspective.[57] Overall, the mandated repairs as a result of the RMP often result in cost savings that exceed compliance costs but varied based on the size of the facility. Appendix F provides the details for this analysis, which may be valuable should New York State consider a similar program.

Commercial refrigeration is a high-priority segment for refrigerant leakage reduction because of the high-refrigerant leak rate compared to other end uses, as emphasized by implementation of the RMP program in California. Addressing these challenges can provide significant HFC emissions reductions. According to the EPA's GreenChill research, the average supermarket has two to four refrigeration racks charged with approximately 3,500 pounds of refrigerant, of which approximately 25 percent, or the equivalent of 875 pounds is lost each year to leaks.[58] Figure 4-7 illustrates the impact of refrigerant leakage in supermarket systems. By 2019, 340 out of the approximately 35,000 supermarket stores (1%) in the U.S. have been certified by EPA's GreenChill Partnership at the "platinum" level, up from five stores in 2015. GreenChill Platinum certification means the supermarket either has a refrigeration system that uses a refrigerant with greater than 150 GWP or has a very small HFC refrigerant charge and achieves an annual leak rate of 5% or less.

Figure 4-7. Impact of Refrigerant Leakage in Supermarket Systems

Source: Emerson



One way to combat supermarket leakage is to use either a manual leak tracking system or tracking system software. Tracking software can help automate the tracking of refrigerant inventories, servicing dates, system capacities, leak amounts and frequencies, and component failures. It can also generate automatic alerts if conditions warrant.

4.5 Research, Development and Deployment Needs for Low-Global Warming Potential and Leak Reduction Solutions

Guidehouse prepared the following set of RD&D opportunities based on the analysis of potential low-GWP technologies and leakage reduction solutions to support New York State's HFC reduction goals. Developing affordable, safe, and high performing HVAC&R technologies with low-GWP refrigerants and reduced leakage potential is critical to reducing economic and environmental impacts from HFC emissions in future years. Table 4-17 provides a brief description for the recommendations along with their expected impacts and benefits.

Table 4-8. Research, Development, and Deployment Recommendations for Low-Global Warming and Leak Reduction Solutions

	Recommendations	Impacts & Benefits
Research & Development Focus	1. Develop, test, and demonstrate low-charge propane and isobutane equipment that minimizes safety risks.	Can aid in compliance with building safety codes, improves technician safety.
	2. Conduct R&D on CO_2 residential and commercial AC and heat pump systems.	Enable long-term transition to ultra-low-GWP systems in residential and light commercial AC/HP.
	3. Develop, test, and demonstrate building AC, heat pump, and HPWH systems with low-GWP refrigerants (non-vapor-compression technologies can also be a focus area).	Provide a range of low-GWP market options suitable for different building types.
	4. Develop and test low-charge ammonia refrigeration equipment that minimize safety risks.	Can aid in compliance with building safety codes, improves technician safety.
	5. Develop retrofit fault detection and diagnostics (FDD) systems to detect leakage from packaged HVAC&R systems.	Enable leakage mitigation in existing systems.
	6. Conduct R&D for VRF charge size and leakage reduction strategies.	Reduce leakage and emission in a high priority heat pump segments
	7. Conduct R&D on microchannel heat exchangers for heat pumps and leak reduction.	Reduce efficiency losses, refrigerant leakage, and costs due to refrigerant replenishment and leak repair.
Deployment & Market Support Focus	8. Develop case studies showing the safety, performance, and cost impacts of alternative refrigerants.	Increase market awareness of alternative refrigerants.
	9. Develop and conduct large scale field studies to determine representative leak rates for VRF systems.	Develop greater understanding of likely HFC emissions impacts from heating electrification.
	10. Provide training for industry technicians, system designers, and other stakeholders on proper use of alternative refrigerants (including transition costs).	Aid industry transition to alternative refrigerants, promotes awareness.
	11. Support low-GWP awareness campaign for consumer and industry stakeholders.	Promote awareness of industry trends and low-GWP alternatives.
	12. Conduct field studies to evaluate impacts of on-board leak mitigation systems for A3 and A2L refrigerants.	Develop greater understanding of expected leak rates in next generation systems.
	13. Develop NYS case studies showing the safety, performance, and cost impacts of proper refrigerant management practices.	Support market awareness and adoption in different NYS building segments.
	14. Develop NYS case studies showing the benefits of low-charge system design with leak mitigation technologies, such as energy efficiency, initial cost, leakage reduction, GHG emissions, lifecycle maintenance costs, and other attributes.	Support awareness and design practices for architects, engineers, and other system designers.
	15. Conduct detailed analysis of charge size differences between AC and HP systems using low-GWP refrigerants.	Develop greater understanding of likely HFC emissions impacts from heating electrification.

5 Potential Hydrofluorocarbon Mitigation Scenarios

This section describes Guidehouse's analysis of a range of potential mitigation options that could reduce future HFC consumption and emissions in New York State, including policy and technology approaches. The potential HFC Mitigation Scenarios in this section are compared to a baseline (Reference Case no. 5) that considers existing HFC phasedown policies in NYS, as well as an anticipated increase in residential AC use and building electrification to achieve Climate Act goals.

5.1 Available Technology and Policy Strategies

Developing and enforcing rules and regulations surrounding HFC mitigation is important to help transition the industry away from the use of high-GWP refrigerants. HFC mitigation policies can be enforced through a variety of avenues ranging from mandatory equipment bans, GWP limits, end-of-life recovery policies, and requirements for the use of reclaimed refrigerants to voluntary incentives and refrigerant price signals. An array of policy and program structures are available to implement, and international, federal, or state agencies can develop programs and initiatives that are best suited for their specific objectives and jurisdiction. This includes taking into consideration cost to consumers, technical and commercial feasibility, and timelines for phase out. For example, supermarkets typically have their own program guidelines for leak reduction since their sector has significantly higher leak rates compared to other building segments, making it a high priority. Furthering the specificity and applicability of the leak reduction measures, the program guidelines stratify supermarkets into three size categories based on refrigerant charge size at the facility. Catering policies and programs by building type, refrigerant, equipment type, or other criteria, is an effective way to smooth the industry transition to low-GWP options and reduce HFC emissions.

Government entities on an international, national, and state level have developed policies to phase down HFCs, regulate appliance disposal, and manage refrigerant leakage. Table 5-1 provides a list of example potential mitigation options and identifies policy organizations and specific policies corresponding to each option.

Table 5-1. Potential Mitigation Options and Associated Policies

Mitigation Option	Policy Example (Organization, Policy Name, Leadership Category)
Consumption / emissions phasedown targets	· UN Kigali Amendment to Montreal Protocol (not adopted by U.S.). · California Legislature, SB 1383 (40% reduction in HFCs from 2013 levels by 2030). · EU, F-Gas Policies (EU's emissions cut by two-thirds by 2030 compared with 2014 levels). · American Innovation and Manufacturing (AIM) Act. **Likely Leadership:** Federal, State
End use prohibitions	· U.S. EPA, Significant New Alternatives Policy (SNAP). · New York State SNAP Rule Link (detailed later in section). · CARB, Short-Lived Climate Pollutant (SLCP) Reduction Strategy. · Association of Home Appliance Manufacturers, a trade association representing 146 companies, announced a goal to phase out the use of HFCs in household refrigerators and freezers after 2024, later advanced informally to between 2021 and 2023 during state legislative processes. **Likely Leadership**: Federal, State, Industry.
End-of-life recovery	· U.S. EPA, Responsible Appliance Disposal Program · U.S. EPA, Refrigerant Recovery and Recycling Equipment Certification · EU, Regulation (EC) 1005/2009, Directive 2008/98/EC, Regulation (EC) 1013/2006. **Leadership:** Federal, State, Industry.
Refrigerant management / leakage policies and incentives	· CARB, Refrigerant Management Program. · US EPA, Revised Section 608. **Leadership:** Federal, State, Individual Consumers.
Low-GWP equipment incentives	· California Legislature, SB 1013 (California Cooling Act). · California Legislature, F-Gas Reduction Incentive Program. · SMUD, Pilot Natural Refrigerant Incentive Program. · NASRC, Aggregated Incentives Program (AIP) Pilot. **Leadership:** Federal, State, Local.
Early replacement incentives	· Although few programs exist today, NYSERDA can leverage existing utility incentive programs for EE to expand into refrigerants. · Con Edison, Commercial & Industrial EE Program Manual maintains an Early-Replacement program that incentives building owners to replace long-life systems before their end-of-life failure. · Con Edison and other utilities have offered incentives to recycle older Refrigerator and Room ACs, ensuring proper disposal and refrigerant reclaim. **Leadership:** Federal, State, Local.

5.2 Methodology and Key Assumptions

Guidehouse developed several potential HFC Mitigation Scenarios to evaluate potential mitigation options to address HFC consumption and emissions in future years. Table 5-2 highlights key attributes of the scenarios considered in this section, with additional details provided in appendix A.2. These potential HFC Mitigation Scenarios are compared to a baseline (Reference Case no. 5) that considers existing HFC phasedown policies in NYS, as well as an anticipated increase in residential AC use and building electrification to achieve Climate Act goals (i.e., 70% electric heat pump sales by 2030 and 100% by 2045).

Table 5-2. Modeled Mitigation Scenarios

Bold highlighted cells denote key change in scenario in relation to previous scenario. Each scenario builds upon the previous scenario. Scenarios are compared against Reference Case no. 5, which assumes maximum residential AC adoption; electric heat pump adoption of 70% of sales by 2030 and 100% by 2045; and the expected impacts of the 2020 NYS SNAP Rule.

Key Parameter	HFC Mitigation Scenario #6A	HFC Mitigation Scenario #6B	HFC Mitigation Scenario #6C	HFC Mitigation Scenario #7	HFC Mitigation Scenario #8A	HFC Mitigation Scenario #8B
Description	Reference Case no. 5+ New Equipment HFC Restrictions in 2024.	no. 6A + Additional New Equipment HFC Restrictions in 2027–2029.	no. 6B + Additional New Equipment HFC Restrictions Post-2030.	no. 6C + Currently Recaptured Refrigerant Used for Maximum Possible Service Reclaim.	no. 7 + Increased Recapture for Large Systems to Increase Maximum Possible Service Reclaim.	no. 8A + Increased Recapture for Small Systems to Increase Maximum Possible Service Reclaim.
Equipment Restriction Policies	**Phase I (2024)**: Low-GWP for commercial & residential room AC/HP, industrial systems, transport HVAC; and supermarket racks to ultra-low-GWP options.	**Phase II (2027–2029)**: Building code updates to allow for low-GWP for commercial central & ductless AC/HP and residential whole-home AC/HP; low-GWP for transport refrigeration; ultra-low-GWP for commercial icemakers and water heating, warehouses, residential water heating and clothes drying.	**Phase III (Post 2030)**: max tech adoption of ultra-low-GWP technologies (<10 GWP) for all residential and commercial AC/HP, chillers (med & small), walk-ins, industrial systems, all residential AC.	Same as no. 6 A, B, C		
Use of Reclaimed Refrigerant	No change in current practice			**100% of recovered refrigerant at end-of-life is applied to HFC service demand.**	Same as no. 7, but with greater reclaim supplies available due to higher end-of-life recovery rate.	
Low-GWP Leak Rates	When new equipment using low-GWP refrigerants enter the market, a 50% reduction in annual leak rate is applied, based on AHRI estimates for improved design and maintenance practices associated with flammable and mildly flammable (A2L) refrigerants.					
End-of-Life Recovery	Assume same EOL recovery rate as Reference Cases for each end-use.				**Recovery rates increase to 90% for large end-uses starting in 2024 (current loss rates are 20–30%).**	**Recovery rates increase to 90% for large and small end-uses starting in 2024 (current loss rates are 50–80%+ for small end-uses).**

Each scenario considers a collection of potential mitigation options, including the following:

- **HFC restrictions or GWP limits**—new equipment transition to low-GWP options in the year the regulations go into effect.
- **Charge size reduction for low-GWP refrigerants**—low-GWP refrigerants with lower charge sizes would further reduce overall emissions, as described in Section 3.2.1.
- **Leakage reduction for low-GWP refrigerants**—leakage rate for new equipment using low-GWP options decreases by 50% in the year the regulations go into effect (applied only once in the case of multiple transition points).
- **Greater use of reclaimed refrigeran**t—HFC supplies for servicing existing systems are sourced from refrigerant that has been recovered and reclaimed from equipment reaching end-of-life, which would reduce the need for new or virgin HFC refrigerant production. See section 4.2.2 for greater details.
- **Refrigerant recovery at end-of-life**—assumes proper equipment disposal at end-of-life, including full recovery of HFC refrigerant, which could then provide greater HFC supplies to meet servicing needs for existing systems. Current loss rates for large systems are 20–30% and small systems experience loss rates 50–80% or greater. Improved technician practices could theoretically raise recovery rates. Guidehouse estimates 90% as a theoretical limit for most equipment categories to account for catastrophic events that results in sudden and complete loss of refrigerant from the system (e.g., major physical damage during extreme weather).

Scenarios no. 6C through no. 8B assume that all applications adopt ultra-low or natural refrigerants by 2030–2035, such as R-1234yf, R-290, R-600, R-744, or R-717. These “max tech” scenarios assume significant technology advances over the next decade and are highly uncertain. Many categories will have already transitioned by this point in scenario no. 6A or no. 6B (e.g., residential refrigeration, supermarket refrigeration), whereas others are technically feasible today but face cost or logistical challenges for certain applications (e.g., R-717 for refrigerated warehouse or industrial process, R-1234yf for mobile AC). The remaining HVAC&R applications require product development to optimize systems for ultra-low refrigerants (e.g., HFOs for HPWHs, propane for PTACs and Room ACs) or technology breakthroughs using natural refrigerants (e.g., commercial RTU and VRF systems using R-744 or R-290). For these more challenging sectors, non-vapor-compression technologies may be suitable (see section 4.2).

5.3 Hydrofluorocarbon Mitigation Potential by Scenario

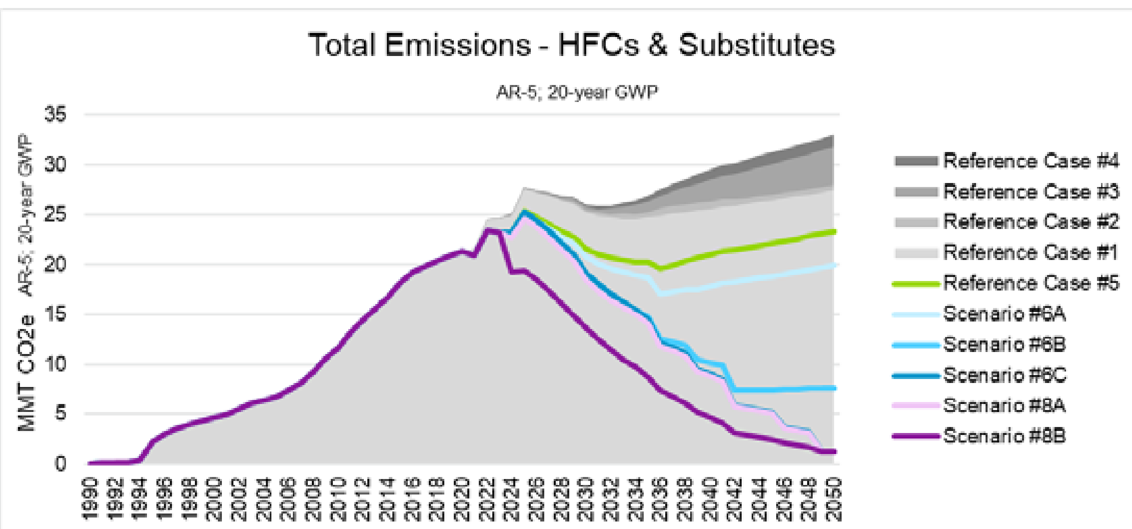
This section summarizes the modeled HFC consumption and emissions reductions associated with each of the potential HFC Mitigation Scenarios described in Table 5-2 above.

5.3.1 Projected Hydrofluorocarbon Emissions under Each Potential Hydrofluorocarbon Mitigation Scenario

Figure 5-1 shows the HFC emissions profile over the period 1990–2050 for each of the potential mitigation scenarios (designated scenario no. 6A, no. 6B, no.6C, no.8A, and no. 8B respectively) in comparison to the Reference Case no. 5 as described in section 3.1. Scenario no. 7 would reduce HFC consumption by using refrigerant currently being recovered (and already reflected in the Reference Cases) for servicing needs but would have no additional impact on HFC emissions and is therefore omitted from Figure 5-1. Potential HFC Mitigation Scenarios no. 6A, B, C and no. 8A, B demonstrate successively lower emissions during the period 2030–2050, reflecting that each scenario builds upon the potential mitigation options of the previous scenario. Because the AIM Act and Kigali Amendment target HFC consumption rather than emissions, figures showing HFC emissions do not include the AIM Act phasedown schedule.

Figure 5-1. Hydrofluorocarbon Emissions by Potential Mitigation Scenario

Each scenario builds upon the previous scenarios. The potential HFC Mitigation Scenarios are quantitatively compared against Reference Case no. 5, and the other Reference Cases are included for qualitative comparison. Scenario no. 7 would provide no additional impact on HFC emissions (only HFC consumption) and is therefore omitted from the figure.



The following trends in HFC emissions are apparent from these modeling results:

- **Potential HFC Mitigation Scenario no. 6A, no. 6B, no. 6C—HFC Restrictions for New Equipment:** These scenarios assume that additional policies are implemented to restrict HFC use in new equipment beyond those in the 2020 NYS SNAP Rule (Reference Case no. 5). Implementing several phases of additional HFC equipment restrictions in New York State, as technology becomes available and as barriers to adoption are overcome, would significantly reduce HFC emissions relative to Reference Cases no. 5 (2020 NYS SNAP Rule). Using 2020 as a baseline year (21 MMT CO_2e AR5 20-year), implementing these mitigation actions would reduce HFC emissions by over 85% by 2050 to 1-2 MMT CO_2e.
  Should the "max tech" scenario no. 6C be realized, most of the installed base of HVAC&R systems in New York State would have near-zero HFC emissions by 2050, since most systems have 10–20-year lifetime. Significant R&D and product development would be needed over the next 5–10-years from now to debut the necessary ultra-low-GWP technologies for key segments such as residential and commercial HVAC systems.
- **Potential HFC Mitigation Scenario no. 8A, no. 8B—Increased Recovery at EOL:** These scenarios increase refrigerant recovery rates at the end-of-life for HVAC&R equipment beginning in 2024, with a focus on larger systems (no. 8A) and smaller systems (no. 8B). End-of-life recovery is an effective near-term strategy to reduce HFC emissions, its impact decreases over time as more systems transition to using low-GWP refrigerants. By 2030, scenarios no. 8B and no. 6C achieve the same goal of 85% HFC emissions reduction compared to 2020 baseline. Developing recovery policies and programs in the next several years would support 2030 Climate Act goals while there is still a large installed base of HVAC&R systems with HFC refrigerants. Furthermore, the increased volume of recovered refrigerant would increase the supply of reclaimed refrigerant to meet service demand, which can help minimize price spikes for NYS industry and consumers when federal HFC allowances decrease through implementation of the AIM Act. Coupling end-of-life recovery and similar policies for existing systems while targeting HFC restrictions for new systems would be the quickest path to HFC emissions reduction in New York State. Nevertheless, scenarios that include improved recovery and reclaim practices achieve the same long-term HFC emissions impacts as equipment-only scenarios, as the majority of HVAC&R equipment will have converted to low-GWP options by 2050. Once a system uses ultra-low-GWP refrigerants, the emissions from its annual leakage is negligible.

