ASSESSMENT OF AVAILABLE LOW GLOBAL WARMING POTENTIAL ALTERNATIVES TO F-GAS REFRIGERANTS

A Report by the Toxics Use Reduction Institute of Massachusetts

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Contact

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About TURI

The Toxics Use Reduction Institute (TURI) of Massachusetts is an independent government agency with a statutory mandate to help protect workers, communities and the environment from toxic chemicals and pollution. TURI is hosted by the University of Massachusetts Lowell. TURI was established in 1989 under by the Massachusetts Toxics Use Reduction Act (TURA) of 1989. The legislation was passed following the emergence of childhood cancer clusters near mismanaged hazardous waste sites in the state.

Since the adoption of TURA, Massachusetts has seen significant reductions in the use of and environmental releases of hazardous chemicals while maintaining competitiveness of Massachusetts businesses. Working in close collaboration with businesses of all sizes, as well as government agencies, local communities and international organizations, TURI helps identify actions companies and communities can take to reduce the use of toxics upstream.

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Assessment of Available Low Global Warming Potential Alternatives to F-gas Refrigerants

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Abbreviations

Acronym	*Meaning*	*Acronym*	*Meaning*
% w/w	Composition, mass percentage	MT	Medium Temperature
AC	Air Conditioning	NH_3	Ammonia
AIHA	American Industrial Hygiene Association	NFPA	National Fire Protection Association
ACGIH	American Conference of Governmental Industrial Hygienists	NRDC	Natural Resources Defense Council
		NRE	Net Refrigerating Effect
AIM	American Innovation and Manufacturing	ODP	Ozone Depleting Potential
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers	ODS	Ozone Depleting Substance
ASTM	American Society for Testing and Materials	OECD	The Organization for Economic Cooperation and Development
CAA	US Clean Air Act	OEL	Occupational Exposure Limit
		OSHA	US Occupational Safety and Health Administration
CARB	California Air Resources Board		
CAS	Chemical Abstracts Service	P	Pressure
CC	Cooling Capacity	P2OASys	Pollution Prevention Options Analysis System
CFC	Chlorofluorocarbon	PBT	Persistent, Bio-accumulative, and Toxic
CMR	Carcinogenic, Mutagenic, and Reprotoxic	PCE	Perchloroethylene
CO_2	Carbon dioxide	PFAS	Poly- and per-fluoroalkyl substances
CoP	Coefficient of Performance	POCP	Photochemical Ozone Creation Potential
CTC	Carbon tetrachloride	ppm	Concentration, parts per million
CWA	US Clean Water Act	q	Heat
ECHA	The European Chemicals Agency	REACH	European Registration, Evaluation, Authorisation, and Restriction of Chemicals
EHS	Environmental Health and Safety		
EJ	Environmental Justice	ROS	Reactive Oxygen Species
EPA	United States Environmental Protection Agency	SDS	Safety Data Sheet
EU	European Union	SNAP	EPA Significant New Alternatives Policy
F-gas	Fluorinated gas	SNAP	EPA Significant New Alternatives Policy
GWP	Global Warming Potential	SVHC	Substance of Very High Concern
GWP100	Global Warming Potential integrated over 100 years	T	Temperature
HC	Hydrocarbon	t-DCE	trans-Dichloroethylene
HCFC	Hydrochlorofluorocarbon	TEWI	Total Equivalent Warming Impact
HCFO	Hydrochlorofluoroolefin	TFE	Trifluoro ethanal
HF	Hydrofluoric acid	TFA	Trifluoroacetic acid
HFC	Hydrofluorocarbon	TLV	Threshold limit value
HFC-23	Fluoroform; trifluoromethane; R-23	TRL	Technology Readiness Level
HFO	Hydrofluoroolefin	TSCA	Toxic Substances Control Act
HVACR	Heating, Ventilation, Air Conditioning, and Refrigeration	TURI	Massachusetts Toxics Use Reduction Institute
		UL	Underwriters Laboratories
		ULC	Ultra Low Charge
LCCP	Life-Cycle Climate Performance	ULT	Ultra Low Temperature
LCI	Life Cycle Impact	USGS	United States Geological Survey
LFL	Lower Flammability Limit	VOC	Volatile Organic Compound
LT	Low Temperature	vPvBT	very Persistent, very Bio accumulative, and Toxic
MAC	Mobile Air Conditioning	W	Mechanical work
MRL	Market Readiness Level	WEEL	Workplace Environmental Exposure Level

Executive Summary

More than 80% of global Heating, Ventilation, Air Conditioning, and Refrigeration (HVACR) systems utilize fluorinated gases (F-gases), particularly hydrofluorocarbon (HFC) refrigerants. Originally adopted as substitutes for ozone-depleting substances, HFCs have an astonishing global warming potential (GWP) that is over 14,000 greater than that of carbon dioxide (CO_2).

Thanks largely to the 2016 Kigali Amendment to the Montreal Protocol, governments have aimed to phase down HFC due to their significant yet preventable greenhouse effects. While an urgent phase-down of HFCs is essential for achieving climate change mitigation goals, problematic alternatives are being adopted despite the availability and ongoing development of safer options.

Concerns Associated with Fluorinated Refrigerants

Currently, laws and policies aimed at reducing the use of HFCs pose a serious risk of substituting one environmental crisis with another. For example, measures that will promote the uptake of alternatives of HFC do not adequately restrict the entry to toxic and otherwise hazardous refrigerants.

Of particular concern is the potential for increased pollution from per- and poly-fluoroalkyl substances (PFAS), which are already a significant public health crisis for many communities. Additionally, the production of F-gas refrigerants involves using certain carcinogens, mutagens, and reprotoxic (CMR) substances alongside HFCs. Considering the lifecycle of hydrofluoroolefins (HFOs), a leading alternative to HFCs, and the ongoing presence of HFCs in HFO blends, this category of alternatives may not mitigate climate change as much as anticipated or required. Environmental justice communities are most likely to endure the adverse impacts of the F-gas production sites.

Safer Alternatives to Fluorinated Refrigerants are Available

Safer alternatives to F-gas refrigerants exist. Carbon dioxide (CO_2), ammonia (NH_3), and hydrocarbons (HCs), particularly propane and isobutane, are well-known refrigerant alternatives that can be safely and efficiently implemented with the right technology. These alternative refrigerants are currently available for some end-uses, such as residential, commercial and industrial refrigeration systems, while they are still being developed for residential air conditioners, heat pumps, and mobile refrigeration applications.