Figure 5-2 shows the HFC emissions by end-use sector for scenario no. 6B, which adopts a 750 GWP limit for major residential and light-commercial HVAC product categories in 2027 along with transport refrigeration, HPWHs, and refrigerated warehouses in 2029. The HFC emissions reductions from this scenario represent those that could be reasonably expected based on today's technology trajectory and assuming current industry practices for installation, service, and disposal.

Figure 5-2. Hydrofluorocarbon Emissions by End-Use Sector for Scenario No. 6B

Each scenario builds upon the previous scenario.

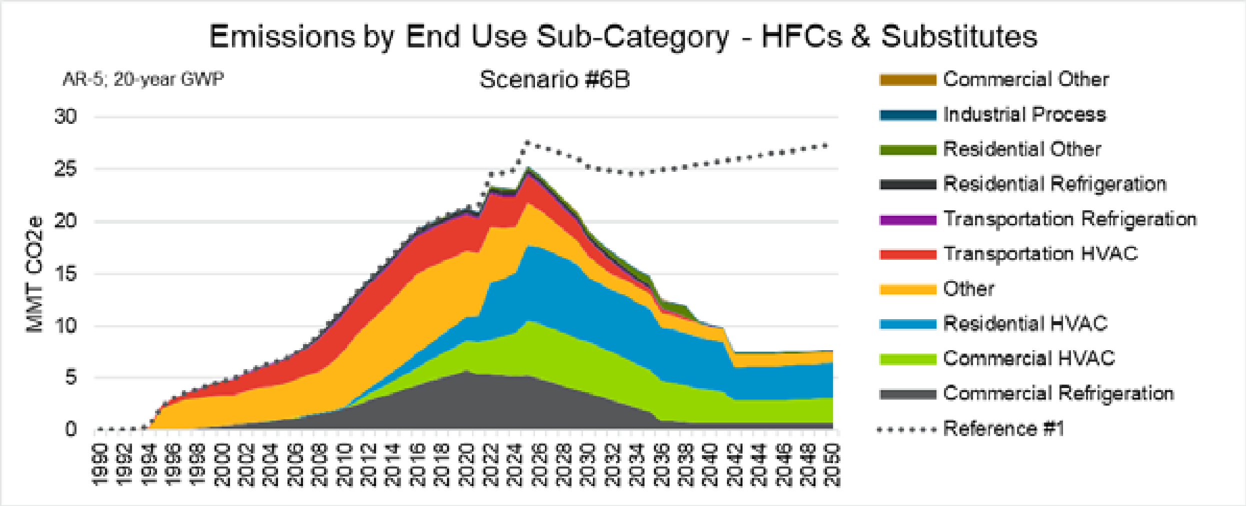


Figure 5-3 shows the HFC emissions by end-use sector for scenario no. 6C, which considers a "max mech" scenario in which all HVAC&R end-uses adopt ultra-low-GWP or natural refrigerants post-2030. In this case, all end-use sectors experience a rapid decrease in HFC emissions and ultimately achieve near-zero emissions by 2050.

Figure 5-3. Hydrofluorocarbon Emissions by End-Use Sector for Scenario No. 6C

Each scenario builds upon the previous scenario.

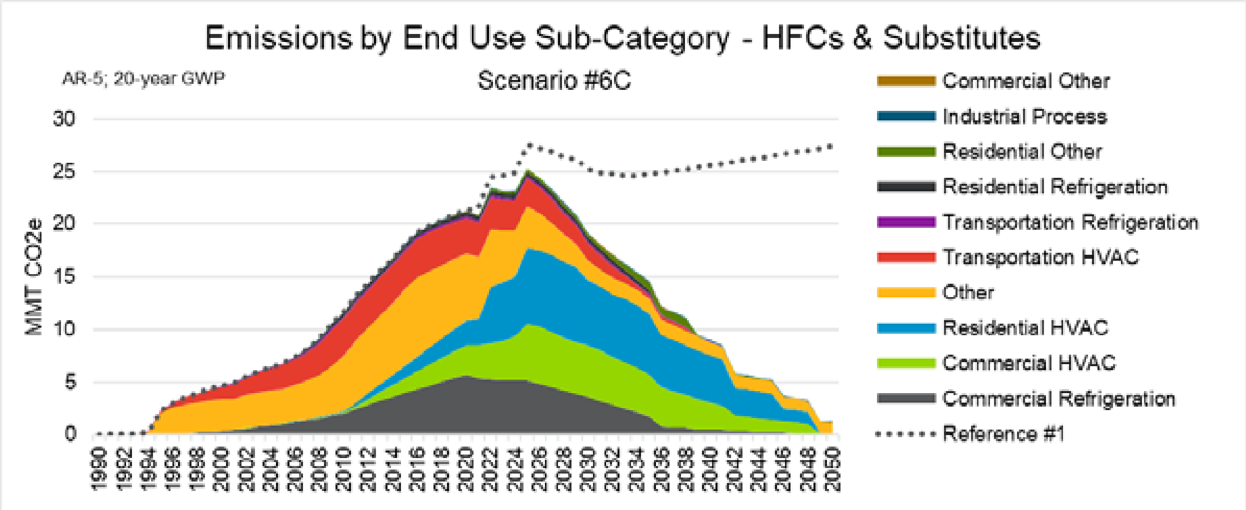
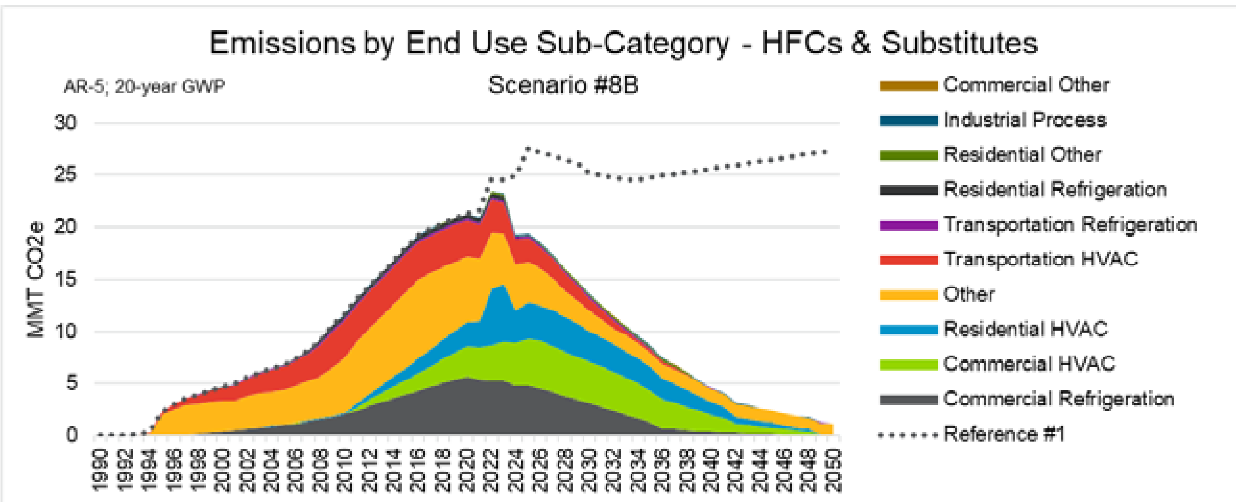


Figure 5-4 shows the HFC emissions by end-use sector for scenario no. 8B, which increases the rate for end-of-life refrigerant recovery starting in 2024 in addition to the "max tech" technology adoption. Developing policies and programs to address end-of-life refrigerant leakage can have a dramatic impact on the HFC emissions for existing systems, particularly smaller HVAC&R systems whose lifecycle emissions are primarily concentrated at end-of-life.

Figure 5-4. Hydrofluorocarbon Emissions by End-Use Sector for Scenario No. 8B

Each scenario builds upon the previous scenario.

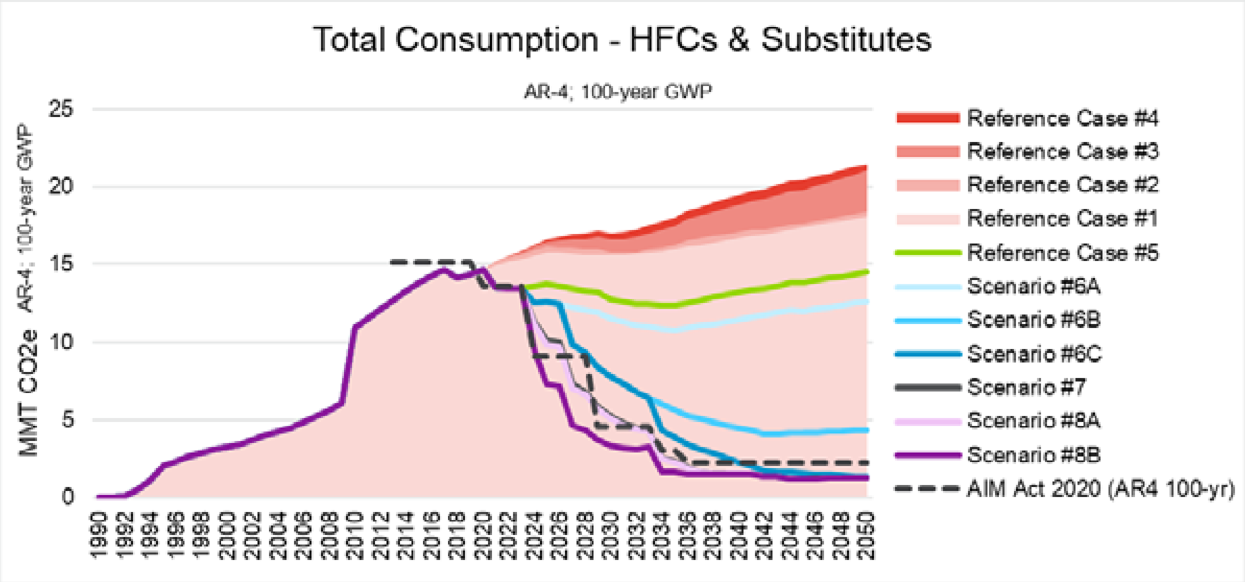


5.3.2 Projected Hydrofluorocarbon Consumption under Each Potential Hydrofluorocarbon Mitigation Scenario

Figure 5-5 shows the HFC consumption profile over the period 1990–2050 for each of the mitigation scenarios (designated scenario no. 6A, no. 6B, no. 6C, no. 7, no. 8A, and no. 8B respectively) in comparison to the Reference Case no. 5, which includes heating electrification as described in section 3.1. The figure also includes HFC consumption phasedown targets established by AIM Act to align with the Kigali Amendment (black dotted line).[59] International and U.S. HFC policies use AR4 100-year GWP values, whereas NYS uses AR5 20-year GWP values. As such, all values have been converted to 100-year GWP values when making comparisons to national and international HFC consumption policies, such as Figure 5-5. Each potential HFC Mitigation Scenario demonstrates successively lower consumption during the period 2030–2050, reflecting that each scenario builds upon the potential mitigation options of the previous scenario.

Figure 5-5. Hydrofluorocarbon Consumption by Potential Mitigation Scenario and AIM Act Target

Each scenario builds upon the previous scenario. The potential HFC Mitigation Scenarios are quantitatively compared against Reference Case no. 5, and the other Reference Cases are included for qualitative comparison.



The following trends in HFC consumption are apparent from these modeling results:

- **Potential HFC Mitigation Scenario no. 6A, no. 6B, no. 6C—HFC Restrictions for New Equipment):** These scenarios assume that additional policies are implemented to restrict HFC use in new equipment beyond those in the 2020 NYS SNAP Rule (Reference Case no. 5).
  - In no. 6A, end-use categories with available low- and ultra-low-GWP options restrict HFC use by 2024, including supermarket refrigeration, mobile AC, and small self-contained HVAC systems such as window AC/HPs and dehumidifiers. Scenario no. 6A would provide modest long-term reductions in HFC consumption compared with Reference Case no. 5.
  - In no. 6B, residential and light-commercial AC/HPs categories that currently face building, fire, and safety code challenges when adopting mildly flammable options transition to low-GWP solutions in 2027 as building code updates are implemented at the state and local level. In addition, end-use categories such as transport refrigeration, refrigerated warehouses, and HPWHs transition to low-GWP solutions by 2029. Scenario no. 6B would provide substantial long-term reductions in HFC consumption compared with Reference Case no. 6A, primarily due to a 750 GWP limit placed on residential and commercial HVAC systems starting in 2027.

- In no. 6C, virtually all HVAC&R product categories adopt ultra-low-GWP or natural refrigerant options for new product sales over 2030–2035. These “max tech” scenarios assume significant technology advances over the next decade and are highly uncertain. Scenario no. 6C would provide modest long-term reductions in HFC consumption compared with Reference Case no. 6B but would be necessary to reach long-term HFC reductions targeted by the Climate Act and the AIM Act and Kigali Amendment.

- **Potential HFC Mitigation Scenario no. 7—Reclaimed Refrigerant for Service:** Scenario no. 7 assumes that all of the refrigerant that is currently recovered from HFC equipment that reaches end-of-life each year is reclaimed and directed to satisfy HFC service demand in existing equipment. This reclaimed supply would offset the need for new HFC supplies and will become particularly important to meet the HFC phasedown targets in the AIM Act and Kigali Amendment. The results of scenario no. 7 show that the use of reclaimed refrigerant for service can reduce HFC consumption beyond the reductions provided by scenario no. 6A, B, C restrictions for new equipment. Nevertheless, this modeling shows that there are insufficient supplies of recovered HFCs under current practices to satisfy the HFC demand for servicing existing equipment. In particular, R-410a for residential and light-commercial AC/HP systems faces significant shortfalls under current practices. Combined with the delay in building code adoption, insufficient reclaim volumes for residential and light commercial HVAC systems are the major factors that would prevent the U.S. in meeting the AIM Act and Kigali Amendment targets. Note that because scenario no. 7 uses refrigerant that is properly recovered today, there is no additional impact on HFC emissions, and therefore scenario no. 7 has been omitted from Figure 5-2 below.
- **Potential HFC Mitigation Scenario no. 8A, no. 8B—Increased Recovery at EOL:** Scenario no. 8A increases refrigerant recovery rates at the end-of-life for large HVAC&R equipment (e.g., supermarket racks, chillers) beginning in 2024, whereas Scenario #8B increases refrigerant recovery rates for smaller HVAC&R systems (e.g., residential and self-contained products) in 2024. The increased volume of recovered refrigerant has a direct impact on available reclaimed refrigerant supplies to meet service demands in existing equipment. Under today’s practices, most of the refrigerant is recovered for larger end-uses (e.g., current loss rates are 20–30%), while smaller systems experience loss rates of 50–80% or greater. Guidehouse assumes the recovery rate increases to 90% (i.e., 10% loss rate) as a theoretical maximum to account for complete charge loss during failure events. Scenario no. 8A provides only a slight incremental reduction relative to scenario no. 7 due to the already high recovery rate for larger systems. Scenario no. 8B provides substantial HFC reduction relative to scenario no. 7, particularly in early years where most HVAC&R equipment has not yet transitioned to lower-GWP options.

5.3.3 Summary of Promising Hydrofluorocarbon Mitigation Strategies

Through this analysis, Guidehouse evaluated a wide range of HFC mitigation strategies by conducting several rounds of scenario testing within the model. Table 5-3 summarizes the findings around the more promising HFC mitigation strategies as well as those that did not provide significant HFC consumption or emissions reduction.

The most promising strategies for reducing HFC emissions include implementing restrictions on new equipment and improving refrigerant recovery rates at EOL for small-size HVAC&R systems. In addition, using reclaimed refrigerant for servicing needs (as opposed to destroying it) can significantly reduce consumption, but has no impact on emissions, as described earlier in this report.

Less promising strategies for reducing HFC emissions include improving refrigerant recovery rates at EOL for large-size HVAC&R systems and reducing the leakage rate of new systems. Under current practices, large-size HVAC&R systems already have high EOL recovery rates, so efforts to increase the recovery rates further would provide limited incremental savings compared to focusing efforts on smaller systems, which have extremely low EOL recovery rates currently. Regarding the leakage rate of new systems, the modeling results indicate that the impact on emissions from reducing the leak rate of new equipment is fairly minor compared to the impact of switching to a low-GWP refrigerant. As discussed earlier in this report, Guidehouse research indicates that low-GWP systems are likely to have a 50% lower leakage rate than the HFC systems they replace (without any specific policy actions); therefore, policy actions should prioritize other strategies that have a greater potential for emissions reduction.

Finally, although not modeled in this report, reducing leakage rates in existing systems (i.e., HFC equipment in the installed base) could have a high impact on both consumption and emissions. Given that annual leakage of the installed base is a major contributor to HFC consumption and emissions, theoretically, this strategy could provide significant near-term reductions in consumption and emissions for existing systems. For example, RMPs for supermarket rack systems has been shown to significantly reduce HFC emissions and consumption, as discussed in section 4.4. The value of this strategy decreases over time as new equipment is replaced with low-GWP options; nevertheless, this strategy may be valuable, and potentially necessary, to achieve the 2024 and 2029 phasedown targets of the AIM Act.

Table 5-3. Summary of Impact of Potential Hydrofluorocarbon Mitigation Strategies

Policy Category	Modeling Scenario / Description	Consumption Impacts	Emissions Impacts
More Promising HFC Mitigation Strategies			
HFC Restrictions for New Equipment	· Reference Case no. 5 and Mitigation Scenario no. 6A, B, C · See discussion earlier in this section	High	High
Use of Reclaimed Refrigerant for Servicing Needs	· Mitigation Scenario no. 7, no. 8A, B · See discussion earlier in this section	High	–
Improved Refrigerant Recovery at End-of-Life for Small HVAC&R Systems	· Mitigation Scenario no. 8B · See discussion earlier in this section	High	High
Less Promising HFC Mitigation Strategies			
Improved Refrigerant Recovery at End-of-Life for Large HVAC&R Systems	· Mitigation Scenario no. 8A · See discussion earlier in this section. Large HVAC&R systems have high EOL recovery rates under current practices (70–80%), so the incremental savings are more limited compared to smaller systems.	Low	Low
Leakage Reduction for New Systems	· Reference Case no. 5 and All Mitigation Scenarios · Scenarios assume that low-GWP systems have 50% lower leakage rates. The scenarios were tested with and without this assumption and indicated that assuming a leak rate reduction provided only a minor impact on HFC consumption and emissions. The switch to low-GWP refrigerant provided the more significant impact.	Low	Low
Promising HFC Mitigation Strategies for Near-Term Reductions			
Leakage Reduction for Existing Systems (*i.e.* the Installed Base)	· Not modeled in this report · Given that annual leakage is a major contributor to HFC consumption and emissions, theoretically, this strategy can provide significant near-term benefits for existing systems. The value of this strategy decreases over time as new equipment is replaced with low-GWP options. Nevertheless, the strategy may be valuable, and potentially necessary, to achieve the 2024 and 2029 AIM Act phasedown targets.	High	High

5.3.4 Federal AIM Act Impacts on New York State Hydrofluorocarbon Consumption and Emissions

The AIM Act will significantly impact the landscape for HFC refrigerants and HVAC&R technologies over the next decade, and its implications will become clearer in the near future due to anticipated EPA regulatory actions in 2021. The AIM Act will require major reductions in HFC consumption through 2050, particularly in large steps scheduled for 2024 and 2029, but the exact pathways and equipment-specific timelines for achieving these reductions are highly uncertain and very challenging. The results of the modeling suggest that the federal HFC targets for 2024 and 2029 are more aggressive than what could be achieved through feasible HFC restrictions on new equipment only (scenario no. 6A, B, C) and would require rapid growth in the use of reclaimed refrigerant for servicing needs. Pre-2030, the supply of reclaimed refrigerant, especially R-410A, will be limited by the amount of recovered HFC refrigerant at end-of-life assuming current practices (scenario no.7). Sufficient reclaim quantities will only be available through improved end-of-life recovery practices that address larger systems (scenario no. 8A) and most importantly, smaller systems (scenario no. 8B).

Scenario no. 8B is the only scenario that achieves the 2024 and 2029 federal HFC consumption phasedown targets, with other less aggressive scenarios resulting in a sizable gap between HFC demand and the expected level of HFC allowances under the AIM Act. This suggests that policies for new equipment HFC restrictions and use of reclaimed HFC refrigerant supplies that would be available today would need to be supplemented by market-based solutions.[60] For example, to the extent that HFC demand exceeds the allowable supply of virgin HFC, the price for HFC supplies would be expected to naturally increase, which could incentivize industry stakeholders to focus efforts on minimizing HFC loss such as by reducing annual leak rates and recovering more HFCs at end-of-life. Forecasting the price of HFC refrigerant is highly uncertain, but recent history of HFC phasedowns in Europe suggests that a significant spike in prices may be expected. Recent European data indicates price increases of 3x to 10x relative to 2014 values for HFC refrigerants subject to phaseout policies.[61]

As noted previously, federal policies and international agreements focus on HFC consumption, rather than HFC emissions. Nevertheless, most activities that limit HFC consumption, such as restrictions on new equipment or programs to reduce system leakage, would have a direct impact on future HFC emissions. NYS may be able to leverage federal policies enacted to achieve AIM Act HFC consumption targets that would subsequently support HFC emissions reduction in alignment with the Climate Act goals.

NYS should closely follow EPA's development of the policy mechanisms, schedules, and pathways for meeting the AIM Act targets and evaluate how these activities will affect future HFC emissions as well as NYS consumers, industry, and other stakeholders. If EPA priorities change in future years or do not align with Climate Act goals, NYS should develop its own HFC policies to achieve its goals. Furthermore, NYS should consider voluntary and mandatory strategies to reduce transition cost and complexity in the State (e.g., businesses that prepare early will not be as impacted by the anticipated HFC price spikes in future years).

5.4 Hydrofluorocarbon Mitigation Impacts and Levelized Abatement Costs

5.4.1 Hydrofluorocarbon Mitigation Impacts

Guidehouse calculated the incremental cost and HFC emissions savings of each potential HFC Mitigation Scenario by comparing the cumulative number of low- and ultra-low-GWP technologies sold and the associated HFC emissions values against Reference Case no. 5 (which includes increased residential AC adoption; heating electrification of 70% of sales by 2030 and 100% by 2045; and impacts of the 2020 NYS SNAP Rule). Section 4.2.1 describes the methodology for estimated incremental cost values for switching to low- and ultra-low-GWP refrigerants in specific end-use categories. In addition to low-GWP switching costs, EOL refrigerant management costs were estimated and applied to scenarios that incorporate increased refrigerant recovery and reclaim (see section 4.2.2 for details). Incremental costs and emission reductions were independently tabulated for each year 2021–2050 and summed over that same period to determine cumulative costs and cumulative emissions.

Figure 5-6 and Figure 5-7 show cumulative emissions reductions and cumulative mitigation costs, respectively. The two sectors with the greatest potential for emissions reduction are residential and commercial HVAC, which together account for more than 80% of potential emissions savings. Cumulative emissions savings range from ~50 MMT CO_2e to more than 350 MMT CO_2e (in terms of AR5 20-year GWP values) across the different scenarios.

The mitigation measure with greatest total abatement cost is low-GWP switching for the residential HVAC industry, followed closely by commercial HVAC. The abatement cost for residential HVAC mitigation increases sharply as the mitigation scenarios become more stringent. The residential and commercial “other” sectors, which consist of HPWHs and clothes dryers, also generate large costs because these low-GWP products have relatively high-purchase prices. Further discussed in section 5.4.2 below, these measures can be removed from consideration to generate lower-cost solutions while retaining comparable emissions savings.

Figure 5-6. Emissions Reduction by Potential Mitigation Scenario and Subcategory, Cumulative 2021–2050

Each scenario builds upon the previous scenario.

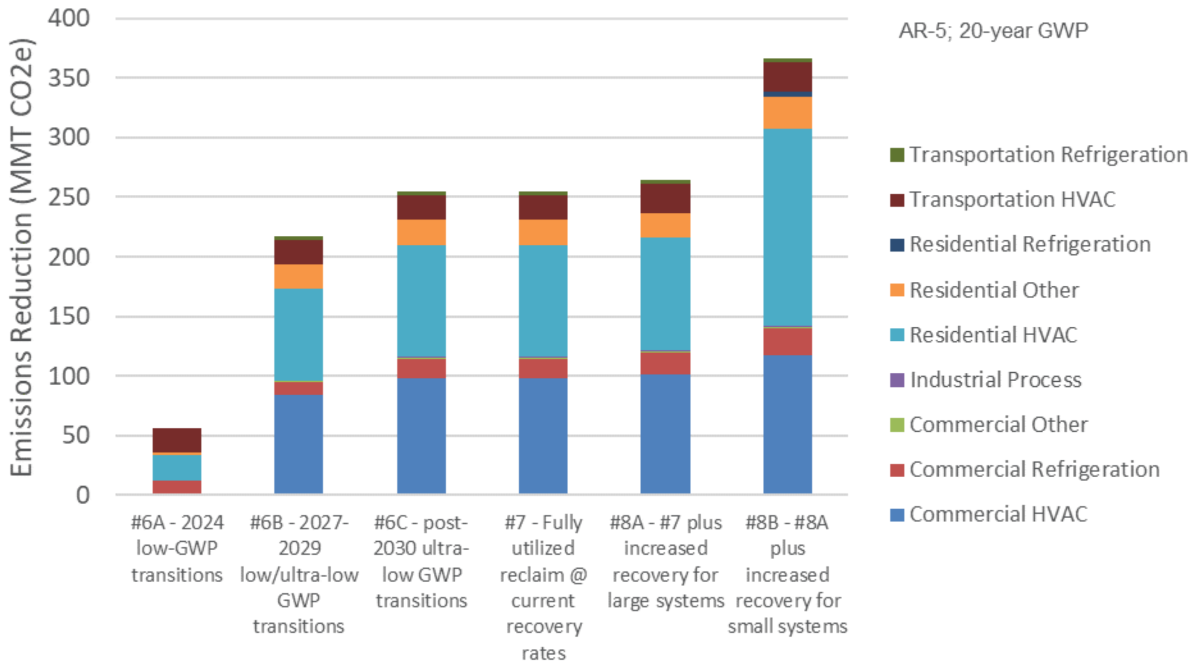
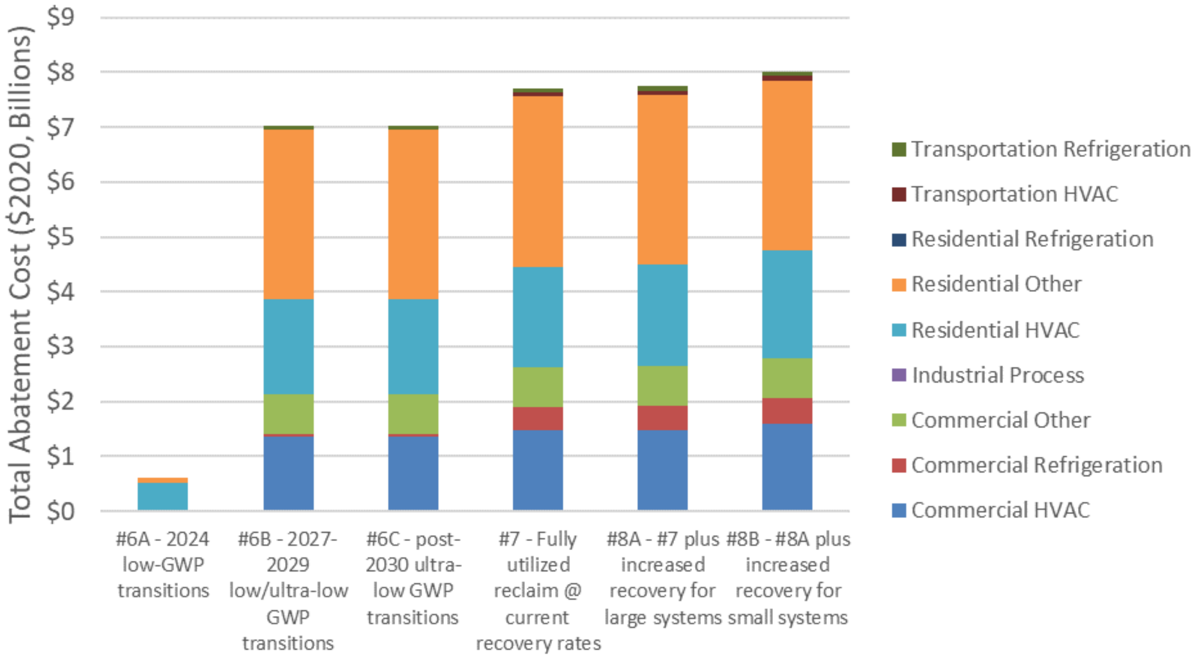


Figure 5-7. Total Abatement Cost by Potential Mitigation Scenario and Subcategory, Cumulative 2021–2050

Each scenario builds upon the previous scenario.



5.4.2 Levelized Abatement Costs of Potential Mitigation Scenarios

After tabulating cumulative costs and emissions for each mitigation scenario, Guidehouse calculated the levelized abatement costs of each potential HFC Mitigation Scenario in terms of dollars per metric ton of CO_2e emissions reduction (in terms of AR5 20-year GWP values). Levelized abatement costs is the ratio of cumulative abatement cost and cumulative GHG emissions reduction over 2021–2050. Evaluating the levelized abatement costs of HFC mitigation solutions may be helpful in prioritizing potential future policy actions in New York State. Table 5-4 shows the levelized abatement costs by end-use subcategory of the various proposals for GWP restrictions on new equipment.

Table 5-4. Levelized Abatement Costs ($2020 per ton CO_2e AR5 20-year GWP) by Potential Mitigation Scenario and Equipment Category, Cumulative 2021–2050

Each scenario builds upon the previous scenario.

Mitigation Scenario	No. 6A - 2024 low-GWP transitions	No. 6B - 2027–2029 low/ultra-low GWP transitions	No. 6C - post-2030 ultra-low GWP transitions	No. 6B (without HPWH)	No. 6C (without HPWH)
Commercial HVAC	$15	$16	$14	$16	$14
Commercial Refrigeration	$0	$5	$4	$5	$4
Commercial Other	--	$673	$673	--	--
Industrial Process	--	--	$8	--	$8
Residential HVAC	$23	$23	$18	$23	$18
Residential Other	$47	$149	$146	$88	$75
Residential Refrigeration	--	--	--	--	--
Transportation HVAC	$0	$0	$0	$0	$0
Transportation Refrigeration	--	$21	$21	$21	$21
Total (weighted)	**$10.9**	**$32.4**	**$27.6**	**$17.3**	**$14.6**

The results in Table 5-4 indicate that the “Commercial Other” and “Residential Other” categories have a significantly lower cost-effectiveness than the other subcategories, when HPWH is included in the calculations. The relatively high-levelized abatement costs of HPWH is due to the following factors:

1. HPWHs have a high-cost relative to other non-HVAC building appliances (e.g., refrigerator/freezers). HPWH options with low-GWP refrigerants have a further incremental cost premium over those with high-GWP refrigerants.
2. HPWHs have relatively small refrigerant charge and typically sealed systems for residential and light-commercial applications. As such, the expectation is that these systems have minimal annual leakage. Therefore, the HFC emissions reduction potential from switching to low-GWP refrigerants would be small. Larger commercial systems will likely have split indoor/outdoor configurations, which may lead to a higher leak rate, but there is minimal installed base today with which to develop more detailed assumptions.
3. The combination of relatively high-incremental cost and relatively small HFC emissions reduction potential leads to a relatively high-levelized abatement cost ($ per MMT CO_2e, AR-5, 20-year GWP) when switching to low-GWP refrigerants. The model does not take into account GHG emissions impacts for HPWHs when replacing fossil fuel water heating systems.

Because of the relatively high-levelized abatement costs of the water heating categories, Guidehouse created two additional mitigation scenarios that show the levelized abatement costs of scenarios no. 6B and no. 6C if water heaters were exempt from the low-GWP requirements modeled in these scenarios. By removing low-GWP requirements for water heaters, the levelized abatement costs of scenarios no. 6B and no. 6C improve significantly, as shown in Table 5-4.

In addition to the mitigation costs associated with enacting GWP restrictions on new equipment, Guidehouse also analyzed costs associated with managing refrigerant from systems at end-of-life (see section 4.2.2 for details). Three additional scenarios were created that show the cumulative impact of (1) reclaimed refrigerant fully utilized for service consumption (scenario no. 7), (2) increasing EOL recovery rates for large equipment (scenario no. 8A), and (3) increasing EOL recovery rates for small equipment (scenario no. 8B).

Figure 5-8 shows the total abatement costs of each mitigation scenario, and Figure 5-9 shows the total abatement cost versus total emissions savings of each scenario. Both figures exclude GWP restrictions for heat pump water heaters.

Figure 5-8. Comparative Abatement Costs of Potential Mitigation Scenarios, Cumulative 2021–2050

Each scenario builds upon the previous scenario.

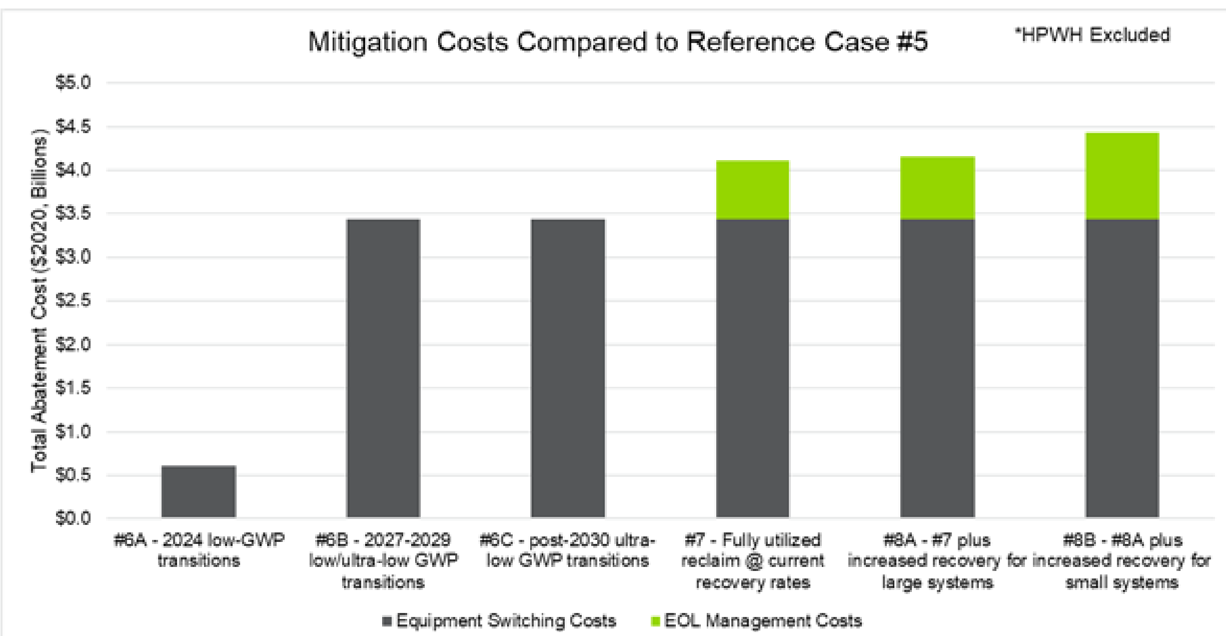
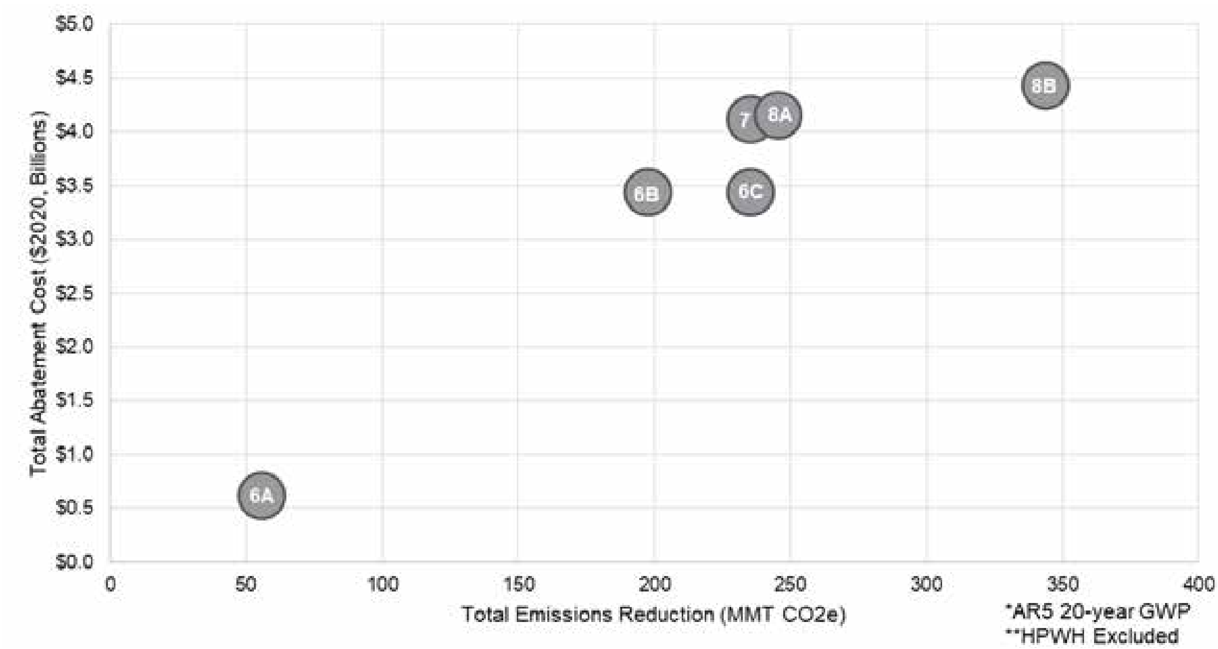


Figure 5-9. Abatement Costs and Emissions Reduction by Potential Mitigation Scenario, Cumulative 2021–2050

Each scenario builds upon the previous scenario.



As described in section 4.2.1, due to the uncertainty of marginal cost impacts for a second transition to ultra-low-GWP refrigerants, Guidehouse assumed no additional incremental transition costs between low-GWP and ultra-low-GWP equipment. As an artifact of this cost modeling assumption, scenarios no. 6B and no. 6C appear to have nearly identical total abatement cost, but no. 6C results in significantly higher emissions reductions. This assumption should be researched further once viable design options with ultra-low-GWP refrigerants are identified in applicable end-use sectors.

Finally, for each mitigation scenario (both with and without HPWH inclusion in low-GWP restrictions), Guidehouse calculated total emission reductions in the years 2030 and 2050 to compare to the Climate Act GHG reduction mandates for those years. Those results are summarized in Table 5-5 below, showing that total GHG reductions of up to 7.7 and 22.0 MMT CO_2e (AR-5 20-year GWP) in 2030 and 2050, respectively, would be achieved via the potential Mitigation Scenarios as defined. Each of the potential mitigation scenarios has levelized abatement costs of less than $32 per ton CO_2e when including HPWHs and less than $17 per ton CO_2e when excluding HPWHs.