The adoption of non-fluorinated HVACR for various applications illustrates their availability and accessibility. Demand for alternatives to F-gases by various commercial and industrial users of refrigeration technologies is rising. To meet demand, the supply of non-fluorinated HVCAR equipment continues to increase. Specialized equipment manufacturers are reevaluating and redesigning their products to capitalize on the demand for systems using non-F-gas refrigerants[1–3]. Novel engineering advancements have addressed safety concerns linked to higher operational pressures that initially restricted adoption. Indeed, the latest safety standards show a growing acceptance of flammable refrigerants for commercial and industrial applications, enabling greater adoption of flammable hydrocarbon alternatives. Table E.S. 1 provides a summarized comparison among refrigerant families.

TABLE E.S.1

Comparative qualitative analysis of the different refrigerant gas families.

Name(s)	Applications	Technology	Cost*	Manufacturing	Benefits	Hazards / Drawbacks	Mitigation measures
Ammonia (NH_3) R-717	Industrial refrigeration and large-scale food storage. Retrofitting of R-22-based HVACR equipment in non-residential buildings.	High efficiency, well established. Mostly used for industrial cooling.	Inexpensive (1 $/kW CC)	Haber process or electrolysis of hydrogen and nitrogen	Non toxic for soil. Zero GWP and ODP.	Highly Toxic for humans (acute respiratory). Elevated risk of immediate death in leaking events. High eutrophication. Corrosive (when wet) to copper, brass, and zinc.	Enforcement of safety standards. Low charge designs.
Carbon dioxide (CO_2) R-744	Motor vehicle air conditioning systems. Refrigerated transport. Commercial HVACR.	High-pressure equipment with heat recovery.	Inexpensive (2-4 $/kW CC)	CO_2 purification	Non-toxic. GWP=1. No water crystallization problems.	Might require the use of ammonia or HCs to increase efficiency. High initial investment.	Enforcement of efficiency standards. Enhance efficiency from equipment design.
Hydrocarbons (HCs)	New household refrigerators and freezers: HC-290; HC-600a. SNAP approved for ULT refrigeration: HC-1170.	Safe use under UL 60335-2-24 equipment standard.	Low to high (3-25 $/kW CC) depending on the application	Hydrocarbon purification	Non-toxic Low-GWP Zero ODP.	Flammability reduction by HFC or CO2 blending reduces efficiency.	Safety standards. Flammability mitigated by equipment design
Hydrocarbons + CO_2	Large-scale food storage and commercial refrigeration.	Cascade systems with heat recovery. Higher efficiencies than CO_2.	Lower cost than pure HCs.	Same as CO_2 and HC	Non-toxic Low GWP	Fire hazard (lower than HCs). High initial investment.	Driving design innovation
Chlorofluorocarbons (CFCs)	Phased out by enforcement of Montreal protocol.				High efficiency. Low corrosion.	High ODP; very high GWP.	Enforcement of Montreal Protocol
Hydrofluorocarbons (HFCs)	80% of currently installed HVACR equipment for residential, mobile, and commercial applications	High efficiency	Low to high (5-31 $/kW CC) depending on the application	Hydrogen Fluoride + chlorinated chemicals.	Zero ozone depletion potential (ODP).	High to very high GWP.	Enforcement of the Kigali Amendment of the Montreal Protocol. GWP>150 F-gases are banned.
Hydrofluoroolefins (HFOs)	Mobile air conditioning (HFO-1234yf); HFO-1336mzz(Z) in refrigeration and air conditioning R-513A in food refrigeration.	Similar efficiency as HFCs, drop-in available	High (19-23 $/kW CC)	Hydrogen fluoride + HFCs. Requires carbon tetrachloride and CFCs for precursor manufacturing.	Low GWP.	PFAS-related pollution HFC-23 (GWP=14800) decomposition products. Moderated flammability.	Essential use and recycling policy
Hydrochlorofluoro-olefins (HCFOs): R-1233zd(E)	Cold storage, ice rinks, and industrial air conditioning (new equipment only); industrial refrigeration (new and retrofit)	Similar efficiency as HFCs, drop-in available	High (23-44 $/kW CC)		Lowest GHG potential halogenated alternative.	Toxicity concerns and moderated flammability. Water crystallization pipe clogging. Very persistent pollutant.	Essential use and recycling policy
Water (R-718)	Large scale HVACR equipment.	Still under development.		Water purification	Non-toxic. GWP=0.	Expensive equipment.	Driving design innovation

Safer alternative · Feasible, but finding an alternative is recommended
Seldom used or mostly unfeasible at the moment · Avoid use, phasing out

* Costs are shown in $/kW cooling capacity, including refrigerant charge and power consumption.
See Table 10 above for equipment prices across domestic (<20kW), commercial (20-350kW), and industrial (>350kW) applications.

Rigorous and holistic evaluations of the environmental performance of non-F-gas refrigeration technologies increasingly illustrate the economic and social benefits of such technologies. For example, the greenhouse gas-related societal costs of F-gas refrigerants are significantly higher than their expected profitability. While F-gas manufacturing relies on highly hazardous chemicals such as carbon tetrachloride (CTC) and perchloroethylene (PCE), alternative refrigerants offer significant upstream and downstream environmental benefits. Non-fluorinated refrigerants are expected to have a lower Life Cycle Impact (LCI), with specific sustainability benefits emerging across multiple impact categories including reduced climate impact of CO_2 systems through energy-efficient designs[4], decreased eutrophication potential from low-charge ammonia systems[5], lower carbon footprint from novel ammonia production methods[6,7], and minimized fossil fuel dependency through bio-based hydrocarbon production[8].

The net climate benefits of phasing down HFCs are substantial[9]. According to the U.S. EPA, the greenhouse gas-related social costs of HFCs, HFOs, and their blends are significantly higher than their expected profitability[10,11]. Given the increasing technical and economic feasibility, as well as their socio-economic benefits, governments and businesses should do more to promote and actively pursue the adoption of safer alternatives to F-gas refrigerants. Otherwise, the phase-down of HFCs will be yet another instance of regrettable substitution, leading to further harm to human health and the environment.