Table 5-5. Cumulative Abatement Costs and Greenhouse Gas Impacts and Target Year Greenhouse Gas Impacts by Potential Mitigation Scenario (AR-5, 20-year GWP)

Each scenario builds upon the previous scenario.

Mitigation Scenario	Include GWP Restrictions for HPWH (Yes/No)	Cumulative Abatement Cost (Billions, $2020)	Cumulative Emissions Reduction (MMT CO_2e)	Levelized Abatement Cost ($2020 / MMT CO_2e)	2030 GHG Reduction (MMT CO_2e)	2050 GHG Reduction (MMT CO_2e)
Mitigation Scenario #6A: Reference Case #5 + 2024 feasible transitions to low-GWP in new equipment	Yes	$0.6	56	$11	0.8	3.3
	No	$0.6	56	$11	0.8	3.3
Mitigation Scenario #6B: #6A + 2027–2029 feasible transitions to low- or ultra-low-GWP in new equipment	Yes	$7.0	217	$32	2.4	15.6
	No	$3.4	198	$17	2.4	13.8
Mitigation Scenario #6C: #6B + Post-2030 transitions to ultra-low-GWP in new equipment	Yes	$7.0	255	$28	2.4	21.9
	No	$3.4	236	$15	2.4	20.1
Mitigation Scenario #7: #6C + Currently recaptured refrigerant is reclaimed and fully utilized for service consumption	Yes	$7.7	255	$30	2.4	21.9
	No	$4.1	236	$17	2.4	20.1
Mitigation Scenario #8A:#7 + Max possible recapture rate for large systems	Yes	$7.8	265	$29	3.1	22.0
	No	$4.2	246	$17	3.1	20.2
Mitigation Scenario #8B: #8A + Max possible recapture for small systems	Yes	$8.0	367	$22	7.7	22.0
	No	$4.4	344	$13	7.7	20.2

5.5 Summary of Key Findings

The key findings regarding the potential HFC Mitigation Scenarios include the following:

- Implementing several phases of additional HFC policies in New York State, as technology becomes available and as barriers to adoption are overcome, would significantly reduce HFC consumption and emissions relative to Reference Case no. 5 (2020 NYS SNAP Rule). Using 2020 as a baseline year (21 MMT CO_2e AR-5 20-year), implementing these mitigation actions would reduce HFC emissions by over 85% in 2050 to 1–2 MMT CO_2e. The following bullets describe the HFC policies analyzed in this project and their potential impacts.

- In particular, facilitating updates to state and local building codes in 2027 to allow the use of low-GWP refrigerants in residential and light-commercial HVAC systems would be a major milestone activity for NYS. Post-2030, the model assumes that virtually all HVAC&R product categories adopt ultra-low-GWP or natural refrigerant options, which would require significant technology advances over the next decade.
- Beyond equipment restrictions, the analysis indicates that the rapid growth in the use of reclaimed refrigerant will be a key strategy to reduce HFC consumption, but that current recovery practices would produce limited reclaim supplies, especially for R-410a. Furthermore, increasing end-of-life recovery rates for small HVAC&R systems (small systems with less than 50 pounds refrigerant charge in particular) would reduce HFC emissions and subsequently reduce HFC consumption by increasing the available supplies of reclaimed refrigerant to be used for servicing needs.
- Improving reclaimed refrigerant and end-of-life recovery practices will be necessary to meet the phasedown schedule in the AIM Act and would support greater near-term HFC emissions reductions. Scenarios that include improved recovery and reclaim practices achieve the same long-term HFC consumption and emissions impacts as equipment-only scenarios but provide greater near-term HFC emissions reductions than equipment-only scenarios.
- The AIM Act will require major reductions in HFC consumption through 2050, particularly in 2024 and 2029, but the exact pathways and equipment-specific timelines for achieving these reductions are highly uncertain and very challenging. NYS may be able to leverage federal policies enacted to achieve AIM Act HFC consumption targets that would subsequently support HFC emissions reduction in alignment with the Climate Act goals.
- The sectors with lowest levelized abatement cost for HFC mitigation are Commercial Refrigeration, Commercial HVAC, and Industrial Processes. Transportation HVAC is not expected to incur any switching costs for low-GWP technologies.
- Nearly all mitigation strategies considered in this report have relatively low-levelized abatement costs[62] (less than $25 per ton CO_2e) with the exception of the residential and commercial water heating sectors.

6 Conclusions and Recommendations

This section summarizes Guidehouse's key findings, conclusions, and recommendations for NYSERDA, DEC, and other stakeholders to consider when evaluating HFC mitigation strategies to achieve Climate Act goals. In addition, Guidehouse identified areas of the analysis that could be enhanced with additional research.

6.1 Project Summary

The purpose of this report is to provide NYSERDA with an updated and more comprehensive inventory for HFC gases in New York State, detailing how (1) statewide HFC usage is expected to change in future years, due to economic growth, appliance electrification, and other trends and (2) the impacts of potential policies that could be considered to significantly reduce HFC emissions. This report covers a wide variety of HFC end-use categories including refrigerants used in space conditioning and refrigeration for residential, commercial, industrial, and transport applications, as well as non-refrigerant HFCs used in foams, aerosol propellants, solvents, and fire protection. This report also considers newer HFC applications such as heat pump water heaters and clothes dryers, sales of which are expected to increase as the Climate Act drives electrification.

Guidehouse first reviewed the current NYS HFC emissions inventory and supporting documentation for the Climate Act [Climate Act] Integration Analysis project. Guidehouse then conducted a thorough literature review of the latest government and industry research into HFC emissions inventories, refrigerant saturations, low-GWP alternatives, and mitigation strategies. Guidehouse also conducted several interviews with industry organizations. This information was used to develop a detailed bottom-up vintaging model to calculate historical, current, and future HFC consumption and emissions for the over 40 end-use categories and analyzed potential HFC Mitigation Scenarios for NYS. Based on these findings, Guidehouse then identified and recommended RD&D activities and policy actions to reduce HFC emissions and achieve the Climate Act goals.

Section 2 of the report provides a summary of historical HFC consumption and emissions projected over 1990–2020 by end-use category, by emissions source, and other parameters. Section 3 provides a summary of future HFC consumption and emissions projections based on expected growth rates, increased residential AC usage, decarbonization pathways to achieve Climate Act goals, and established HFC phasedown policies. Section 4 provides a detailed analysis of available low-GWP refrigerants,[63] leakage reduction technologies and policies, and RD&D initiatives to increase their adoption in NYS.

Section 5 provides analysis into the projected impacts and timelines for several mitigation scenarios that could reduce future HFC consumption and emissions in NYS. Finally, this section summarizes Guidehouse's key findings, conclusions, and recommendations for NYSERDA, DEC, and other stakeholders to consider when evaluating potential HFC mitigation strategies to achieve Climate Act goals.

6.2 Conclusions

Guidehouse's key conclusions regarding NYS HFC emissions and potential mitigation strategies are summarized below.

- HFC emissions in New York State have grown from near-zero in 1990 to 21.2 MMT in 2020 (AR-5, 20-year GWP), driven by the use of HFCs to replace CFCs/HCFCs as they were phased down (primarily) and economic growth in the State (secondarily). Beyond 2020, as all vintage CFC/HCFC equipment reaches end-of-life, business-as-usual growth in HFC emissions will be much slower. Commercial refrigeration is the largest contributor to HFC emissions in 2020, followed by aerosol propellants and light-duty MVAC. For most categories, annual leakage throughout the equipment lifetime is a much greater source of emissions than end-of-life leakage.
- Commercial and residential HVAC&R systems are the fastest-growing sources of emissions historically and are expected to increase further in future years. Heat pump systems have a relatively small contribution to total emissions in 2020 but are expected to grow substantially as heating electrification increases in New York State because heat pump systems, particularly VRF systems, have higher refrigerant charge than comparable AC-only systems. Heat pump water heaters are unlikely to be a significant contributor to HFC emissions, assuming leakage rates are similar to other self-contained systems (i.e., very minor).
- Building electrification is expected to drive a substantial decrease in overall building GHG emissions (not evaluated in this analysis), but the analysis suggests that this would also cause a notable increase in HFC emissions during the period 2035–2050. However, HFC emissions reduction achieved by the 2020 NYS SNAP Rule outweighs the impacts of heating electrification, reflecting a net overall reduction in HFC emissions.
- The 2020 NYS SNAP Rule restricting the use of high GWP refrigerants for residential and commercial refrigeration, commercial chillers, and other segments will have a significant impact on decreasing future HFC emissions in NYS, reducing HFC emissions by approximately 30% in 2050 compared to a reference case that includes heating electrification goals.
- Implementing several phases of additional HFC policies in New York State—as technology becomes available and as barriers to adoption are overcome—would significantly reduce HFC consumption and emissions further. Using 2020 as a baseline year (21 MMT CO_2e AR-5 20-year), implementing these mitigation actions would reduce HFC emissions by over 85% in 2050 to 1–2 MMT CO_2e. The following bullets describe the HFC policies analyzed in this project and their potential impacts.

- In the near term (i.e., by 2024), HFC prohibitions for new product sales could be implemented on room and window AC/HPs, industrial systems, transport HVAC; and ultra-low-GWP (greater than 10) limits could be placed on supermarket systems. These technologies are commercially available, although early products may be more expensive and complex than conventional options.
- Low-GWP alternatives are available for certain applications, but face significant challenges to adoption, most notably with building and safety codes for residential and commercial central HVAC systems. Under the currently projected code cycle, New York State building code updates in 2027 could allow the use of mildly flammable A2L refrigerants for these key applications.
- The use of ultra-low-GWP technologies will be required in the long-term to further reduce HFC emissions beyond what is achievable with current technologies. Significant RD&D is necessary to support the technological advances that would be required over the next decade to develop ultra-low-GWP options for many key HVAC product categories.
- Although equipment restrictions would significantly reduce HFC emissions in 2050 to 85% below a reference case including heating electrification, such restrictions would not provide enough emissions reduction to achieve the consumption phasedown limits established by the AIM Act for 2024 and 2029 (40% and 70% reduction, respectively). Improving reclaimed refrigerant and end-of-life recovery practices will be necessary to meet the consumption phasedown schedule in the AIM Act and would support greater near-term HFC emissions reductions.
- Beyond equipment restrictions, the analysis indicates that a rapid growth in the use of reclaimed refrigerant for servicing needs will be a key strategy to reduce HFC consumption, but that current recovery practices, as well as the relatively small number of HFC systems reaching end-of-life between now and 2024, would produce a limited supply of reclaimed refrigerant, especially for R-410a. Additional supply of reclaimed refrigerant will be required to fulfill servicing needs to achieve the 2024 and 2029 consumption reduction targets.
- Increasing end-of-life recovery rates for small HVAC&R systems (generally less than 50 pounds refrigerant charge), which currently have low end-of-life recovery rates, would substantially reduce HFC emissions and would subsequently reduce HFC consumption by increasing the available supplies of reclaimed refrigerant that can be used for servicing needs. Whereas, increasing end-of-life recovery rates for large systems would have little additional impact, given that large systems already have relatively high end-of-life recovery rates.
- The federal AIM Act will require major reductions in HFC consumption through 2050, particularly in 2024 and 2029, but the exact pathways and equipment-specific timelines for achieving these reductions are highly uncertain and very challenging. NYS may be able to leverage federal policies enacted to achieve AIM Act HFC consumption targets that would subsequently support HFC emissions reduction in alignment with the Climate Act goals.
- Nearly all mitigation strategies considered in this report have relatively low-levelized abatement costs[64] (less than $25 per ton CO_2e) with the exception of the residential and commercial water heating sectors, which have relatively minimal emissions savings and would therefore have higher levelized abatement costs.

6.3 Recommendations

Based on these conclusions summarized above, Guidehouse recommends the following actions to NYSERDA, DEC, and other stakeholders when evaluating potential HFC mitigation strategies to achieve Climate Act goals.

- Reducing HFC emissions is critical to achieving Climate Act statewide emission reduction goals. Aggressive equipment restrictions are needed in the short-term, mid-term, and long-term to reduce HFC emissions. These strategies have relatively low-levelized abatement costs (less than $25 per ton CO_2e), given the findings from the model regarding incremental equipment costs and cumulative emissions savings during the period 2021–2050. These actions would reduce emissions by over 85% by 2050:
    - **Phase I (Before 2024):** Low-GWP refrigerants for commercial and residential room AC/HP, industrial systems, transport HVAC, and supermarket racks to ultra-low-GWP options.
    - **Phase II (2027–2029):** Building code updates are made by 2027 to allow for low-GWP refrigerants for commercial central and ductless AC/HP and residential whole-home AC/HP; low-GWP refrigerants for transport refrigeration; ultra-low-GWP refrigerants for commercial icemakers and water heating, warehouses, residential water heating and clothes drying.
    - **Phase III (Post-2030):** Ultra-low-GWP refrigerants for all residential and commercial AC/HP, chillers (medium and small), walk-ins, industrial systems, and all residential AC.
- NYS should ensure that local building codes are updated by 2027 to allow for commercial and residential AC/HP systems that use mildly flammable low-GWP refrigerants (i.e., ASHRAE Classification A2L). These HVAC&R segments represent major opportunities for GHG emissions reduction in NYS through the combination of low-GWP refrigerants when replacing HFCs and heating electrification when replacing fossil fuel systems.
- NYSERDA should provide RD&D support over the next decade to develop ultra-low-GWP, natural refrigerant, and non-vapor-compression systems (“max tech” technologies) for key end-use sectors such as residential and light commercial HVAC. These sectors do not have a “max tech” option available today. Supporting manufacturer product development, laboratory testing, field demonstrations, and pilot incentive programs can advance these technologies into the U.S. market. In particular, heat pumps for residential and commercial space heating are most critical, whereas heat pump water heaters are less important.
- NYS may be able to leverage federal policies enacted to achieve AIM Act HFC consumption targets that would subsequently support HFC emissions reduction in alignment with the Climate Act goals. NYS should closely follow EPA’s development of the policy mechanisms, schedules, and pathways for meeting the AIM Act targets, and work with industry partners to identify how best to guide the State through this transition. NYS should consider voluntary and mandatory strategies to reduce transition cost and complexity (e.g., businesses in the State that prepare early will not be as impacted by the anticipated HFC price spikes in future years). These strategies could consider regulations earlier than EPA timelines, as well as incentives and financial support.

- If EPA priorities change in future years or do not align with Climate Act goals, NYS should develop its own HFC policies to achieve its goals. The major activities and implementation timelines should align with those envisioned in the potential HFC Mitigation Scenarios.

- Beyond equipment restrictions, a significant increase in recovery/reclaim rates and proper disposal at equipment end-of-life will be needed at a national level to achieve AIM Act targets in 2024 and 2029. In support of this, NYSERDA should do the following:
  - Conduct a market assessment of current HFC recovery and reclaim practices in NYS.
  - Develop an education and outreach strategy for local industry stakeholders.
  - Provide technical, economic, and training support to aid local industry with this transition.

- NYSERDA should conduct further research to address a number of known data gaps and uncertainties that have high sensitivity for these modeling results. For example, further analysis is needed to determine the expected market share of packaged, split, and VRF heat pumps, specifically for commercial sector; and to determine prototypical leak rates and charge size for VRF systems.
- As discussed in section 4.5, Guidehouse has identified a series of RD&D activities that NYSERDA could support to advance low-GWP and leak reduction solutions, as outlined in Table 6-1.

Table 6-1. Research, Development, and Deployment Recommendations for Low-Global Warming Potential and Leak Reduction Solutions

Recommendations	
Research and Development Focus	1. Develop, test, and demonstrate low-charge propane and isobutane equipment that minimizes safety risks. 2. Conduct R&D on CO_2 residential and commercial heat pump systems. 3. Develop, test, and demonstrate building AC/HP systems with low-GWP refrigerants (non-vapor-compression technologies can also be a focus area). 4. Develop and test low-charge ammonia refrigeration equipment that minimizes safety risks. 5. Develop fault detection and diagnostics (FDD) systems to detect leakage from packaged HVAC&R systems. 6. Conduct R&D for VRF charge size and leakage reduction strategies. 7. Conduct R&D on microchannel heat exchangers for heat pumps and leak reduction.
Deployment and Market Support Focus	8. Develop case studies showing the safety, performance, and cost impacts of alternative refrigerants. 9. Develop and conduct large scale field studies to determine representative leak rates for VRF systems. 10. Provide training for industry technicians, system designers, and other stakeholders on proper use of alternative refrigerants (including transition costs). 11. Support low-GWP awareness campaign for consumer and industry stakeholders. 12. Conduct field studies to evaluate impacts of onboard leak mitigation systems for A3 and A2L refrigerants. 13. Develop NYS case studies showing the safety, performance, and cost impacts of proper refrigerant management practices 14. Develop NYS case studies showing the benefits of low-charge system design with leak mitigation technologies, such as energy efficiency, initial cost, leakage reduction, GHG emissions, lifecycle maintenance costs, and other attributes. 15. Conduct detailed analysis of charge size differences between AC and heat pump systems using low-GWP refrigerants.

6.4 Gaps and Areas for Future Research

This section discusses limitations of the analysis due to data gaps and modeling sensitives and outlines future potential research opportunities to address these gaps and additional needs for low-GWP and leak reduction solutions.

6.4.1 Data Gaps

- Limited data is available regarding retail and installation cost premium estimates for switching to low-GWP refrigerants for many equipment categories including chillers, refrigerator/freezers, heat pump water heaters, clothes dryers, and transportation refrigeration. Few studies have been done to analyze cost premiums from switching to low-GWP refrigerants, and available data is based on stakeholder feedback and interviews. Due to the uncertainty of marginal cost impacts for a second transition to ultra-low-GWP refrigerants, Guidehouse assumed no additional incremental transition costs between low-GWP and ultra-low-GWP equipment. This assumption should be researched further once viable design options with ultra-low-GWP refrigerants are identified in applicable end-use sectors.
- The types of low-GWP refrigerants that will be used, and the ultimate costs once they are commercialized, are highly uncertain. More research is needed to estimate refrigerant cost premiums in commercialized technologies and understand how costs may change over time.
- Limited data is available on the cost of recovering refrigerant at the end-of-life. More research is needed to estimate these costs for each type of equipment and factor them into abatement cost calculations for these mitigation scenarios.
- Few studies exist that estimate the energy efficiency impacts of equipment for switching to new low-GWP refrigerants. More research is needed to understand how refrigerant charge, leak rates, and equipment design may change as a result of using new low-GWP refrigerant options.
- The NYSERDA residential and commercial baseline studies provided stock/saturation estimates for NYS in many technology categories, but gaps remain. The residential baseline study uses data collected 2011 to 2014, which is now dated, and Guidehouse's analysis of the survey responses showed significant gaps in the survey responses. In addition, the commercial baseline study was not comprehensive of all technology categories; in particular, data was missing for supermarket racks, refrigerated warehouses, transportation refrigeration, industrial process cooling, and other segments.

6.4.2 Analysis Sensitivities

- The greatest uncertainty in the analysis is how EPA plans to implement the AIM Act by establishing limits on the production and consumption of HFCs, delisting HFC refrigerants and listing alternative low-GWP refrigerants for specific end-uses—encouraging the development of robust refrigerant recovery and reclaiming programs. Even with aggressive restrictions for new equipment, the analysis shows that HFC supply shortages may occur due to HFC allowance limits under the AIM Act, particularly in years 2024 and 2029. How EPA and the HVAC&R industry at large will react to the AIM Act and future HFC prices is uncertain.
- Estimates for future HFC emissions in sectors outside of building HVAC&R systems, such as aerosols and foams, rely on information provided through expert interviews. Guidehouse has developed these projections through top-line estimates rather than a detailed bottom-up stock analysis, so there is greater uncertainty for these segments than for the building HVAC&R equipment categories.

- There is uncertainty in average charge sizes in current technologies and how they will change with low-GWP refrigerant models. Most charge size data came from CARB TSD estimates, but Guidehouse's literature review found that charge sizes can be highly variable.
- Uncertainty remains around what future low-GWP refrigerants will be used to replace HFCs in certain categories. Product development and approval processes are still underway, and the issue of flammability of likely low-GWP alternatives remains a major barrier to adoption.
- Due to the uncertainty of marginal cost impacts for a second transition to ultra-low-GWP refrigerants, Guidehouse assumed no additional incremental transition costs between low-GWP and ultra-low-GWP equipment. This assumption should be researched further once viable design options with ultra-low-GWP refrigerants are identified in applicable end-use sectors.
- As a conservative estimate, the Guidehouse model assumes that cost premiums will remain constant over time. However, generally new technologies entering the market decrease in cost over time as adoption increases. In addition, installation costs are assumed to be constant over time. Installation costs may be higher in the short term because current technicians are not familiar or trained to work with low-GWP refrigerants, but any such increase in installation costs in the short-term would be expected to decrease over time.
- Due to a lack of data, the Guidehouse model does not take into account maintenance costs. Any differences in maintenance costs between high-GWP and low-GWP equipment could impact the results of abatement cost calculations for certain mitigation scenarios.

6.4.3 Research Areas for Hydrofluorocarbon Mitigation Topics

- Future baseline studies should document the HFC refrigerants in use and should capture the age of the equipment.
- Pilot studies and laboratory testing can be used to analyze the charge size, leakage rate, and energy efficiency impacts of using new low-GWP refrigerants.
- Recovered or reclaimed refrigerant could be used for new equipment and service, which would reduce the need for new or virgin HFC refrigerant production. Guidehouse has developed several potential HFC Mitigation Scenarios that analyze the role of end-of-life recovery rates on reclaimed refrigerant supplies. However, significant uncertainty remains surrounding EOL recovery practices, reclamation costs and availability, and incentive schemes to encourage reclaim. NYSERDA could consider such an analysis in the future.
- More research is needed to understand the costs that manufacturers will incur to develop new low-GWP products and how those costs will affect final consumer prices. Research should involve working with and interviewing manufacturers directly.

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Appendix A. Key Data Inputs and Assumptions

A.1 Key Data Inputs and Resources

The complete set of input assumptions is located within the HFC Emissions Inventory spreadsheet.

Table A-1 lists the methodologies, assumptions, and resources used to inform the key data inputs to the Guidehouse model. The key data inputs are grouped by equipment stock, lifetime, leakage rates/charge size, service frequency, backward growth rates, refrigerant adoption timeline, and GWP values.

Table A-1. Key Model Data Inputs and Resources

The complete set of input assumptions is located within the HFC Emissions Inventory spreadsheet.

Key Data Inputs	Methodology/Key Resources
Equipment Stock	· Stock estimates input for year 2018 (commercial) and 2014 (residential) based on the NYSERDA baseline studies. · Al other years 1990–2020 were extrapolated based on appropriate growth indicator (households, commercial square footage, or vehicle registrations). · Stock represents the stock on January 1 at the start of the year. · Sales and retirements derived from stock and growth estimates. · For each equipment type, annual sales by refrigerant type are apportioned using F-Gas ODS to HFC Transition workbook.
Lifetime	· Input in years for each Equipment Type. · CARB Kigali Potential Impact Study (2017) and New York State Technical Reference Manual (2020).
Leakage Rates / Charge Size	· Leakage rates for each Equipment Type input as Annual Leak Rate (%) and End of Life Loss Rate (%). · Charge size is input in pounds. · CARB Kigali Potential Impact Study (2017) supplemented with review of manufacturer literature.
Service Frequency	· Input as “Serviced Every X Years” for each Equipment Type. · A value of 0 indicates the equipment type is never serviced. · A service frequency of 1 (every year) is assumed if no data is available to suggest otherwise. · Derived from CARB Kigali Potential Impact Study (2017).
Backward Growth Rates	· Backward annualized growth rates are calculated for various indicators using data from: o U.S. Census o U.S. BEA o EIA (CBECS) o NYS Department of Motor Vehicles o NYS Department of Transportation

Key Data Inputs	Methodology/Key Resources
Refrigerant Adoption Timeline	· California F-Gas ODS Substitute Worksheet.
GWP Values	· AR4 20-year and 100-year GWP from IPCC. · AR5 20-year and 100 year-GWP from IPCC. · GWP assumptions are made, as appropriate, for refrigerants not listed in IPCC, including: o Weighted averages for blends. o Setting 20-year value equal to 100-year value. o Setting AR5 value equal to AR4 value. o Others

A.2 Example Hydrofluorocarbon Refrigerant Global Warming Potential Values

Table A-2 lists the AR4 20-year and 100-year and AR5 20-year and 100-year global warming potentials of refrigerants. This report discusses results for both AR5 20-year values and AR4 100-year values. Twenty-year GWP values are used for New York State policy development and 100-year values are the main choice of GWP values for many industry models and estimations.

Table A-2. Hydrofluorocarbon Refrigerant GWP Values

The complete set of input assumptions is located within the HFC Emissions Inventory spreadsheet.

Source: IPCC as applied to refrigerant composition information from EPA.

Refrigerant	GWP - AR4 20-yr	GWP - AR4 100-yr	GWP - AR5 20-yr	GWP - AR5 100-yr
R-134a	3830	1430	3710	1300
R-410a	4340	2088	4260	1920
R-404A	6010	3922	6437	3940
R-448A	3062	1387	2995	1273
R-32	2330	675	2430	677
R-466A	1872	733	1891	696
R-454B	1606	466	1675	467
R-513A	3748	631	3633	573
R-1234yf	1	4	1	1
R-290 (Propane)	3	3	3	3
R-600 (Isobutane)	3.3	3.3	3.3	3.3
R-744 (CO_2)	1	1	1	1
R-717 (Ammonia)	0	0	0	0

A.2 Hydrofluorocarbon Transition Timeline by End-Use Sector and Potential HFC Mitigation Scenario

Table A-3 outlines a reference case and potential HFC Mitigation Scenarios implemented in the model. The HFC transition timelines and brief description are included for applicable end-uses. Potential HFC Mitigation Scenarios no. 7, no. 8A, and no. 8B build on the activities outlined in scenario no. 6C.

Table A-3. Hydrofluorocarbon Transition Timeline by End-Use Sector and Potential HFC Mitigation Scenario

End Use Sector (Equipment Type)	Reference Case No. 5 (Included in NYS HFC Rule)	HFC Mitigation Scenario No. 6A – 2024 Restrictions	HFC Mitigation Scenario No. 6B – 2029 Restrictions	HFC Mitigation Scenario No. 6C– Post-2030 Restrictions
Central AC	No	No	750 GWP limit, 2027	Max tech, 2034
Central HP	No	No	750 GWP limit, 2027	Max tech, 2034
Window AC	No	No	750 GWP limit, 2027	Max tech, 2034
Res GSHP	No	No	750 GWP limit, 2027	Max tech, 2034
Ductless Split AC	No	No	750 GWP limit, 2027	Max tech, 2034
Ductless Split HP	No	No	750 GWP limit, 2027	Max tech, 2034
Res Refrigerator / Freezer	High GWP prohibited, Jan 1, 2022 (built ins are 2023)	n/a, already ultra-low-GWP/natural	n/a, already ultra-low-GWP/natural	n/a, already ultra-low-GWP/natural
Res Freezers	High GWP prohibited, Jan 1, 2022 (built ins are 2023)	n/a, already ultra-low-GWP/natural	n/a, already ultra-low-GWP/natural	n/a, already ultra-low-GWP/natural
Res HPWH	No	No	150 GWP limit, 2029	n/a, already ultra-low-GWP/natural
HP Clothes Dryer	No	No	150 GWP limit, 2029	n/a, already ultra-low-GWP/natural
Dehumidifier	No	750 GWP limit, 2024	750 GWP limit, 2024	Max tech, 2034
Central Split & Package AC, Large	No	No	750 GWP limit, 2027	Max tech, 2034
Central Split & Package AC, Small	No	No	750 GWP limit, 2027	Max tech, 2034
Central Split & Package HP, Large	No	No	750 GWP limit, 2027	Max tech, 2034
Central Split & Package HP, Small	No	No	750 GWP limit, 2027	Max tech, 2034
Room / PTAC / PTHP	No	750 GWP limit, 2024	Same as 2024	Max tech, 2034
Com GSHP	No	No	750 GWP limit, 2027	Max tech, 2034
VRF HP	No	No	750 GWP limit, 2027	Max tech, 2034
Ductless Split AC	No	No	750 GWP limit, 2027	Max tech, 2034
Ductless Split HP	No	No	750 GWP limit, 2027	Max tech, 2034
Small Chiller	High GWP prohibited Jan 1, 2024 (410a, 134a, others)	No	No	Max tech, 2034
Medium Chiller	High GWP prohibited Jan 1,	No	No	Max tech, 2034

End Use Sector (Equipment Type)	Reference Case No. 5 (Included in NYS HFC Rule)	HFC Mitigation Scenario No. 6A – 2024 Restrictions	HFC Mitigation Scenario No. 6B – 2029 Restrictions	HFC Mitigation Scenario No. 6C– Post-2030 Restrictions
	2024 (410a, 134a, others)			
Large Centrifugal Chiller	High GWP prohibited Jan 1, 2024 (410a, 134a, others)	n/a, already ultra-low-GWP/natural	n/a, already ultra-low-GWP/natural	n/a, already ultra-low-GWP/natural
Com Refrigerator / Freezer	High GWP prohibited, Jan 1, 2022	n/a, already ultra-low-GWP/natural	n/a, already ultra-low-GWP/natural	n/a, already ultra-low-GWP/natural
Supermarket Racks, Large	High GWP prohibited Jan 1, 2021 (R404, R407, R507, others)	150 GWP limit, 2024	n/a, already ultra-low-GWP/natural	n/a, already ultra-low-GWP/natural
Supermarket Racks, Medium	High GWP prohibited Jan 1, 2021 (R404, R407, R507, others)	150 GWP limit, 2024	n/a, already ultra-low-GWP/natural	n/a, already ultra-low-GWP/natural
Walk-ins/Remote Condensing, Large	High GWP prohibited, Jan 1, 2021 (R404, R407, R507, but not R410a or R134)	No	No	Max tech, 2034
Walk-ins/Remote Condensing, Small	High GWP prohibited, Jan 1, 2021 (R404, R407, R507, but not R410a or R134)	No	No	Max tech, 2034
Self-Contained Display Cases / Reach-ins	High GWP prohibited, Jan 1, 2021, depending on design (medium-R134a, R410a, R404, R507, R507, low-temp does not ban 134a)	n/a, already ultra-low-GWP/natural	n/a, already ultra-low-GWP/natural	n/a, already ultra-low-GWP/natural
Vending Machines	High GWP prohibited, new Jan 1, 2022 (R134a, R410a), retrofits is 2021 (404, 507)	n/a, already ultra-low-GWP/natural	n/a, already ultra-low-GWP/natural	n/a, already ultra-low-GWP/natural
Ice Makers	No	No	150 GWP limit, 2029	n/a, already ultra-low-GWP/natural
Refrigerated Warehouse, Medium	High GWP prohibited, Jan 1, 2023 (410, 404, 407, 507, others)	No	150 GWP limit, 2029	n/a, already ultra-low-GWP/natural
Refrigerated Warehouse, Large	High GWP prohibited, Jan 1, 2023 (410, 404, 407, 507, others)	No	150 GWP limit, 2029	n/a, already ultra-low-GWP/natural
Com HPWH	No	No	150 GWP limit, 2029	n/a, already ultra-low-GWP/natural
Industrial Process	No	750 GWP limit, 2024	Same as 2024	150 GWP limit, 2034

End Use Sector (Equipment Type)	Reference Case No. 5 (Included in NYS HFC Rule)	HFC Mitigation Scenario No. 6A – 2024 Restrictions	HFC Mitigation Scenario No. 6B – 2029 Restrictions	HFC Mitigation Scenario No. 6C– Post-2030 Restrictions
Light Duty Vehicles	No, most already ultra-low	150 GWP limit, 2024	n/a, already ultra-low-GWP/ natural	n/a, already ultra-low-GWP / natural
Medium Duty Vehicles	No, most already ultra-low	150 GWP limit, 2024	n/a, already ultra-low-GWP/natural	n/a, already ultra-low-GWP/natural
Heavy Duty Vehicles	No	150 GWP limit, 2024	n/a, already ultra-low-GWP/natural	n/a, already ultra-low-GWP/natural
Buses	No, most already ultra-low	150 GWP limit, 2024	n/a, already ultra-low-GWP/natural	n/a, already ultra-low-GWP/natural
Transport Refrigeration	No	No	150 GWP limit, 2029	n/a, already ultra-low-GWP/natural
Aerosols, Foams, Solvents, other HFCs	High GWP prohibited Jan 1, 2021 (134a, 227, and others)	n/a, already ultra-low-GWP/natural (where feasible)	n/a, already ultra-low-GWP/natural (where feasible)	n/a, already ultra-low-GWP/natural (where feasible)

A.3 Estimated Baseline Equipment Costs and Premiums for Low-Global Warming Potential Refrigerants

Table A-4 shows the estimated baseline equipment retail and installation cost premiums for switching to low-GWP refrigerants. The cost premiums were used to analyze the abatement costs of potential HFC Mitigation Scenarios (see section 5.4). The estimated baseline equipment costs and premiums are estimated based primarily on data from CARB[65] and EIA.[66] Cost premiums range from 3% to 20% as shown in Table 4-2 and come primarily from CARB's Proposed Amendment Staff Report.[67] CARB's cost premium estimates come from stakeholder meetings and interviews, though it is unclear what assumptions are made on future policy adoption. However, there were significant data gaps for transportation, chillers, ice makers, vending machines, dehumidifiers, room AC, heat pump water heaters, and heat pump clothes dryers. In cases with no data available, cost premiums were assumed to be 10% or the same as similar technologies categories that had cost premium estimates (marked with asterisks in Table 4-2). The estimated 10% equipment and installation cost premium assumption is based on the AHRI *Consumer Cost Impacts of the US Ratification of the Kigali Amendment Report* (2018).[68] These estimates are also likely based on national incremental costs, and they have not been adjusted to reflect costs that would occur if only a portion of the U.S. market adopted HFC phasedown policies.

Table A-4. Estimated Baseline Equipment Costs and Premiums

Sources: CARB's Proposed Amendment Staff Report,[69] AHRI's Consumer Cost Impacts of U.S. Ratification of the Kigali Amendment,[70] DC Engineering's Refrigeration System Study,[71] EIA Updated Buildings Sector Appliance and Equipment Costs and Efficiencies,[72] and cost data from online retailers.

Equipment Type	Equipment Retail Cost	Equipment Cost Premium	Equipment Installation Cost	Installation Cost Premium	Total Upfront Cost Premium
Commercial Central Split & Package AC, Large	$21,120	$1,267	$6,600	$198	$1,465
Commercial Central Split & Package HP, Large	$22,810	$1,369	$7,240	$217	$1,586
Commercial VRF HP, Large	$30,000	$2,250	$24,000	$1,200	$3,450
Commercial Central Split & Package AC, Small	$7,150	$715	$3,100	$93	$808
Commercial Central Split & Package HP, Small	$7,750	$775	$3,400	$102	$877
Commercial GSHP	$5,550	$555	$13,500	$405	$960
Commercial VRF HP, Small	$10,153	$761	$3,400	$170	$931
Commercial Chiller, Large Centrifugal	$212,500	$21,250	$31,250	$3,125	$24,375
Commercial Chiller, Medium	$105,000	$10,500	$11,250	$1,125	$11,625
Commercial Chiller, Small	$73,625	$7,363	$23,750	$2,375	$9,738
Commercial Ductless Split AC	$2,400	$240	$1,730	$173	$413
Commercial Ductless Split HP	$3,840	$384	$1,990	$199	$583
Commercial Ice Makers	$2,565	$257	$325	$33	$289
Commercial Refrigerated Warehouse, Large	$1,130,000	$226,000	$507,000	$101,400	$327,400
Commercial Refrigerated Warehouse, Medium	$245,000	$49,000	$110,000	$22,000	$71,000
Commercial Refrigerator / Freezer	$1,420	$0	$0	$0	$0
Commercial Room AC / PTAC / PTHP	$620	$31	$95	$3	$34
Commercial Self-Contained Display Cases / Reach-ins	$6,152	$1,230	$2,301	$230	$1,460
Commercial Supermarket Racks, Large	$800,000	$140,000	$400,000	$40,000	$180,000
Commercial Supermarket Racks, Medium	$452,000	$79,100	$400,000	$40,000	$119,100
Commercial Vending Machines	$3,551	$0	$111	$0	$0
Commercial Walk-ins/Remote Condensing, Large	$12,000	$2,400	$4,200	$420	$2,820

Equipment Type	Equipment Retail Cost	Equipment Cost Premium	Equipment Installation Cost	Installation Cost Premium	Total Upfront Cost Premium
Commercial Walk-ins/Remote Condensing, Small	$6,000	$1,200	$4,200	$420	$1,620
Commercial Water Heater HP	$8000	$800	$1,200	$120	$920
Industrial Process	$293,000	$58,600	$132,000	$26,400	$85,000
Residential Clothes Dryer HP	$1,400	$140	$110	$10	$150
Residential Dehumidifier	$275	$14	$0	$0	$14
Residential Freezer	$500	$0	$0	$0	$0
Residential Refrigerator/Freezer	$1,420	$0	$0	$0	$0
Residential Window AC	$620	$31	$95	$3	$34
Residential Water Heater HP	$1,350	$135	$725	$73	$208
Residential Central AC	$2,250	$113	$1,300	$39	$152
Residential Central HP	$3,600	$180	$1,500	$45	$225
Residential Ductless Split AC	$2,400	$120	$1,730	$52	$172
Residential Ductless Split HP	$3,840	$192	$1,990	$60	$252
Residential GSHP	$4,650	$233	$11,500	$345	$578
Transportation Refrigeration	$12,500	$1,250	$0	$0	$1,250

Appendix B. Hydrofluorocarbon Emissions Inventory for New York State

B.1 Hydrofluorocarbon Emissions Inventory—20-year Global Warming Potential (AR5)

Table B-1. HFC Emissions Inventory 2005–2020 (20-year GWP)

Because “Other” category is estimated through scaling of emissions and not bottom-up modeling of refrigerant consumption, a 20-year GWP value is unable to be determined for this category; therefore, 100-year values were used instead.