The technical and economic feasibility of non-fluorinated HVACR has translated to instances of customer adoption for certain applications. Some HVACR equipment manufacturers plan to convert their sales portfolio to fully F-gas free by 2027[1,12]. In the United States, CO_2, HC, and cascade HC/CO_2 commercial refrigeration systems are increasing. Grocery retailers are investing in non-fluorinated refrigerant-based HVACR as an effective way to achieve GHG emission goals,[13,14] while avoiding potential liabilities related to using F-gas refrigerants.

Technical innovations have overcome initial adoption barriers for non-F-gas refrigerants:

- Transcritical CO2 (R-744) shows promising prospects for commercial refrigeration, including supermarkets[15,16].
- Heat recovery systems that provide sanitary water heating can enhance CO2 refrigeration systems in large food storage facilities[17,18].
- Numerous manufacturers[19,20] and commercial operators[12,21] have successfully switched to halogen-free HC/CO2 cascade equipment.
- Novel ULC Ammonia (R-717) designs fulfill cooling capacity demands while reducing, though not eliminating, liabilities related to toxicity and eutrophication[5,22].
- The latest safety standards show a growing acceptance of flammable refrigerants for commercial and industrial applications, enabling indoor adoption of hydrocarbons[23,24].

Some industry projections suggest that non-F-gas systems are projected by technical reports to gain substantial market share in commercial and industrial refrigeration1 by 2036, though this timeline may not reflect the urgency required to address climate and environmental health concerns. Without accelerated policy intervention, F-gas emissions will continue to cause significant damage to public health over the next decade.

New equipment working with safer refrigerants provides increased efficiency and compliance with safety standards[12,19,25,26]. Switching to new equipment also avoids the limitations and inefficiencies of upgrading existing refrigeration systems to use HFC/HFO blends (retrofitting), which is a common short-term fix but not a long-term solution. Recent precautionary policy on F-gases[1,27,28] and PFAS[29–31] are expected to further limit the supply of F-gases. Furthermore, retrofitted HVACR equipment generally demonstrates lower efficiency compared to the latest models, which contributes to unnecessary indirect carbon emission[32].

Given recent technological progress and proven instances of successful adoption, it is feasible to completely transition from F-gas refrigeration systems to alternative, non-halogenated, non-PFAS refrigerants. Purpose-built systems utilizing CO_2, hydrocarbons, and low-charge ammonia have demonstrated success in commercial, industrial, and residential applications. For instance, transcritical CO_2 systems are used in supermarkets, hydrocarbon refrigerants are found in residential refrigerators, and there are standalone commercial refrigeration units and heat pumps. Redesigned ammonia systems have significantly reduced refrigerant charge volumes while maintaining the high performance required by large scale industrial applications.

1. Goals and Objectives

As companies worldwide consider their course of action in response to potential legislative and regulatory restrictions on their use of HFC and PFAS products, it is important to provide holistic and objective information about available alternatives and updated refrigeration schemes. The information found in this report is intended to advise commerce, manufacturing operations, and governments on HVACR decisions. It can also inform residential customers seeking more sustainable HVACR solutions.

The assessment compares the availability, safety, effectiveness, and affordability of alternative refrigerants to HFCs following the framework set by the U.S. National Research Council for identifying and evaluating safer alternatives[33]. This approach is essential for making informed decisions to improve the sustainability of HVACR systems.

1.1 – Scope of this study

This report examines alternatives to legacy hydrofluorocarbon gases (HFCs) and emerging low-GWP alternatives across fluorinated and non-halogenated options used in vapor compression air conditioning, refrigeration, and heat pumps. While HFCs have applications beyond refrigerants, including aerosol propellants, foam-blowing agents for insulation, heat transfer liquids in industrial processes, and as precursors in the synthesis of certain PFAS[34], this report focuses on alternatives for HFC refrigerant gases. Our aim is to provide stakeholders with information on feasible alternatives to help in making decisions regarding the adoption of effective and affordable refrigerants that are safer over their life cycles for human health and the environment.

The report analyzes approved refrigerants listed under Rule 26 of the U.S. EPA's SNAP (Significant New Alternatives Policy), specifically targeting replacements for very-high-GWP HFCs: HFC-32, HCFO-1233zd, HFO-1234yf, HFO-1234ze(E), CO_2 (R-744), HC-600, HC-290, and HC-1150. Data from 14 legacy HFCs and 5 emerging HFOs are included as reference points to establish assessment benchmarks. Ammonia (R-717), a widely used incumbent refrigerant, is included in the assessment, while water (R-718), HC-1270, and HC-170 are considered for their potential future applications.

We examine these refrigerants through a comprehensive lens encompassing environmental, human health, performance and economic dimensions. The analysis extends to environmental justice and socioeconomic implications throughout their life cycle, including performance metrics, implementation costs, and potential economic benefits.

- Section 2 compares environmental impacts, ozone depletion potential, contribution to photochemical smog, and water pollution along with both acute and chronic human health hazards and Environmental Justice (EJ) .
- Section 3 explores the technical feasibility of alternative refrigerants to HFCs, capturing the current refrigerants market, including prevailing conditions and emerging patterns in residential, mobile, commercial, and industrial applications.
- Section 4 assesses the socioeconomic aspect of alternative refrigerant adoption, comparing alternative refrigerants to HFCs that are currently relevant in the market.
- Section 5 provides concluding remarks and lists research directions toward safer refrigeration systems. This assessment does not, however, constitute an endorsement or recommendation of any HVACR product, service, or provider.

1.2 – Study methodology

This study leverages information on refrigeration technology currently available in the market, obtained from various sources including government databases, industry reports, patents and applied research literature from refrigeration and chemistry journals. The information gathered is cross-referenced with current data on the Environmental, Health and Safety (EHS) hazards of chemicals and Environmental Justice (EJ) concerns. The report examines the following criteria for HFC alternatives:

- Environmental impact (Sections 2.1 and 2.2): Metrics include ODP, GWP, and Photochemical Ozone Creation Potential (POCP) as well as hazards related to ecosystem disruption, persistence, mobility, and bioaccumulation.
- Human health hazards (Sections 2.3 and 2.4): Fire safety, acute toxicity, carcinogenicity, reproductive toxicity and endocrine disruption are comprehensively assessed using the Safer Chemicals Assessment Framework[33] and the TURI Pollution Prevention Options Analysis System (P2OASys)[35].
- Transportation and end-of-life management (Section 2.5): Includes a qualitative comparison of the transportation and end-of-life management requirements.
- PFAS pollution (Section 2.6): The pervasive nature of PFAS and their long-term public health implications warrant special attention in the assessment process.
- Environmental Justice (Section 2.7): Considers whether the production, use, or disposal of an alternative refrigerant could cause disproportionate harm to low-income fence line communities.
- Technical feasibility (Section 3): Performance metrics are defined in Section 3.1. Compatibility with existing refrigeration systems (drop-in substitutes) versus adopting newer equipment is compared for residential, commercial, mobile, and industrial applications.
- Economic feasibility (Section 4): Includes availability, cost, efficiency, and market potential, as well as the long-term economic impacts of climate change and the need for sustainable solutions.
- Comparative analysis (Section 5): The report concludes with a comparative evaluation of the overall performance across the environmental, human health, socioeconomic, and economic dimensions.