Category	2005	2010	2015	2020	% of 2020	Notes
Res. HVAC	0.03	0.14	1.16	2.32	10.9%	Includes AC, HP, GSHP, and room products
Res. Refrigeration	0.05	0.40	0.41	0.42	2.0%	Includes refrigerators and freezers
Res. Other	0.00	0.00	0.02	0.06	0.3%	Includes HPWHs, dehumidifiers,
Com. HVAC	0.02	0.05	1.40	2.84	13.3%	Includes AC, HP, PTAC, VRF, ductless, GSHP, and chiller products
Com. Refrigeration	1.03	2.06	3.98	5.71	26.8%	Includes supermarket, walk-ins, reach-ins, vending machines, icemakers
Com. Other	0.00	0.00	0.00	0.00	0.0%	Includes HPWHs
Industrial Process	0.01	0.02	0.03	0.04	0.2%	
Transport. HVAC	2.23	3.51	3.62	3.39	15.9%	Light-, medium-, heavy-duty, and buses
Transport. Refrigeration	0.13	0.17	0.18	0.19	0.9%	
Other	3.29	5.35	7.32	6.34	29.8%	Aerosols, Foams, Solvents
TOTAL					**100%**	

B.2 HFC Emissions Inventory—100-year Global Warming Potential (AR4)

Table B-2. HFC Emissions Inventory 2005–2020 (100-year GWP)

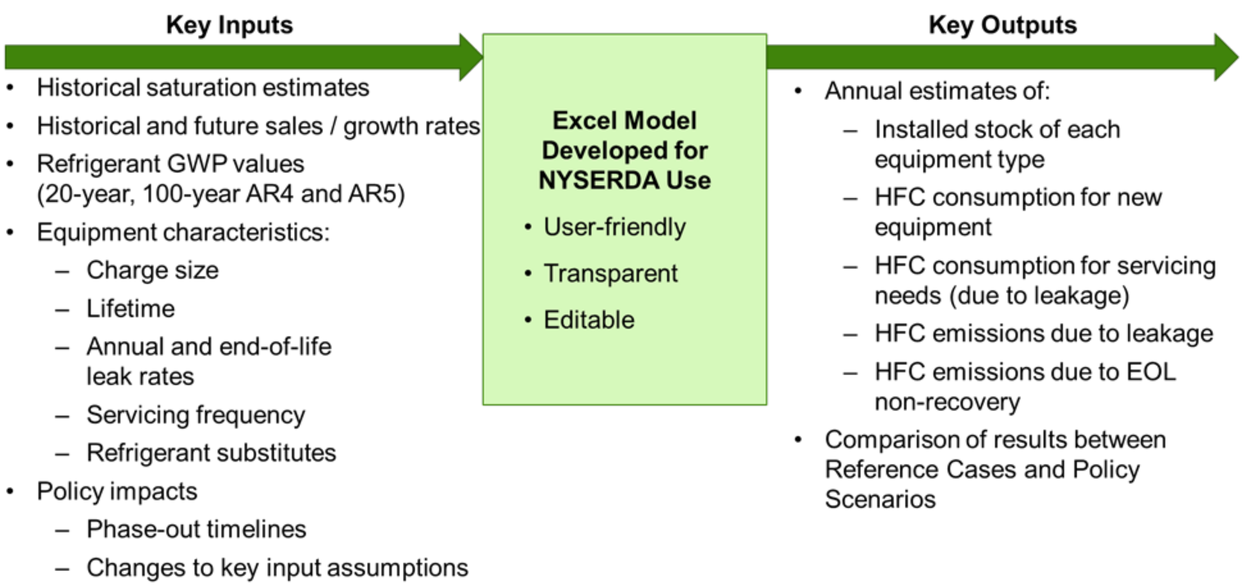
Category	2005	2010	2015	2020	% of 2020	Notes
Residential HVAC	0.01	0.07	0.57	1.13	11.8%	Includes AC, HP, GSHP, and room products
Residential Refrigeration	0.02	0.16	0.16	0.16	1.7%	Includes refrigerators and freezers
Residential Other	0.00	0.00	0.01	0.02	0.3%	Includes HPWHs, dehumidifiers,
Commercial HVAC	0.01	0.03	0.68	1.38	14.3%	Includes AC, HP, PTAC, VRF, ductless, GSHP, and chiller products
Commercial Refrigeration	0.58	1.18	2.34	3.38	35.0%	Includes supermarket, walk-ins, reach-ins, vending machines, icemakers
Commercial Other	0.00	0.00	0.00	0.00	0.0%	Includes HPWHs
Industrial Process	0.00	0.01	0.01	0.02	0.2%	
Transportation HVAC	0.86	1.35	1.40	1.31	13.6%	Light-, medium-, heavy-duty, and buses
Transportation Refrigeration	0.06	0.08	0.08	0.08	0.9%	
Other	1.22	1.93	2.51	2.15	22.3%	Aerosols, Foams, Solvents
Total	**2.77**	**4.80**	**7.76**	**9.64**	100%	Includes AC, HP, GSHP, and room products

Appendix C. Source Documentation for the Hydrofluorocarbon Emissions Model

The foundation for the HFC Emissions Inventory Analysis is an Excel-based vintaging model customized to New York State. The vintaging HFC Emissions Model estimates the annual installed stock, new shipments, and end-of-life (EOL) retirements of HFC-using equipment. Using a bottom-up accounting methodology, the model calculates annual HFC consumption due to new equipment installations and the servicing of existing equipment to replenish refrigerant leakage; as well as annual HFC emissions to the atmosphere due to equipment leakage and disposition at EOL retirement. The model can be used to project future consumption and emissions over a variety of scenarios defined by the user.

The figure below shows the key inputs and outputs of the model. The following sections provide the sources of data inputs used in the HFC Emissions Model.

Figure C-1. HFC Emission Model Inputs and Outputs



C.1 Refrigerant Specifications

This section of the model defines the GWP of baseline HFC refrigerants and of potential low-GWP refrigerant alternatives. Four different GWP values are defined for each refrigerant: IPCC 4th Assessment Report (AR4) 20-year, AR4 100-year, 5th IPCC Assessment Report (AR5) 20-year, and AR5 100-year. The refrigerants listed represent the most common refrigerants in use and the most promising low-GWP alternative refrigerants for each equipment type modeled. Table 2-2 provides the primary sources used to define the 20-year and 100-year GWP values for each refrigerant.

Table C-1. Sources for Global Warming Potential Values

GWP Value	Source
AR4 20-year	IPCC 4th Assessment Report (2007), Table 2.14[73]
AR4 100-year	
AR5 20-year	IPCC 5th Assessment Report (2013), Table 8.A.1[74]
AR5 100-year	

- For some of the refrigerants, 20-year, or 100-year GWP values are not available from the IPCC reports. For 20-year GWP values not defined in the IPCC reports, the 100-year GWP is used (as noted in the spreadsheet). For 100-year GWP values not defined in the IPCC reports, the Bitzer's Refrigerant Report 20, Table 6, is used as an alternative source.[75]
- GWP values are not defined (i.e., defined as 0) for CFC and HCFC refrigerants, since emissions of these refrigerants are not intended to be accounted for in this model.

C.1.2 Refrigerant Blend Composition Sources

- The GWP values for HFC and HFC/HFO refrigerant blends were estimated by calculating a weighted average of the GWP of the pure refrigerants comprising each blend. The source for the refrigerant blend composition is the U.S. Environmental Protection Agency (EPA) webpage "Compositions of Refrigerant Blends."[76] The sources for the 20-year and 100-year GWP values for the pure refrigerants within in the blends are listed in Table 2-2 above.

C.1.3 Refrigerant Allocation to Equipment Types

- For each equipment type, refrigerant allocations represent the portion of shipments each year containing each refrigerant. The CARB F-Gas ODS-to-HFC Transition Timeline spreadsheet (provided by NYSERDA) was the primary source used to apportion refrigerant types by equipment category for the historical period 1990–2020.

- For some equipment categories, HFC apportionments were verified through additional literature review and consultation with internal product experts.
- For future years 2020–2050, the 2020 allocation was maintained for years leading up to the year of assumed transition to a low-GWP alternative. The assignment of low-GWP refrigerants for each category are based on the current commercial availability of low-GWP alternatives for certain equipment types, or knowledge of the most promising low-GWP alternatives as described in industry research publications. For example, Guidehouse modeled the transition for residential refrigerators to R-600 and mobile AC systems to R-1234yf based on industry expectations and regulations.
- For equipment types in which the future transition to low- and ultra-low-GWP refrigerants is still uncertain, Guidehouse selected representative refrigerants with GWP values that reflect the most likely approximate GWP values of a future low-GWP refrigerant to be used in such equipment (e.g., < 10 GWP, < 750 GWP, < 1500 GWP). For example, for some equipment categories R-1234yf (with a GWP value of 1) is assigned as the max tech option as a means for representing a near-zero GWP value, even if flammability concerns or other technical limitations would prevent the use of R-1234yf itself in such equipment.

C.2 Equipment Specifications

This section of the model defines the key characteristics of each equipment category that relate to HFC emissions. These input specifications are used throughout various calculation tabs in the model.

C.2.1 Lifetime

- For most equipment types, Guidehouse used the lifetimes available in the NYSERDA *New York Standard Approach for Estimating Energy Savings from Efficiency Programs (Version 7)*, available in Appendix P.[77]
- For some of the equipment types not available in the NYSERDA report, Guidehouse used the lifetime available from CARB (used in their modeling) from the 2017 report *Estimates and Methodology used to Model Potential Greenhouse Gas Emissions Reductions in California from the Global Hydrofluorocarbon (HFC) Phasedown Agreement of October 15, 2016, in Kigali, Rwanda,* available in Table A6.[78]
- For a few equipment types (e.g., Freezers, Mini-Splits, Beverage Merchandisers), Guidehouse used lifetime data reported in the U.S. Energy Information Administration's *Updated Buildings Sector Appliance and Equipment Costs and Efficiencies* (2018),[79] which primarily relies on data from U.S. DOE Appliance Standards rulemakings.
- For some equipment types (e.g., residential GSHP), the assigned lifetime represents the same lifetime as the other substitutes within the same main application category, despite there being a different lifetime estimate provided from one of the sources described above. To provide the capability to reflect the future electrification of buildings, the model incorporates the concept of equipment substitutions for "main applications." For example, central AC, central HP, and GSHP are categorized under the main application of "residential whole-home AC." Due to the stock accounting structure of the model, equipment types that are categorized as substitutes for

the same main application must be assigned the same lifetime in order to maintain consistency among the installed stock, new shipments, and end-of-life calculations in each year. The definition of equipment lifetime has minimal impact on the calculated emissions because: (1) for most product categories, annual emissions are dominated by the leakage rate from the installed stock, which is not affected by product lifetime; (2) defining a different product lifetime would shift the future year in which new equipment placed into service in a specific year reaches end-of-life, but such a shift would not substantially change the number of units reaching end-of-life in any given year.

C.2.2 Charge Size

- For most equipment types, Guidehouse used charge size data available from CARB from the 2017 report Estimates and Methodology used to Model Potential Greenhouse Gas Emissions Reductions in California from the Global Hydrofluorocarbon (HFC) Phasedown Agreement of October 15, 2016, in Kigali, Rwanda, available in Table A3.[80]
- For equipment types not available in the CARB report, assumptions and estimates are used to fill in gaps, as noted in the "source" column. Generally, charge sizes are assumed to be the same as other similar equipment types. For a few equipment types, charge size was taken from product specification sheets available online and verified by consulting internal product experts at Guidehouse.
- Additional research was done to estimate charge size differences for heat pumps and variable refrigerant flow heat pumps relative to air conditioners by comparing manufacturer specifications for large HVAC manufacturer products on the market. Based on this research, Guidehouse estimated that the charge size for heat pumps is 33% more than an equivalent air conditioner, and the charge size for variable refrigerant flow heat pumps is 100% more (i.e., twice the size) than the equivalent air conditioner charge size. Refer to Section 2.1.5 in the report for more information on this analysis.

C.2.3 Leak Rates and End-of-Life Loss

- For most equipment types, Guidehouse used leak rate and end of life loss rate data available from CARB from the 2017 report Estimates and Methodology used to Model Potential Greenhouse Gas Emissions Reductions in California from the Global Hydrofluorocarbon (HFC) Phasedown Agreement of October 15, 2016, in Kigali, Rwanda, available in Table A3.[81]
- For equipment types not available in the CARB report, assumptions and estimates are used to fill in gaps, as noted in the "source" column. Generally, leak rates and end of life loss are assumed to be the same as other similar equipment types. In these cases, Guidehouse also conducted a literature review and consulted with internal equipment experts to verify findings.

C.2.3 Service Frequency

- Service frequency was derived from data available from CARB in the Estimates and Methodology used to Model Potential Greenhouse Gas Emissions Reductions in California from the Global Hydrofluorocarbon (HFC) Phasedown Agreement of October 15, 2016, in Kigali, Rwanda, available in Table A3.[82] Based on the average charge, average annual leak rate, and average charge at the end of life in the CARB resources, the service frequency assumed by CARB could be derived.
- A service frequency of 1 (every year) is assumed if no data is available to suggest otherwise. A service frequency of 0 is assigned to equipment types that are unlikely to ever be serviced (e.g., residential refrigerators).

C.2.4 Equipment Capacity

- Equipment capacity is provided as an average estimated range for each equipment type and is primarily used for informational and comparison purposes only. Equipment capacity is not directly used in downstream calculations. Capacity ranges were derived from CARB in the *Estimates and Methodology used to Model Potential Greenhouse Gas Emissions Reductions in California from the Global Hydrofluorocarbon (HFC) Phasedown Agreement of October 15, 2016, in Kigali, Rwanda*, available in Table A3.[83] These equipment ranges were also compared with the available data in the NYSERDA Residential[84] and Commercial[85] baseline studies.

C.3 Growth Indicators

Growth indicators are used to estimate the growth in stock of each equipment type in New York State. Each equipment type is assigned to one of four different growth indicators: residential housing units, commercial business square footage, vehicle registrations (generally), and transport refrigeration vehicle registrations. For each growth indicator, a reference value was determined for a specific year, and then a historical growth rate was applied to extrapolate values for the entire historical period 1990–2020. Although some of the data sources (e.g., Census data) provide annual values that could be used directly, the model requires a constant growth rate as one of the parameters in the calculation that extrapolates the initial shipment values for year 1990 from stock estimates in year 2018 (as described further below). All of the growth indicator values are provided in the model.

C.3.1 Reference Value for Each Growth Indicator

- For residential housing units, the reference value is defined for 2018 based on data from the U.S. Census Bureau data for New York State.[86]
- For commercial business square footage, the reference value is defined for 2018 based on data from the NYSERDA Commercial Baseline Study (Vol 1) (page 6 and page 130).[87]

- For vehicle registrations (generally), the reference value is defined for 2015 based on data from the NY Department of Motor Vehicles from the E3 Transportation Stock Climate Act.[88]
- For transportation refrigeration vehicle registrations, the reference value is defined for 2018 based on data from the CARB Emissions Inventory Methodology and Technical Support Document (page 10), which was scaled to New York State based on the ratio of population in each state.[89]

C.3.2 Historical Growth Rate

- For residential housing units, the historical growth rate for the period 1990–2020 (0.44%) was calculated as the average annual growth rate from 1990 to 2015 using data on the number of housing units in NYS from the US Census Bureau.[90] [91]
- For commercial business square footage, the historical growth rate for the period 1990–2020 was calculated as the average annual growth rate from 1990 to 2015 using data scaled down from the Mid-Atlantic from U.S. EIA's Commercial Building Energy Consumption Surveys (CBECS) from 1992, 1995, 1999, 2003, and 2012.[92] Because CBECS data is only available for certain years, gap years were extrapolated using a linear regression.
- For vehicle registrations (both general and for transportation refrigeration specifically), the historical growth rate for the period 1990–2020 was calculated as the average annual growth rate from 2007 to 2015 using vehicle registration data from the NY Department of Motor Vehicles.[93]

C.4 Equipment Stock

This section of the model provides estimates of the total stock values in New York State for each modeled equipment type. The sources for the baseline year are provided in sections 2.4.10 to 2.4.12 and the future projected stock values are calculated using the growth indicators described in section 2.3.

C.4.1 Commercial Stock

- The primary source for commercial equipment stock data is the 2018 NYSERDA Commercial Baseline Study (Vol 1).[94] The data in this study is provided as a saturation per commercial business in NY, so the total number of units of each type of equipment was calculated for 2018 by multiplying the saturation value of each equipment type by the total number of NY businesses in 2018 (367,223). For certain equipment categories that contain equipment of different sizes (e.g., small, medium, or large commercial chillers), the stock breakdown by size was approximated from the available data in the baseline study that broke out the stock proportion by equipment capacity. For a few equipment type breakdowns that were not available from the baseline study, the breakdowns were determined using data from the California equipment units available in the CEC EPIC Low-GWP NVC analysis (from the CARB TSD).

- To verify the accuracy of these stock estimates, the equipment stock for each equipment type from the NYSERDA Commercial Baseline Study was compared with the stock data from CARB and the stock data from CBECS 2012 (using the microdata tables)[95] for the Mid-Atlantic region. The data was normalized by population in those NYS, California, and the Mid-Atlantic regions in the years the data was collected for comparison.
  - Based on this analysis, the equipment numbers for refrigerated warehouses, commercial residential-style refrigerator/freezers, and refrigerated vending machines were updated by scaling the CBECS 2012 data for the Mid-Atlantic to NYS based on population.
- The number of supermarket rack refrigeration equipment units was estimated using the number of supermarkets in NYS multiplied by the average saturation per store (four per store).

C.4.2 Residential Stock

- The primary source for the residential equipment stock data is the 2015 NYSERDA Residential Statewide Baseline Study of New York State, which collected data on single-family and multifamily housing units from 2011 to 2014.[96] The data was provided as the raw survey responses with weights that were used to calculate the total equipment stock in NYS in 2014. The weighted units were divided by the total households represented in the survey (6,930,295) to estimate a saturation rate for each equipment type. Finally, these saturations were multiplied by the total number of residential households in 2014, according to US census data[97] (8,219,287) to determine the total stock values.
- To verify the accuracy of these stock estimates, the equipment stock for each equipment type from the NYSERDA Residential Statewide Baseline Study of New York State was compared with the stock data from CARB and the stock data from RECS 2015 (using the microdata tables)[98] for the Mid-Atlantic region. The data was normalized by population in those NYS, California, and the Mid-Atlantic in the years the data was collected for comparison. No additional data adjustments were found to be necessary based on this analysis.

C.4.3 Vehicle Stock

- Vehicle registration data is available from the NY Department of Motor Vehicles from the E3 Transportation Stock Climate Act.[99]
- For transportation refrigeration units, stock was estimated using data from the CARB Emissions Inventory Methodology and Technical Support Document (page 10), which was scaled from 2014 California to 2018 New York State based on the ratio of population.[100]

C.5 Saturation Rate

- Saturation rate (defined as a decimal) represents the number of equipment stock units per market growth indicator (e.g., number of refrigerators per household, or number of commercial vending machines per million square feet of commercial space). Saturation rate is defined at the "main application" level.

- The initial saturation rates were determined for the year 2018 for the commercial equipment and 2014 for the residential equipment, corresponding to the available data from the NYSERDA baseline studies in those years, as described above.
- For vehicle categories, the concept of building saturation does not apply, so the saturation rates are defined as 1.0.

Appendix D. Source Documentation for the Scenario Cost Model

This section provides the sources of data inputs used in the Scenario Cost Model. This portion of the model estimates the costs and emissions savings of various HFC mitigation strategies that could be enacted by New York State. This model attempts to isolate the costs borne by NYS from the costs borne by other parties (e.g., costs imposed from federal HFC regulations or from natural industry transitions). Costs are calculated by comparing a "reference case" that describes the natural growth and equipment adoption within NYS to a "mitigation scenario" that is identical to the reference case except for additional HFC mitigation policies enacted by NYS. Due to recent federal legislation on HFCs, the vast majority of costs associated with GWP restrictions for new equipment may eventually be attributable to the federal government instead of New York State. However, due to uncertainties on the future direction of federal action to address HFC consumption and/or emissions, all costs for measures beyond the 2020 NYS HFC rule are attributed to New York State in this report. This tool relies heavily on outputs from the HFC emissions model. The HFC emissions model tabulates the number of baseline, low-GWP and ultra-low-GWP equipment for a variety of reference cases and mitigation scenarios across the years 2021–2050. Several spreadsheet tabs in the emissions model are use as outputs that are manually copied into the Scenario Cost Model tool in order to examine the relative cost/benefit of a variety of state-level policy options.

D.2 Equipment Cost Premiums

- Baseline equipment cost data and installation cost data were derived primarily from the U.S. Energy Information Administration's *report Updated Buildings Sector Appliance and Equipment Costs and Efficiencies* (June 2018).[101] For some equipment types, equipment and maintenance cost data was available from CARB in the presentation "Technical Working Group Meeting Proposed GWP Limit for New Stationary Air Conditioning Equipment" (2019) and the CARB report *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* (2020).[102]
- Cost premiums for low-GWP refrigerants were provided as a percentage of total equipment cost and a percentage of total installation cost for many equipment types. For most equipment types, cost premiums were available in the CARB in the presentation "Technical Working Group Meeting Proposed GWP Limit for New Stationary Air Conditioning Equipment" (2019) and the CARB report *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* (2020).[103] This data was compiled data from interviews with

stakeholders. In cases when an estimated cost premium range is given, the median value was used. These premiums percentages were applied to the baseline equipment and installation cost data to give a total estimate cost premium value in dollars.

  - For equipment types for which no estimated cost premium was available, cost premiums were estimated by using the cost premium percentage of a similar equipment type. For a few equipment types with no available data, a 10% cost premium was assumed.

- Maintenance cost premiums for servicing low-GWP equipment were excluded from this analysis because of the uncertainty around refrigerant prices and any additional costs associated with handling mildly flammable refrigerants.

D.2 End-of-Life Cost Premiums

Using reports from the Environmental Investigation Agency[104] and UNEP Technology and Economic Assessment Panel,[105] the Guidehouse team estimated the incremental cost of EOL-management policies as a part of NYS mitigation strategies. These reports offer a two-step hierarchy for estimating EOL management costs. First, differential abatement costs were assigned at the equipment subcategory level, which assumes that certain applications would require more or less time to recover and transport refrigerant. These costs were further characterized as “low effort” or “medium effort” based on geographic spread, reflecting the increased transportation and storage costs associated with highly dispersed systems. For example, the EIA and UNEP TEAP reports estimate that EOL management costs are more than six times higher for a commercial refrigeration system under a “medium effort” scenario versus a mobile air conditioning system in a “low effort” scenario. The Guidehouse then team applied additional steps to arrive at a simplified EOL cost analysis. First, wherever costs were presented as a range for a given sector and effort level (e.g., “low-effort” stationary AC), the lower end of the range was assigned to commercial equipment while the upper end of the range was assigned to residential equipment. This assumes that recovering refrigerant in a residential setting would likely be more time- and cost-intensive than in a commercial setting. Finally, Guidehouse averaged the “low-effort” and “medium-effort” costs across each end-use subcategory to come up with a representative value.

Appendix E. Comparison of Hydrofluorocarbon Accounting Practices

Guidehouse conducted a literature review to assess the methodologies and assumptions of several HFC emissions accounting practices. This section provides details around HFC accounting methodologies and assumptions from various tools and models and a comparison of key assumptions across the different methodologies. Many of the methodologies and assumptions in HFC accounting methods are derived from the EPA Vintaging Model or IPCC Guidelines.

E.1 United States Environmental Protection Agency Vintaging Model (2018)[106]

E.1.1 Overview

- Within the five sectors (refrigeration and air-conditioning, foams, aerosols, solvents, and fire-extinguishing) there are 67 independently modeled end-uses. As ODS are phased out, a percentage of the market share originally filled by the ODS is allocated to each of its substitutes.
- Models the consumption of chemicals based on estimates of the quantity of equipment or products sold, serviced, and retired each year, and the amount of the chemical required to manufacture and/or maintain the equipment.
- Synthesizes data from: ODS Tracking System, the Greenhouse Gas Reporting Program, and Significant New Alternatives Policy (SNAP) program. Additional published sources, conference proceedings, coordination with trade associations and companies are also referenced.
- **Methodology:** Step 1: Gather historical data, Step 2: Simulate the implementation of new, non-ODS technologies, Step 3: Estimate emissions of the ODS substitutes. (Additional approach details: screening method, method for purchased gases, material balance method, simplified material balance method).

E.1.2 Major Assumptions/Limitations

- The model requires information on the market growth for each of the end-uses, a history of the market transition from ODS to alternatives, and the characteristics of each end-use such as charge sizes and loss rates.
- The simulation is considered to be a “business-as-usual” baseline case and does not incorporate measures to reduce or eliminate the emissions of these gases other than those regulated by U.S. law or otherwise common in the industry. Emissions are estimated by applying annual leak rates, service emission rates, and disposal emission rates to each population of equipment.
- Full public disclosure of the inputs to the Vintaging Model would jeopardize the security of the Confidential Business Information (CBI) that has been entrusted to the EPA.

E.2 California Air Resources Board (2016)[107]

E.2.1 Overview

- CARB has implemented detailed inventory estimations based on comprehensive research completed by CARB staff and studies completed by CARB contractors. Historical net consumption of each ODS was first compiled at a detailed product and equipment level to establish the basis for future emissions.
- The following emission categories are included in the CARB Greenhouse Gas (GHG) Emission Inventory: Refrigeration and air conditioning (AC), aerosol propellants, insulating foam, solvents and fire protection.
- F-gases are estimated using the **Tier 2 emission factor approach** from the 2006 IPCC Guidelines. **The Tier 2 methodology** follows two general steps:
    - **Step 1:** Calculate the time series of net consumption of each individual HFC at a detailed product and equipment level as the basis for emission calculations (e.g., inventory of refrigerators, other stationary refrigeration/AC equipment, appliance foams, pipe insulation, etc.).
    - **Step 2:** Estimate emissions using the activity data and resulting bank calculations derived from Step 1 and either emission factors that reflect the unique emission characteristics related to various processes, products, and equipment (Tier 2a) or, relevant new and retiring equipment data at the sub-application level to support a mass balance approach (Tier 2b).

E.2.2 Major Assumptions/Limitations

- Emissions were estimated using activity data, equipment specific storage capacity, maintenance and recharging assumptions, and emission factors that reflect the individual characteristics of the various equipment types, processes, and products.
- F-gas emissions are organized into ten broad categories with 29 detailed sub-categories (details in link).
- Emissions of each individual F-gas is reported by subcategory on a mass and CO_2-equivalent basis.

E.3 Intergovernmental Panel on Climate Change (2006)[108]

E.3.1 Overview

- Inventory compilers in different countries can search the IPCC Emissions Factor Database if national data is difficult to obtain.
- Contains Tier 1 A/B and Tier 2 A/B Methodologies that result in estimates of actual emissions rather than potential emissions. Approach A is emission-factor approach and Approach B is mass-balance approach.
    - **Tier 1:** data aggregation is at a more aggregated application level (refrigeration, AC, etc.). Uses composite emission factors based on weighted averages of known sub-application emission factors.

- o **Tier 2:** data aggregation is at the sub-application level (e.g., categories that make up AC). Determine emission factors based on circumstances surrounding sub-applications in their specific countries.

E.3.2 Major Assumptions/Limitations

- Takes into account time lag between consumption of ODS substitutes and emission
- Accounts for the potential development of banks (amounts of chemical accumulated throughout lifecycle).
- Includes assumptions for product lifetimes, first year losses, annual losses, default emission factors, end of life emission %, charge (when applicable), activity data, and uncertainty assessment, on the application and sub-application level.

E.4 American Carbon Registry (2015)[109]

E.4.1 Overview

- Sectors eligible under this methodology are (1) the use of reclaimed HFC refrigerants and (2) use of zero/low-GWP alternative technologies.
- This methodology is based on a robust data set, including United Nations Environment Programme, Technical Options Committee for Refrigeration, Air Conditioning and Heat Pumps, the U.S. EPA Vintaging Model, the U.S. EPA GreenChill Partnership, the CARB Offsets Methodology for Destruction of Ozone Depleting Substances, and the 2006 IPCC Guidelines.
- Avoided emissions generated under this Methodology from the use of reclaimed HFC refrigerants would be considered within direct emissions.
- For the reclaimed HFC refrigerant Methodology, the baseline emissions are defined for a specific HFC refrigerant by the weighted-average emission rate for the equipment in which that refrigerant is typically used.
- Additional references: Methodology for Advanced Refrigeration Systems (2018),[110] Methodology for Certified Reclaimed HFC Refrigerants (2018).[111]

E.4.2 Major Assumptions/Limitations

- Uses a conservative estimate for R-22 reclaim rate (8.9%).
- Average annual emissions rates for major refrigeration and AC end-use categories come from US EPA Vintaging Model and 2006 IPCC Guidelines.
- Under any scenario, percentage of supermarkets in the US with advanced, low-GWP refrigeration systems is negligible.
- For refrigerants that are predominantly used in 1 application, the average emission rate for that refrigerant is the average emission leak rate for that application.

E.5 United Nation Framework Convention on Climate Change (UNFCCC)[112]

E.5.1 Overview

- Annex 1 parties should use the methodologies provided in the 2006 IPCC Guidelines and report Actual Emissions of HFCs by chemical.
- Non-Annex 1 parties are encouraged but not required to express HFC emissions as either potential or actual.
- Potential Emissions should be estimated using the Tier 1 approach of IPCC Guidelines.
- Actual Emissions should be estimated using the Tier 2 approach of IPCC Guidelines and reported on a gas-by-gas basis.

E.5.2 Major Assumptions/Limitations

- Base year is typically 1990 within UN programs.
- The inventory data are provided in the annual GHG inventory submissions by Annex I Parties and in the national communications and biennial update reports by non-Annex I Parties.[113]

E.6 State Inventory Tool (2018)[114]

E.6.1 Overview

- EPA's State Inventory Tool (SIT) is an “top-down” interactive spreadsheet model designed to help states develop GHG emissions inventories, and provides a streamlined way to update or complete an inventory.
- There is no input data required for consumption of substitutes for ozone-depleting substances because emissions of HFCs from ODS substitutes can be estimated by apportioning national emissions to each state based on population. Therefore, the emissions factors and activity data for these sources are not required.

E.6.2 Major Assumptions/Limitations

- The methods used and the sectors covered are the same as those in the U.S. GHG Inventory.[115]
- The SIT only allows scaling of HFC emissions based on state population.
- No inputs are required for consumption of ODS substitutes, only for HCFC-22.

E.7 Comparison of Key Hydrofluorocarbon Accounting Models

Table E-1. Comparison of Assumptions for HFC Accounting Models

Assumption	EPA Vintaging Model (2018)	CARB (2016)	IPCC (2006)	NYS (2019)
1. Emission Rate	EPA estimates, based on EPA Vintaging Model Version 4.4, recent market research, and expert judgement.	Emission factors that reflect the individual characteristics of the various equipment types, processes, and products are referenced from various sources.	Can be derived from actual measurements of products or equipment at a national level during various phases of their lifecycle (country-specific) or can be inferred from wider regional or global sub-applications (default). The most significant emission factors are included in the Emissions Factor Database (EFDB) administered by IPCC.	Follows CARB methodology.
2. GWP Values	100-year values from IPCC Fourth Assessment Report (AR4) (source).	100-year values from IPCC AR4 (source).	Most recent values - IPCC AR5	Follows CARB methodology.
3. Equipment Stock Estimates	Market for each equipment type is assumed to grow independently, according to annual growth rates.	Uses EPA Vintaging model.	Detailed accounting for imports and exports of refrigerant and equipment details included in link. Inventory compilers should account for imports and exports of both chemicals and equipment. This will ensure that they capture the actual domestic consumption of chemicals and equipment.	Emission stocks scaled from CA inventory using USCA tool on a $MMTCO_2e$ basis Most categories scaled by population, some scaled by households and technology penetration. Light duty vehicles scaled by vehicle registrations.

Assumption	EPA Vintaging Model (2018)	CARB (2016)	IPCC (2006)	NYS (2019)
4. Size Assumption per Equipment	Primary research and Confidential Business Information (CBI).	New equipment and materials are assumed to use the same amount and type of F-gas as used in baseline years and previous years, until adopted regulations prohibit the use of specific F-gases in new equipment and materials. Example: equipment profiles for 12 specific types and sizes of refrigeration and AC equipment were developed using SCAQMD Rule 1415 reporting data from approximately 6,000 systems in 2,000 facilities over reporting years. Each profile includes refrigerant types used, average refrigerant charge size, and average annual loss. Some profiles for HFC use in refrigeration and AC equipment were augmented by U.S. EPA Vintaging Model estimates.	Estimates for charge (kg) for refrigeration and air-conditioning systems are based on information contained in UNEP RTOC Reports. In the given ranges, use a lower value for developed countries and high value for developing countries.	Follows CARB methodology.
5. Annual Leak Rate per Equipment	Primary research and CBI	Assume a linear reduction each year from 2011 to 2021 until the lower limit of 10 percent leak rate is achieved. Annual leak rates and equipment end-of-life loss rates remain the same as baseline years, unless acted upon by exterior forces such as regulations that have been adopted at the state or national level. Leak rate assumptions are checked against actual reported data to CARB Refrigerant Management Program, then revised and updated annually.	Annual leakage from the refrigerant banks represents fugitive emissions, i.e., leaks from fittings, joints, shaft seals, etc. but also ruptures of pipes or heat exchangers leading to partial or full release of refrigerant to the atmosphere. Information contained in UNEP RTOC Reports.	Follows CARB methodology.
6. Lifetime	Primary research and CBI	The equipment end-of-life (EOL) retirement for a given year is modeled using an appliance and equipment survival curve based on equipment retirement ages. Data on the retirement ages of very large commercial refrigeration and AC equipment were not available, so it was assumed that commercial equipment follows a similar functional life and survival curve as smaller equipment.	Estimates for equipment lifetime for refrigeration and air-conditioning systems are based on information contained in UNEP RTOC Reports. In the given ranges, use a lower value for developed countries and high value for developing countries.	Follows CARB methodology.

Assumption	EPA Vintaging Model (2018)	CARB (2016)	IPCC (2006)	NYS (2019)
7. End of Life Leakage	Primary research and CBI	The normal distribution of functional life and retirement age, or "survival curve", was applied to the emission equations for all refrigeration and AC equipment.	Estimates for end of life emission factors for refrigeration/AC systems are based on info in UNEP RTOC Reports Methodology and values for recovery efficiency and initial charge remaining used to calculation end of life leakage included in link.	Follows CARB methodology.
8. Other	The HFC default refrigerant is the one assumed to represent the single highest share of installed refrigerants for a particular equipment type according to the U.S. EPA Vintaging Model.	F-gas emissions are assumed to increase proportionally to population, unless data indicates otherwise. For years 2012 and later, they use the California Department of Finance (DOF) population projections showing a 0.75 percent annual growth rate in California through 2030.	N/A	Follows CARB methodology.

Appendix F. Details for Refrigerant Management Program Economic Impact Assessment

Section 4.4 describes causes and solutions to refrigerant leakage in today's systems, including CARB's Refrigerant Management Program (RMP). In 2009, CARB conducted a detailed economic impact analysis for the RMP from both a facility's perspective and enforcement agency's perspective. Appendix F provides the details for this analysis, which may be valuable should New York State consider a similar program. The analysis estimated the costs and cost savings for facility reporting and leak detection and repair in 2008 dollars. Overall, the mandated repairs as a result of the RMP often result in cost savings that exceed compliance costs but varied based on the size of the facility.

The recurring annual costs for facilities under the RMP include implementation fees, costs associated with reporting and recordkeeping, and leak inspections or annual leak detection monitoring system audits. The implementation fees and reporting costs calculated by CARB are single costs per facility based on the largest system at the facility. Each facility with large or medium refrigeration systems pays this initial and annual implementation fee to CARB, which will be used by the enforcing agency, either CARB or its authorized agent, to recoup their implementation, inspection, and enforcement costs. These costs include, but are not limited to: staff training expenses, reporting system development, and inspection and recordkeeping time. Under the RMP, facilities with small refrigeration systems only will not be subject to the initial or annual implementation fee requirements but still need to be registered and maintain records of system inspection, refrigerant leaks and repairs.

The initial and annual implementation fees are estimated to approximately balance the costs of administration and inspections. The proposed fee amounts in CARB's analysis are $170 for facilities with medium systems, $370 for facilities with large systems, and $208 overall weighted average for all facilities with medium or large systems.[116] Table F-1 summarizes the average cost to inspect approximately 25% of large/medium facilities a year and the total annual revenue from large and medium facilities. CARB estimated that, on average, approximately 25% of the large and medium facilities will be inspected each year based on the relative risk of emissions and potential amount of emissions.[117] It was assumed that compliance with the Refrigerant Management Program could be maintained with periodic enforcement inspections prioritized by facilities' potential or demonstrated leak risk. For example, facilities whose annual report indicates frequent leaks and substantial emissions may have a higher priority and be inspected more frequently.

Table F-2. Statistics Relevant to Large, Medium, and Small Facilities

Source: *CARB Appendix C Economic Impact Estimates—High-Global Warming Potential Stationary Source Refrigerant Management Program.*

System Inspection Costs	Number or Cost
Approximate number of facilities	10,700
Inspections per year	2,900
Average hours per inspection	6.5
Average hours per inspection for program administration	1.2
*Estimated total cost per inspection	$760
Total cost of inspections	$2.2 million
Average annual implementation costs per facility	$208
Total annual revenue from large and medium facilities	$2.2 million
****Annual Personnel Years (PYs) Needed**	
Administrative PYs (ARB)	2
Inspection and Enforcement PYs (ARB and District)	11**
Total PYs cost (@$175,000 per position)	$2.2 million

* Cost per personnel hour (salary, benefits, office, supplies, travel) = $98

** Work hours per Personnel Year (PY) = 1780 hours

**** For discussion purposes 10.7 PYs has been rounded to 11 (total of 13 PYs)*

The average number of hours needed per facility inspection as shown in the table above includes pre-inspection time for:

- Facility records review.
- On-site equipment inspection.
- Review of equipment service records and leak repair records.
- Review of refrigerant purchase, use, and shipping records.
- Travel planning.
- Cross referencing related records with the annual report submitted by the facility.
- Report writing.

The total annual cost of the program ($2.2 million as show in Table F-1) is the product of the number of facilities inspected annually, the hours per inspection, and hourly rate of the inspector. There is also a need for administrative positions for program administration, reporting, payment system development and maintenance, training for air district staff and facility owners and operators, and outreach to the impacted facilities. This staff will also assist in prioritizing which facilities are inspected each year. CARB states that all the positions hired for the RMP enforcement will be funded by revenue from the implementation fees.

Many facilities, especially those with large systems, already have a process in place for tracking repairs, refrigerant use, and leak rates. CARB developed Refrigerant Registration and Reporting System, in which the reports will be transferred to a centralized database for access by CARB and, in certain cases, the air districts.[52] CARB's detailed cost analysis includes time estimates for recording leaks and submitting the report. For example, the total reporting and recordkeeping costs per large facility are estimated to be $488 per year based on time needed to record leaks, maintain records of automatic leak detection system and electronically submit the report at a fully loaded labor rate estimate of $75 per hour as shown in Table F-2.

Table F-2. Estimated Reporting and Recordkeeping Costs per Large Facility

Source: CARB Appendix C Economic Impact Estimates—High-Global Warming Potential Stationary Source Refrigerant Management Program.