1.3 – Study limitations

This assessment evaluates the benefits and hazards of drop-in alternatives approved under the latest U.S. Environmental Protection Agency (EPA) Significant New Alternatives Policy (SNAP) program. These alternatives are intended to replace incumbent halogenated refrigerants such as HCFC-22, HCFC-124, HFC-134a, and HFC-152a. It's worth noting that some of these replacements can also function as direct substitutes for existing F-gas-based blends (e.g., R-407C, R-410A and R-404A), also being phased out.

The assessment evaluates non-halogenated alternative refrigerants, such as carbon dioxide and ammonia, and selected hydrocarbons identified as SNAP-approved options. It is important to note that non-halogenated alternatives are generally not drop-in substitutes for HFCs. Adopting non-halogenated refrigerants to replace the use of HFCs typically requires purchase of new equipment and infrastructure, introducing additional costs and operational considerations. This report emphasizes the importance of carefully considering refrigerant characteristics and equipment design for optimal system performance. The vast array of existing HVACR equipment, however, makes an exhaustive analysis impractical. The assessment therefore focuses on the key criteria for evaluating potential HFC alternatives, balancing environmental, health, socioeconomic, and economic factors.

This report focuses on refrigerants recently approved under the latest EPA-SNAP rules. However, it is worth acknowledging that several refrigerants were approved and then rejected within the history of the SNAP program. As we specifically want to understand the fundamental properties of component refrigerants, we have not analyzed most blends individually in this assessment. In many cases, the individual component refrigerant properties are often more informative and available than when blended. Nevertheless, we encompass the latest EPA-SNAP-approved refrigerant blends (Rule 26, first approved in May 2023 and amended in June 2024) to provide a complete picture of currently accepted alternatives. The type of hazard criteria discussed in this study can be extended to the full list of EPA-SNAP-approved refrigerants[36] (single component and blends). Appendix I provides a detailed list of single-component refrigerants on the EPA-SNAP list.

This report prioritizes key criteria for refrigerant selection with an emphasis on practical considerations for stakeholders. While a quantitative life cycle assessment falls outside the scope of this work, we do qualitatively compare important aspects across a refrigerant life cycle, such as manufacturing, transport, and end-of-life implications. This includes EJ considerations (e.g., potential impacts on nearby communities) during manufacturing. Additionally, the environmental degradation products of each refrigerant are evaluated to understand their potential ecological consequences.

The data used in this study was accessed before November 2024. The technical and economic market landscapes are volatile — technology efficiencies and prices change with time. Sections 3 and 4 discuss the technical and economic feasibility of safer refrigerants and the most relevant research and development regarding their Market Readiness Level (MRL) and expected economic benefits. Future prospects briefly mentioned in Section 5.2 include optimization of HVACR equipment, sustainable building design, and solid-state-based refrigerant-free technologies. Although a detailed discussion of these actively developing innovation lines is beyond the scope of this report, the reader is encouraged to explore the cited references for further information.

1.4 – Evolution of policies affecting refrigerants

HVACR is critical in maintaining comfortable environments for homes, businesses, vehicles, and industrial facilities. These systems are essential for preserving food and medicine, regulating temperatures in hospitals and data centers, and enabling various manufacturing processes. Refrigerants are essential working fluids for vapor compression technology applied in countless refrigeration, air conditioning, and heat pumps. This assessment compares the human health, environmental, economic, and social impact of emerging refrigerants in light of current trends in environmental protection policy.

The history of refrigerants provides a cautionary example of the unintended consequences of prioritizing narrow performance metrics at the expense of broader environmental and health considerations. This is particularly relevant when developing technologies or creating policies. HVACR systems at around the beginning of the 20th century relied on non-halogenated refrigerants like carbon dioxide (CO_2), ammonia (NH_3), and hydrocarbons (HCs), but efficiency and safety concerns due to toxicity and flammability prompted the search for alternatives. The industry then started using chlorofluorocarbons (CFCs) as refrigerants in the early 1930s for their desirable properties of chemical stability, low acute toxicity, cooling capacity, efficiency, and relatively low cost. However, CFCs remain in the atmosphere for many years, still causing damage to Earth's stratospheric ozone layer and climate[37]. This is a paradigmatic example of a "regrettable substitution": A problematic chemical is replaced with another chemical or technology, but upon further investigation, it is revealed that the alternative is no safer than the original chemical.

By the end of the 20th century, the primary concern with halogenated refrigerants was their Ozone Depletion Potential (ODP). The Montreal Protocol successfully led to a significant reduction in the use of Ozone-Depleting Substances (ODS)[38]. CFCs and hydrochlorofluorocarbons (HCFCs) were the primary chemicals that the first version of the Protocol banned for use as refrigerants, foam-blowing agents, and aerosol propellants. This ban was also a significant benefit for the climate, as both CFCs and HCFCs have an extremely high GWP, thousands of times higher than CO_2. Afterward, global refrigerant users turned to HFCs and a few HCFCs as low- or zero-ODP drop-in replacements for CFCs. Their performance was comparable, and this change required minimal retrofitting of existing HVACR equipment. However, HFCs and HCFCs proved to be regrettable substitutes for CFCs as they also have high GWPs.

1.4.1 – The Kigali Amendment to the Montreal Protocol

The impact of fluorinated gas (F-gas) emissions on climate led to a globally recognized need to amend the Montreal Protocol for an 85% global phase-down of HFCs by 2050. This amendment was adopted in Kigali, Rwanda, in 2016 and entered into force in 2019. The Kigali Amendment is being implemented in phases. Developed countries began to reduce their overall F-gas production and consumption and HFC production in 2019; developing countries began to reduce their HFC consumption in 2024. Meanwhile, the global market for refrigeration continues to grow rapidly, with an estimated 1.3 and 4.5-fold increase in HVACR demand by 2050 for the Organization for Economic Cooperation and Development countries (OECD) and non-OECD countries, respectively[25]. Regional, national, and international commitments to reducing greenhouse gas (GHG) emissions created big market opportunities for innovative refrigeration technologies. Numerous governments have taken or are considering measures that may affect the use of F-gases, with positive and negative implications for both climate change and human health.