Activity	Minutes	Occurrences per Year	Systems / Units	Percent Leaking Systems	Hours
Recordkeeping – Recording Leaks	15	(variable by probability of leak)	2	67.5%	0.3
Recordkeeping – ALD System Performance Records	15	12	2	N/A	6.0
Reporting	10	1	N/A	N/A	0.2
Total Hours					**6.5**
Total Costs (@ $75 / hour)					**$488**

CARB used their estimate of facilities' labor rate of $75 for annual audits of ALD systems and leak inspection costs. This audit and inspection could be conducted by facility personnel, a contracted inspection services, or enforcement agency personnel. Under RMP, medium and small facilities can substitute automatic leak detection for the quarterly or annual inspections. Table F-3 summarizes the ALD system audit and leak inspection costs per system.

Table F-3. ALD System Audit and Leak Inspection Costs per System

Source: CARB Appendix C Economic Impact Estimates—High-Global Warming Potential Stationary Source Refrigerant Management Program.

Leak Inspection	Hours	Times per Year	Total Hours per System	Total Cost per System
ALD Audit	2	1	2.0	$150
Medium Sized Leak Inspections	1	4	4.0	$300
Small Sized Leak Inspections	1	1	1.0	$75

For facilities with large refrigeration systems, required to have ALD systems, the capital costs are estimated to be $8,130 for an 8-sensor system.[118] The typical monitoring system requires annual maintenance which includes the replacement of filters and, depending on system design, calibration of the sensors. These costs are typically around $90 per monitoring point per year which comes out to $720/year for the average eight-point monitoring system.

Another cost to the facility is the cost of leak repairs. There are two types of leak repairs—operating leaks and catastrophic leaks. The leak repair costs in CARB's analysis are calculated as the base cost of making the repair (parts, labor, recovery of remaining refrigerant in the system) and the cost of refrigerant to recharge the system. CARB calculated the refrigerant needed to recharge the system from the modeled average target leak amount per system of that size and type and a refrigerant cost of $11 per pound, shown in Table F-4.

Table F-4. Base Annual Repair Costs

Figures rounded to the nearest whole number.

Source: *CARB Appendix C Economic Impact Estimates—High-Global Warming Potential Stationary Source Refrigerant Management Program.*

System Size	Labor hours / cost (@ $75 per hour)	Parts	Cost to recover the remaining refrigerants prior to repair	Total labor, parts, and recovery
Large Systems	16 hrs / $1,200	$600	$650	$2,450
Medium Systems	12 hrs / $900	$300	$350	$1,550
Small Systems	8 hrs / $600	$100	$200	$900

One of the effects of the RMP includes a quicker repair timeframe in some cases. This help reduces the cost of purchasing new replacement refrigerant due to leaks. Current repair practices typically "top-off" refrigerant systems without checking and repairing leaks—which may cost businesses hundreds to thousands of dollars per year in refrigerant purchased (shown as refrigerant savings in Table F-5). Previously, CARB modeled repairs that would be initiated when refrigerant loss reaches 35%. A typical medium system containing 689 pounds of refrigerant that leaks an average of 17% of the charge per year under the current practices would lose 119 pounds per year. After approximately two years (2.1 years), the refrigerant loss would equal 35% of the charge; therefore, a repair would be made at that time. Under the proposed regulation requirements, the repair would made as quickly as possible upon the first indication of a leak (repairs are made within 14 days after discovery) rather than at a later date. NYS could implement a similar repair strategy based on system refrigerant loss thresholds.

Table F-5. Annual Leak Repair Refrigerant Costs and Savings

Source: CARB Appendix C Economic Impact Estimates—High-Global Warming Potential Stationary Source Refrigerant Management Program.

System Size	Current average annual refrigerant leak (pounds)	Target average annual refrigerant leak*	Annual refrigerant savings (pounds)	Annual refrigerant cost savings (@ $11/pounds)**
Large Systems	1,090	447	$642	$7,060
Medium Systems	119	69	$50	$548
Small Systems	18	6	$12	$127

* Expected amount needed to recharge following repair (pounds).

** $11/pound refrigerant cost estimate differs from the previously stated $7/pound estimate due to substantial variation in prices by refrigerant and application. HFC prices will likely increase in the future with the federal HFC phasedowns.

Table F-6 illustrates the effective cost of funds of incurring the cost of the repairs immediately and is the portion of the repair costs that are attributed to the rule. It is important to note that the AIM Act may result in higher HFC refrigerant prices in the future.

Table F-6. Effective Cost of Funds for the Average Facility Leak Rate

Source: CARB Appendix C Economic Impact Estimates—High-Global Warming Potential Stationary Source Refrigerant Management Program.

System Size	Annual Average Leak Rate	Average Charge (pounds)	Time frame	Effective Cost of Early Repair
Large Systems	23%	4663	1.5 years	8%
Medium Systems	17%	689	2.0 years	10%
Small Systems	14%	122	2.4 years	12%

The cost-effectiveness of the RMP program to facilities is calculated as the ratio of the net costs to the emission reductions expected due to the enhanced leak detection and repair requirements of the rule, in dollars per metric ton of CO_2e ($/MT$CO_2$e). In 2020, when the rule is in full effect, the statewide net annual costs are expected to result in a savings of approximately $20 million savings for large facilities, $0.3 million cost for medium facilities, and $0.2 million cost for small facilities. This results in emissions reductions of 8 MMT CO_2e (4, 3, 1 MMT CO_2e for large, medium, and small facilities, respectively) and a cost-effectiveness of approximately $5/MT$CO_2$e savings for large, approximately break-even for medium and small facilities ($0.08/MT$CO_2$e cost for medium and $0.26/MT$CO_2$e cost for small) with an overall average of $2/MT$CO_2$e savings). The cost-effectiveness metrics demonstrate the greater impact RMP has on large-size systems.

The total costs of the rule for facilities are calculated for calendar years 2011 through 2020 (estimated costs in the year 2020 are summarized in Table F-7). New facilities and systems are assumed to exist for the entire year they enter service and costs are calculated for a given whole year. Table F-8 shows example average costs for a typical facility.

Table F-7. Statewide Average Annual Cost of Stationary Refrigerant System Registration and Leak Repair for All Facilities in 2020

Source: CARB Appendix C Economic Impact Estimates—High-Global Warming Potential Stationary Source Refrigerant Management Program.

	Annual Cost (HFC plus ODS Systems) ($Millions)	Annual Cost (HFC Systems Only) ($Millions)
Recurring Annual Costs		
Implementation	$2.4	$2.0
Reporting and recordkeeping	$7.0	$6.4
Leak inspection	$21.0	$19.7
ALD and Monitoring		
Capital and installation cost	$4.1	$3.2
Annual Maintenance	$3.2	$2.5
Leak Repair* (labor, parts, and refrigerant recharge)	$11.3	$10.2
Gross Cost	$49.0	$44.0
Refrigerant savings	$68.1	$56.8
Net cost	**$19.1 savings**	**$12.8 savings**
Emissions reductions	**8 MMT CO_2e**	**7 MMT CO_2e**
Cost-effectiveness (annual average)	**$2/MT$CO_2$e savings**	**$2/MT$CO_2$e savings**

* Leak repairs provided as 5% real discount rate cost of funds per year.

Table F-8. Example Average Costs to Typical Facilities

	Facilities with small systems	Facilities with medium systems	Facilities with large systems
Annual implementation fee	0	$170	$370
Annual reporting and recordkeeping costs	$115	$422	$488
ALD annual audit, quarterly inspection, or annual inspection costs	$375	$1,500	$300
ALD capital costs	N/A	N/A	$1,830/year ($16,260 annualized over 12 years)*
ALD operational costs	N/A	N/A	$1,440
Leak repair costs	$161	$677	$984
Total Gross Cost	**$651**	**$2,770**	**$5,410**
Refrigerant savings	$637	$2,740	$14,130
Total Net Annual Costs	**$14**	**$30**	**$8,720 savings**

* Multiple monitoring systems since the average facility has multiple large systems.

The cost resulting from the refrigerant use, sale, and disposal component of the Refrigerant Management Program proposed rule are primarily placed on U.S. EPA certified technicians, refrigerant reclaimers, and refrigerant distributors or wholesalers. Overall, the RMP will achieve emissions reductions at an average cost-effectiveness of about $2/MT$CO_2$E and an average savings of approximately $700 per facility per year, as show in Table F-9.

Table F-9. Statewide Annual Cost of the Entire Proposed Rule for the Year 2020

Source: CARB Appendix C Economic Impact Estimates—High-Global Warming Potential Stationary Source Refrigerant Management Program.

	Annual Cost (HFC plus ODS Systems) ($ millions)	Annual Cost (HFC systems Only) ($ millions)
Net Costs: General Requirements for Stationary Refrigeration System Registration and Leak Repair.	$19.1 savings	$12.8 savings
Net Costs: General Requirements for Refrigerant Use, Sale, and Disposal.	$0.2	$0.1
Entire Rule Net Cost	$18.9 savings	$12.7 savings
Proposed Rule Emissions Reductions (overall average)	**8 MMT CO_2E**	**7 MMT CO_2E**
Proposed Rule Cost Effectiveness (overall average)	**$2/MT CO_2E**	**$2/MT CO_2E**

Endnotes

1 These reports can be found at https://climate.ny.gov/Climate-Resources

2 GHG emissions under the Climate Act use AR-5, 20-year GWP values. 2020 emissions are 9.6 MMT CO2e when measured using AR-4, 100-year GWP.

3 6 NYCRR Part 496 Statewide GHG Emission Limits.

4 NYS adopted prohibitions on new equipment and products previously promulgated by the U.S. Environmental Protection Agency Significant New Alternatives Policy (SNAP) Program. https://www.dec.ny.gov/regulations/119032.html

5 The spreadsheet model can be updated to consider Reference Case #4 or any other Reference Case as the baseline, update key parameters in #3-5, or create other Reference Cases of interest, based on the progression of the Climate Act Scoping Plan development and Integration Analysis.

6 Statewide emissions refer to emissions subject to the Climate Act as provided in 6 NYCRR Part 496, "Statewide Greenhouse Gas Emission Limits."

7 The scenarios in this analysis consider similar HFC restrictions for new equipment as those proposed in California, with a delayed timeline to account for building code updates where necessary For example, CARB established a 750 GWP limit for most residential and light-commercial HVAC categories for 2025 and VRF systems in 2026. Due to the building code update timeline in NYS, Guidehouse assumes a similar policy to be enacted in 2027 in this analysis.

8 Guidehouse defines ultra-low GWP as refrigerants with less than 10 GWP (AR-4, 100-year) because this represents the lowest achievable GWP level for HVAC&R systems including HFOs (e.g., R-1234yf), natural refrigerants (e.g., propane, isobutane, carbon dioxide, ammonia), and various non-vapor-compression cycles.

9 The American Innovation and Manufacturing Act of 2020 (AIM Act) was signed into law on December 27, 2020 and requires a 40% reduction in HFC consumption and production by 2024; 70% reduction by 2029; 80% reduction by 2034; and 85% reduction by 2036.

10 The Guidehouse model analyzes consumption as end-use refrigerant demand for new and service applications, whereas national and international agreements often define consumption as national production and imports, minus exports.

11 EPA Proposed Rule - Phasedown of Hydrofluorocarbons: Establishing the Allowance Allocation and Trading Program under the AIM Act. May 19, 2021. https://www.epa.gov/climate-hfcs-reduction/proposed-rule-phasedown-hydrofluorocarbons-establishing-allowance-allocation

12 Guidehouse has not estimated and compared the relative levelized abatement cost for all mitigation options being considered in the Climate Act Integration Analysis project. Nevertheless, Guidehouse's knowledge and experience in evaluating abatement measures suggests that many options being considered will have levelized abatement costs ranging from tens to hundreds of dollars more than the HFC mitigation options.

13 New York State Climate Act https://climate.ny.gov/

14 New York State Climate Action Council https://climate.ny.gov/Climate-Action-Council

15 NYS adopted prohibitions on new equipment and products previously promulgated by the U.S. Environmental Protection Agency Significant New Alternatives Policy (SNAP) Program. https://www.dec.ny.gov/regulations/119032.html

16 The October 14, 2020 Notice of Action adopted regulatory provisions previously promulgated by the U.S. Environmental Protection Agency (EPA) Significant New Alternatives Policy (SNAP) Program, which were partially vacated in 2017. This rule adopted prohibitions on certain HFC substances in the specific end-uses identified by the EPA as having safe and available alternatives. https://www.dec.ny.gov/regulations/119032.html

17 These reports can be found at https://climate.ny.gov/Climate-Resources

18 See Appendix A and Appendix C for details on equipment stock estimates and other input assumptions.

19 New York State Joint Utilities. 2019. "New York State Technical Resource Manual: New York Standard Approach for Estimating Energy Savings from Energy Efficiency Programs." Version 7. April 15, 2019. https:/www3.dps.ny.gov/W/PSCWeb.nsf/96f0fec0b45a3c6485257688006a701a/72c23decff52920a85257f1100671bdd/$FILE/TRM%20Version%207%20-%20April%202019.pdf

[20] This project focuses on consumption and emissions of HFCs rather than for CFCs and HCFCs. The Guidehouse model was designed to track the installed stock of HVAC&R systems using ODS refrigerants starting in 1980 to accurately model the overall stock of equipment and the anticipated shipments and demands for HFC models following ODS restrictions in the 1990s. To accurately model the consumption and emissions for ODS, the model would need to be updated to begin tracking ODS installed base and shipments much earlier than 1980 to capture at least one complete lifetime of all HVAC&R equipment categories by the 1990s. Furthermore, ODS refrigerants are not tracked in most GHG inventories because of the assumed global phasedown in the Montreal Protocol.

[21] EPA established a "credit" program to incentivize certain air conditioning technologies in mobile vehicles as part of a final rule published in the Federal Register on May 7, 2010. See 75 FR 25323.

[22] U.S. Environmental Protection Agency. 2020. "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2018." April 2020. https://www.epa.gov/sites/production/files/2020-04/documents/us-ghg-inventory-2020-main-text.pdf

[23] This analysis relied on expert interviews to project how foam consumption and emissions will change over time and does not break out the specific HFC alternatives in the same manner as for HVAC&R equipment. Furthermore, the analysis does not consider any health impacts related to the use of HFOs or other HFC alternatives for foams and other end-use sectors.

[24] 6 NYCRR Part 496 Statewide GHG Emission Limits.

[25] NYS adopted prohibitions on new equipment and products previously promulgated by the U.S. Environmental Protection Agency Significant New Alternatives Policy (SNAP) Program. https://www.dec.ny.gov/regulations/119032.html

[26] Guidehouse can readily update the spreadsheet model to consider Reference Case #4 or any other Reference Case as the baseline, update key parameters in #3-5, or create other Reference Cases of interest, based on the progression of the Climate Act Integration Analysis project.

[27] Statewide emissions refer to emissions subject to the Climate Act as provided in 6 NYCRR Part 496, "Statewide Greenhouse Gas Emission Limits."

[28] Uselton, D and Crawford, T. 2015. "System Drop-in Test of R-32 and Refrigerant Blends ARM-71a, HPR2A, L-41-2 and DR-5A in a Five-Ton R-410A Rooftop Packaged Unit." Lennox Industries, Inc. Prepared for AHRI's Low-GWP AREP. September 23, 2015. http://www.ahrinet.org/App_Content/ahri/files/RESEARCH/AREP_Final_Reports/AHRI_Low_GWP_AREP_Rpt_047.pdf

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[30] Pardo and Mondot. 2018. "Experimental Evaluation Of R410A, R407C and R134a Alternative Refrigerants in Residential Heat Pumps." International Refrigeration and Air Conditioning Conference. Paper 1991. https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=2990&context=iracc

[31] Turpin, Joanna. 2020 "Nonflammable Alternatives to R-410A." ACHR News Article. October 14, 2020. https://www.achrnews.com/articles/143923-nonflammable-alternatives-to-r-410a

[32] ASHRAE 34 classifies A2L refrigerants as having higher flammability, lower flammability, and no flame propagation. The industry commonly uses the equivalent terms flammable, mildly flammable, and non-flammable.

[33] Meade, D. and Steed, J. 2018. "Consumer Cost Impacts of U.S. Ratification of the Kigali Amendment." Report Prepared for the Air-Conditioning, Heating, & Refrigeration Institute and the Alliance for Responsible Atmospheric Policy. Inforum and JMS Consulting. November 9, 2018. http://www.ahrinet.org/App_Content/ahri/files/RESOURCES/Consumer_Costs_Inforum.pdf

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[35] As per EPA's April 27, 2018 guidance (83 FR 18431), based on the court's partial vacatur, in the near term EPA will not apply these HFC listings in the 2015 Rule, pending a rulemaking. https://www.epa.gov/snap/substitutes-propellants#ref1a

[36] Goetzler et al. 2016. "The Future of Air Conditioning for Buildings." July 2016. Prepared by Navigant Consulting, Inc. and Oak Ridge National Lab for the U.S. Department of Energy. https://www.energy.gov/sites/prod/files/2016/07/f33/The%20Future%20of%20AC%20Report%20-%20Full%20Report_0.pdf

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[57] CARB. 2009. “Appendix C Economic Impact Estimates – High-Global Warming Potential Stationary Source Refrigerant Management Program.” https://ww3.arb.ca.gov/regact/2009/gwprmp09/refappc.pdf

[58] Emerson Climate Solutions. 2016. E360 Outlook. Volume 2. Number 2 https://climate.emerson.com/documents/v2-n2-reducing-refrigerant-leaks-es-mx-3703288.pdf

[59] The Guidehouse model analyzes consumption as end-use refrigerant demand for new and service applications, whereas national and international agreements often define consumption as national production and imports.

[60] Today, only a small percentage of HFC refrigerant that is recovered goes through the full reclaim process due to the price premium of reclaimed refrigerant over new virgin supplies. Scenario #7 assumes that 100% of HFC refrigerant that is recovered under today’s practices would be available for use as reclaimed refrigerant. Guidehouse projects that demand will exceed supply in 2024 and 2029.

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[62] Guidehouse has not estimated and compared the relative levelized abatement cost for all mitigation options being considered in the Climate Act Integration Analysis project. Nevertheless, Guidehouse’s knowledge and experience in evaluating abatement measures suggests that many options being considered will have levelized abatement costs ranging from tens to hundreds of dollars more than the HFC mitigation options.

[63] Low-GWP refrigerants have less than 750 GWP (AR4 100-year) and ultra-low-GWP refrigerants have less than 10 GWP (AR4 100-year).

[64] Guidehouse has not estimated and compared the relative levelized abatement cost for all mitigation options being considered in the Climate Act Integration Analysis project. Nevertheless, Guidehouse’s knowledge and experience in evaluating abatement measures suggests that many options being considered will have levelized abatement costs ranging from tens to hundreds of dollars more than the HFC mitigation options.

[65] 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.” Staff Report: Initial Statement of Reasons. October 20, 2020. https://ww3.arb.ca.gov/regact/2020/hfc2020/isor.pdf?_ga=2.228383838.233283915.1605125304-212465881.1592581875

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[116] They were calculated based on estimates provided by California Air Pollution Control Officers Association (CAPCOA) and CARB Enforcement Division concerning the staff time and materials needed to conduct inspections.

[117] This percentage is an expected average and does not imply the actual annual number of inspections.

[118] CARB annualized the capital cost over project 12-year life of the monitoring system. This cost estimate for an ALD system takes into account (1) the cost of a new monitoring system on each refrigeration system (2) the cost of a somewhat larger system that is capable of monitoring more than one refrigeration system at the facility and (3) the cost of enhancing an existing system installed to monitor the machine room for health and safety purposes. Additional information on the source of the number is in the CARB Report.

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New York State Energy Research and Development Authority

17 Columbia Circle
Albany, NY 12203-6399

toll free: 866-NYSERDA
local: 518-862-1090
fax: 518-862-1091

info@nyserda.ny.gov
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