1.4.2 – U.S. regulations on refrigerant gases

The US-EPA established the SNAP program in 1990 to implement section 612 of the Clean Air Act (CAA)[‡], allowing and banning the use of certain gases for the protection of the ozone layer while evaluating new CFCs and HFCs substitutes[39]. The information required for a new substitute chemical submission under the EPA-SNAP program includes[40]:

- **Name and description of the substitute:** The substitute should be identified by its chemical name, trade name(s), identifiers, chemical formula, and chemical structure.
- **Physical and chemical information:** The substitute should be characterized by its key properties, such as molecular weight, melting point, boiling point, density, odor threshold, solubility, partition coefficients, atmospheric lifetime, reactivity, and vapor pressure.
- **Substitute applications:** The applications within each sector end-use in which the proposed substitute is likely to be used should be identified.
- **Process description:** Descriptive data on process conditions, including in-place pollution controls, are required for each application identified.
- **Ozone depletion potential:** The predicted ODP of substitute chemicals, relative to CFC-11, including supporting documentation or references, is required to be submitted.
- **Global warming impacts:** The GWP must be calculated over a 100-year integrated time horizon under Intergovernmental Panel on Climate Change Fourth Assessment Report (Working Group 1 - Chapter 2) definition[41,42], relative to CO_2. Atmospheric lifetime is also required to be submitted.
- **Flammability:** The flash point and flammability limits are required, along with the procedures used for determining the flammability limits and equipment design for fire mitigation measures.
- **Toxicity data:** Information on the effects of its components, its impurities, and its degradation products on any organism (e.g., humans, mammals, fish, wildlife, and plants). Human acute irritation and genetic endpoints are specifically required. Other toxicity endpoints and ecotoxicological information are optional.
- **Environmental fate and transport:** Considered useful for database completion but not required. Such data includes information on bioaccumulation, biodegradation, adsorption, volatility, environmental fate, and other data necessary to characterize the transport and reaction of substitutes in the environment.
- **Exposure data:** Available modeling or monitoring data on exposures associated with the manufacture, formulation, transport, use, and disposal.

‡ CAA Section 612(c) key points:

- EPA must ban the use of substitutes for class I (halocarbon gases containing chlorine and bromine) or class II (HFCs) substances posing EHS risks if there is an alternative that is safer and available.
- EPA must publish lists of acceptable and unacceptable substitutes for specific uses.
- Anyone can petition EPA to add or remove a substance from the SNAP list.
- Producers of chemical substitutes for class I substances must notify EPA 90 days before commercialization.
- Producers must also provide EPA with unpublished health and safety studies on proposed substitutes.

  More information at: https://www.govinfo.gov/content/pkg/USCODE-2013-title42/html/USCODE-2013-title42-chap85-subchapVI-sec7671k.htm

- **Environmental release data:** Data on emissions from the substitute application and equipment and pollutant releases or discharges to the environment are not mandatory but encouraged to be submitted.
- **Replacement ratio for a chemical substitute:** Information on the replacement ratio for a chemical substitute versus class I (ODP > 0.2) or class II (non-zero ODP < 0.2) substances being replaced.
- **Required changes in application technology:** Details on the changes in technology needed to use the alternative should be submitted. Such information should include a description of whether the substitute can be used in existing equipment—with or without some retrofit—or only in new equipment.
- **Cost of substitute:** Data on the expected average cost of the alternative.
- **Availability of substitute:** If it is not currently available, the timing for availability should be provided.
- **Anticipated market share:** Data on the anticipated near-term and long-term U.S. nationwide sales.
- **Applicable regulations under other environmental statutes:** Information on whether the substitute is subjected to other regulations, in particular the Clean Water Act (CWA) and the Clean Air Act (CAA), Safe Drinking Water Act, the Resource Conservation and Recovery Act, the Federal Insecticide, Fungicide, and Rodenticide Act, the Toxic Substances Control Act, the Comprehensive Environmental Response, Compensation and Liability Act, and the Emergency Planning and Community Right-to-Know Act, among other titles.

Submitters must provide sources and documentation for all submitted data to allow verification. Independent testing is not required. Submission data may be claimed as confidential, but the EPA reviews confidentiality claims to determine if the information meets the criteria for nondisclosure. Toxicological data submission is not necessary if a refrigerant is listed in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 34 and if Occupational Exposure Limits (OELs) have been established.

Following the Kigali Amendment, the American Innovation and Manufacturing (AIM) Act[43], enacted by the U.S. Congress in 2020, authorized the EPA to phase down 85 percent of HFC consumption stepwise by 2036. In response to this commitment, the EPA has issued several rules that have phased out the use of certain F-gas refrigerants based on their GWP level. As a result, there is a growing shift towards the use of low-GWP refrigerants, such as HFOs, CO_2, ammonia (NH_3), and hydrocarbons (HCs).

According to the OECD, low-GWP refrigerants are those with a GWP of less than 150. Under SNAP Rules 22 to 26, EPA has approved several low-GWP zero-ODP alternative refrigerants for residential, commercial, and industrial HVACR equipment, and mobile air conditioning (AC) units. Difluoromethane (CH_2F_2; HFC-32) is the only SNAP-approved HFC as a substitute for higher GWP HFCs in “difficult-to-place” industrial equipment. From May 1, 2023, Rule 26 of EPA-SNAP listed eleven refrigerants as acceptable[44] low-GWP substitutes (subject to use conditions) to HFCs for refrigeration and air conditioning: HFOs (HFO-1234yf and HFO-1234ze(E)), HFO/HFC blends (R-454A; R-454B; R-454C; R-455A; R-457A; R-516A) and propane (HC-290). Ethene (HC-1150) is reserved for Ultra Low Temperature (ULT) refrigeration[44].

1.4.3 – EU regulations on refrigerant gases

On the 1st of January 2022, the EU banned F-gas refrigerants[45] with a GWP integrated over 100 years (GWP100) higher than 150, relative to CO_2. The European Union (EU) has committed to reducing greenhouse gas emissions by 80-95% below 1990 levels by 2050. This includes a 70-78% reduction in non-CO_2 emissions[46], such as those from F-gases. Moreover, the EU recently updated its F-gas regulation in February 2024 (Regulation EU 2024/573)[47] to impose stricter controls on fluorinated greenhouse gases, particularly HFCs, including a faster phase-down schedule, bans on high-GWP refrigerants in new and existing equipment, enhanced recovery and recycling, increased focus on technician training, and stricter market surveillance. These measures aim to reduce greenhouse gas emissions and promote climate-friendly alternatives following the Kigali Amendment to the Montreal Protocol. To meet the dictated CO_2 emission savings requirements, the EU F-gas import cap severely restricts the import of HFCs for industrial retrofits[45].

1.4.4 – Intersection with PFAS policies

In addition to HFC restrictions, the use of HFOs are being scrutinized in Europe as part of the broad class of per and polyfluoroalkyl substances (PFAS)[48,49]. PFAS is a group of more than 7 million fluorinated chemicals[50], of which only about 14,000 are listed in EPA's CompTox Database[51]. PFAS are synthetic persistent pollutants[49] and systemic toxicants[52,53] associated with various health issues, including endocrine disruption[54–56], cancer[57,58], developmental disorders[54,59], pregnancy-related problems[60], and immune system dysfunction[59,61].

Many PFAS are included in the EU Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Candidate List of Substances of Very High Concern (SVHCs) because they are carcinogenic, mutagenic, and reprotoxic (CMR), and persistent, bio accumulative, and toxic (PBT) or very persistent, very bio accumulative and toxic (vPvBT) substances[62]. Many discrete, non-polymeric PFAS have high mobility[63], allowing them to be transported long distances from the source. When it rains, PFAS are washed from the land, polluting drinking water[64–66] and fish[67]. Bioaugmentation of PFAS leads to dietary exposure[68] and accumulation in human blood[57,69–71] that exceeds safety thresholds.

The EPA and the OECD have differing definitions of PFAS[72,73]. The OECD PFAS definition[74] is broader, including any chemical with more than one carbon with at least one perfluorinated methyl ($-CF_3$) or perfluorinated methylene ($-CF_2-$) group. The EPA Toxic Substances Control Act (TSCA) PFAS definition[75] is narrower, encompassing only substances with two adjacent carbon atoms, one fully fluorinated and the other partially fluorinated. The European Chemicals Agency (ECHA) recently published a long list of PFAS proposed for REACH restriction[76], using the OECD definition. This list included commercial HFOs, such as HFO-1234yf and HFO-1234ze(E), two major components of the low-GWP blends deemed acceptable by EPA under the SNAP program.

HFC and HFO production involves using the same building blocks for the production of PFAS, such as fluorine, hydrofluoric acid (HF), carbon tetrachloride (CTC), CFCs, and perchloroethylene (PCE)[77,78], generating short and medium-chain PFAS as by-products[79]. Moreover, many F-gases are short-chain PFAS and can transform into other PFAS after reacting with sunlight and water. Currently, EPA-SNAP approved F-gases are not listed as PFAS following the EPA definition but are classified as PFAS by internationally accepted definitions[76,80,81].

2. Environmental, human health, and safety hazards

Refrigerants are released into the environment from venting at the production and fractionation stages as well as from HVACR equipment manufacturing, assembling, installation, use, and decommissioning. Leakage from disposal of manufacturing, use, and improper equipment operation contaminates soil and freshwater sources with refrigerants and their related by-products or degradation products. The extent of their impact on workers, consumers, climate, the ozone layer, and ground-level smog formation depend upon their chemistry. Refrigerants can have broader environmental impacts beyond their primary function in cooling systems. Their effects may extend to public health, water resources, and soil quality, depending on the inherent biodegradability of the original refrigerant compounds as well as the nature of any partial degradation byproducts that may form[37]. The specific environmental implications can vary considerably based on the refrigerant formulation and the local environmental conditions.

2.1 – Atmospheric hazard comparison

The primary atmospheric environmental impacts associated with refrigerant emissions can be categorized into the following key areas of concern:

- The **Ozone Depletion Potential (ODP)** of a Volatile Organic Compound (VOC) represents its ability to form reactive species that contribute to the depletion of the stratospheric ozone layer. Ozone-depleting substances (ODS) react with stratospheric ozone, reducing its protective effect against UV radiation. The ODP reference compound is CFC-11 (ODP=1). Due to the implementation of the Montreal Protocol, most modern SNAP-approved refrigerants have zero ODP, except for HFC-152a and its blends.
- Photochemical Smog Formation: VOCs can react with sunlight to form ground-level ozone[37], contributing to smog. This is measured by **Photochemical Ozone Creation Potential (POCP)**[82]. The reference substance for relative POCP is ethene, with a value of 100. While most refrigerants have low POCP compared to other VOCs, they're not zero like CO_2 or water. Ground-level ozone can cause or intensify existing respiratory problems[83] and crop damage[84]. Applied research literature provides well-characterized POCP values for common VOCs, including low-GWP refrigerant gases[85–87].
- Climate hazard is typically measured by **Global Warming Potential (GWP)**[42], which quantifies a substance's climate impact relative to carbon dioxide over 100 years. GWP factors in a compound's ability to absorb infrared radiation and its atmospheric lifespan. Related metrics such as Total Equivalent Warming Impact (TEWI) and Life Cycle Climate Performance (LCCP) offer a more holistic but complex assessment[88], encompassing energy use and emissions throughout a refrigerant's life cycle[89–91]. Particularly, F-gases contribute to climate change through the following life cycle hazards:
    - ◊ High GWP F-gas emissions: Fluorinated gases, including many incumbent refrigerants, are the fastest-growing cause of climate change[92]. F-gases account for 1-2% of global greenhouse gas emissions[93,94] but could contribute to 25% of excess global warming by 2050 if their use remains unchecked[37]. This underscores the importance of proper regulation, handling and disposal of refrigerants.

◊ The concept of "average GWP", when the components are weighted by mass percentage of their GWPs, can be misleading as it downplays the fact that some gases in a blend may have a much higher GWP than others, and it does not avoid the release of high-GWP gases into the atmosphere, even if the overall GWP of the blend is relatively low. For industrial equipment retrofitting, the GWP threshold is set at 700 for higher-GWP HFC equipment manufactured or imported before January 1, 2025, to be installed until January 1, 2026[95].

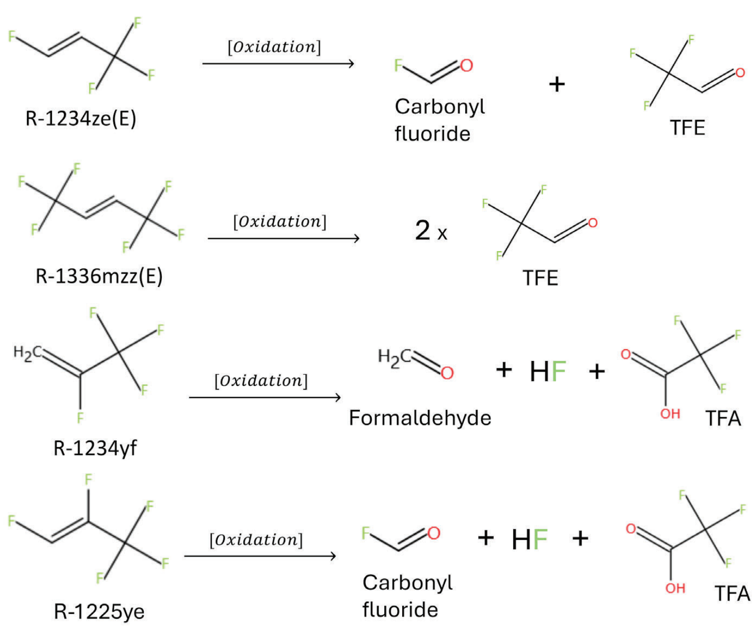
◊ HFO degradation products: HFOs can potentially degrade in the atmosphere into trifluoromethane (HFC-23; GWP=14800)[96,97]. Even small conversion rates to HFC-23 could significantly increase the effective GWP, potentially undermining their intended environmental benefits.

Rule 26 of EPA-SNAP approves commercializing F-gas refrigerants, including HFC-32, two HFOs (HFO-1234ze(E) and HFO-1234yf), and six HFO/HFC blends: R-454A, R-454 B, R-454C, R-455A, R-457A, and R-516A. Although the SNAP-approved HFO/HFC blends present a mass-averaged GWP below regulatory thresholds for their intended application, their composition incudes high-GWP HFC refrigerants.

The annual emission rate is highly dependent on the equipment type and maintenance status. The product of the GWP and the atmospheric lifetime are simple but comprehensive metrics that help us understand and compare climate impact among refrigerants. Moreover, GWP and atmospheric lifetimes are available in the scientific literature[98,99].

Current GWP calculations, however, omit life cycle impacts from precursor chemicals or breakdown products. In atmospheric conditions, HFOs are prone to degradation (Figure 1) by reaction with atmospheric Reactive Oxygen Species (ROS)[37,100–102], such as ozone, hydroxyl radical (HO•), and HO2 or nitrogen oxides, to form trifluoro ethanal[37] (TFE; trifluoro acetaldehyde) or trifluoroacetic acid

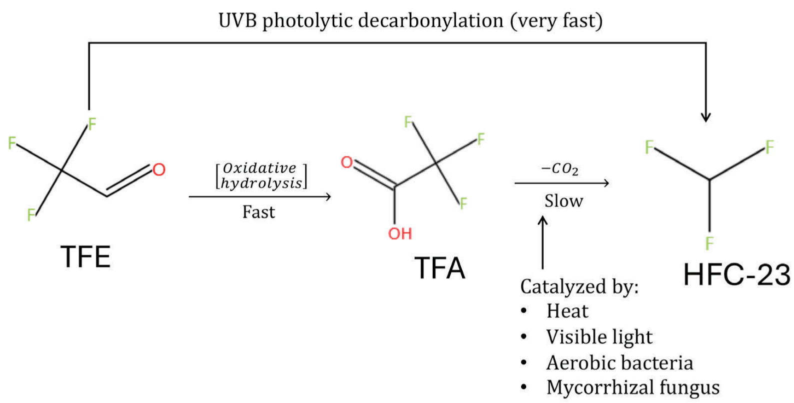
FIGURE 1
Primary degradation pathways of HFO refrigerant gases.



(TFA), depending on the relative position of the carbon-carbon, carbon-fluorine and carbon-hydrogen bonds. TFE promptly decomposes (Figure 2) into trifluoro methane (fluoroform, HFC-23; GWP=14800) by photolytic decarbonylation[97,103–106] or into TFA by hydrolysis followed by oxidation[100,107]. Although TFA is well known for its chemical stability, it can degrade over time. Reactions with water and sunlight result in a slow TFA to HFC-23 conversion that might be significant over a 100-year time window[96,108]. The self-decomposition path for transforming TFA into HFC-23 in water can be decarboxylation through reaction with visible sunlight (overtone dissociation)[100,108,] or via thermal reaction with water (hydrolysis)[109,110] induced by heat. Oxic biodegradation of TFA mediated by aerobic microbiota[111,112] and mycorrhizal fungi[113] also leads to the formation of HFC-23. Figure 2 summarizes the secondary breakdown reactions of TFE and TFA.

FIGURE 2

Secondary degradation pathways of HFOs. An outstanding environmental fate product of HFO refrigerants is the superpollutant HFC-23 (GWP=14800).



Adapted from references: 37, 96, 97, 100, 104, 106-109, 111, 113, 114

Other HFOs can yield HFC-23 via the TFA decomposition pathways described in Figure 2, leading to a GWP contribution that potentially exceeds regulatory thresholds. Although the atmospheric fate complexity of HFOs makes it difficult to state the exact contribution of HFC-23 production to their GWP, if there is more than 1.2% likelihood of forming HFC-23 (GWP100=14800), HFOs would have a GWP higher than regulatory thresholds, undermining climate change mitigation objectives and contradicting "low GWP" claims for HFOs.

Potential Climate Impact of HFO Degradation Products

To give an example on the environmental fate impact on the effective GWP of an HFO, TFE is formed in 100% molar yield from the atmospheric decomposition of HFO-1234ze(E)[37], while HFO-1336mzz(E) yields two molecules of TFE, a 200% molar yield. TFE has such a short atmospheric lifetime that its GWP can be considered zero. However, Campbell et al. (2021)97 confirmed that TFE can undergo a very fast photo-dissociation in the lower atmosphere to produce HFC-23 and carbon monoxide, potentially delivering HFC-23 in up to 17% yield[96]. This conversion potentially contributes a GWP up to 2516 for HFO-1234ze(E), which produces one TFE molecule that can produce HFC-23 with up to 17% yield, or a potential 5032 GWP contribution for HFO-1336mzz(E), with the doubled value reflecting its production of two TFE molecules. These values are derived from the 17% conversion rate to HFC-23 multiplied by HFC-23's high GWP, taking into account the number of TFE molecules produced. However, as this process depends upon sunlight and other competing atmospheric reactions, the effective GWP contribution is uncertain. The additional GWP introduced by HFC-23 production could go from 100 to 14800 considering all potential pathways[96].

2.2 – Persistence, Bioaccumulation and Eutrophication

For persistent organic pollutants like PFAS, the longer these substances remain in the biosphere, the greater their potential to amplify their concentration through the food chain (bioaccumulation). This can lead to known and unknown adverse effects, potentially on the planetary scale[115], as persistent chemicals are transported long distances. HFCs and HCFCs can last between 1 and 127 years in the atmosphere[116] and are not readily soluble nor biodegradable in water[117]. Table 1 and Table 2 allow the reader to compare halogenated and non-halogenated refrigerants' main environmental hazard metrics, respectively.

HFOs have a short atmospheric lifetime, but their final degradation product is mostly TFA, which is an eminently synthetic rather than naturally occurring molecule[101,118], and is gaining recognition as contaminant of emerging concerns[119,120]. TFA readily dissolves in water, forming the TFA anion, with a high solubility that minimizes sorption to sediments. The TFA anion is persistent and mobile in soils and water[121] contaminates drinking water resources, resists most water treatment methods[122] and accumulates in plants[122,123]. Ice core records show that freshwater TFA first appeared in 1990, which coincides with the introduction of HFCs[124]. A recent surge in TFA levels in drinking water is linked to the use of HFOs[125–127]. Moreover, high levels of TFA were found in human blood[69,128] with potential effects on glucose metabolism[129]. It is worth recalling that HFCs degrade into TFA[100] at a slower yet inevitable rate compared to HFOs.

Ammonia and carbon dioxide, on the other hand, are biodegradable, although ammonia is known to promote eutrophication[130,131] if released in large quantities into water bodies. Hydrocarbons have varying levels of biodegradability and require specific environmental conditions for degradation, which makes it difficult to consistently categorize them as PBT substances across regulatory agencies. Saturated HCs biodegrade sufficiently slowly to be considered persistent by the Canadian Domestic Substance List[132] but are not considered as PBT by ECHA or EPA.

TABLE 1
Relevant environmental hazard metrics of most common single-component halogenated refrigerants.

Denomination	Chemical class	CAS No.	GWP100	ODP	POCP	Atmosphericlifetime(y)	PBT or vPvBT	SNAP approved
HFC-134a	HFC	811-97-2	1430	0	0.1	13.4	vPvBT	In blends
HCFO-1233zd	HCFO	102687-65-0	1	3·10-4	3.9	0.07	Yields TFA	No
HFO-1336mzz(E)	HFO	66711-86-2	2	0	3.1	0.07	Yields TFA	No
R-1130(E)	t-DCE	156-60-5	25	2.4·10-4	34	5	vPvBT	No
HCFC-123	HCFC	306-83-2	77	0.04	N/A	1.3	vPvBT	No
HCFC-124	HCFC	2837-89-0	470	0.02	N/A	5.9	vPvBT	No
HFO-1336mzz(Z)	HFO	692-49-9	1030	0	3.1	0.07	Yields TFA	No
HCFC-22	HCFC	75-45-6	1810	0.06	0	11.9	vPvBT	No
HCFC-142b	HCFC	75-68-3	1980	0.07	0	17.2	vPvBT	No
HFC-125	HFC	354-33-6	3450	0	0	28.1	vPvBT	No
HFC-227ea	HFC	431-89-0	3500	0	0	38.9	vPvBT	No
HFC-143a	HFC	420-46-2	3800	0	0	47.1	vPvBT	No
HFC-23	HFC	75-46-7	14800	0	0	270	vPvBT	No
HFO-1234ze(E)	HFO	29118-24-9	1	0	5.6	0.05	Yields TFA	Yes
HFO-1234yf	HFO	754-12-1	4	0	7	0.03	Yields TFA	Yes
HFC-152a	HFC	75-37-6	124	0.07	1	1.5	vPvBT	Yes
HFC-32	HFC	75-10-5	675	0	0.2	5.2	vPvBT	Yes

Concerning features are highlighted in red. Acronyms: CAS registry number is used to uniquely identify chemical substances; GWP100: Global Warming Potential over 100 years; ODP: Ozone Depletion Potential; PBT: Persistent, Bioaccumulative and Toxic; POCP: Photochemical Ozone Creation Potential; SNAP: Significant New Alternatives Program (US-EPA).

TABLE 2
Relevant environmental hazard metrics of most common single-component halogen-free refrigerants.

Denomination	Chemical class	CAS No.	GWP100	ODP	POCP	Atmospheric lifetime (y)	PBT	SNAP approved
HC-600	Saturated HC	106-97-8	7	0	30	0.01	Uncertain	In blends
R-718	Water	7732-18-5	0	0	0	0	No	Yes
R-E170	Dimethyl ether	115-10-6	1	0	17	0	No	N/A
HC-1270	Olefin	115-07-1	2	0	160	0	No	No
HC-170	Saturated HC	74-84-0	6	0	9	0.12	Uncertain	No
R-717	Ammonia	7664-41-7	0	0	0	0	No	Yes
R-744	Carbon dioxide	124-38-9	1	0	0	5 to 200	No	Yes
HC-290	Saturated HC	74-98-6	3	0	13	0.03	Uncertain	Yes
HC-600a	Saturated HC	75-28-5	3	0	28	0.02	Uncertain	Yes
HC-1150	Olefin	75–85–1	4	0	100	0	No	Yes

Concerning features are highlighted in red. CAS registry number is used to uniquely identify chemical substances; GWP100: Global Warming Potential over 100 years; ODP: Ozone Depletion Potential; PBT: Persistent, Bioaccumulative and Toxic; POCP: Photochemical Ozone Creation Potential; SNAP: Significant New Alternatives Program (US-EPA).

2.3 – Environmental, human health, and safety evaluations

The SNAP program was established under the Clean Air Act for EPA to evaluate substitutes for ODS. It is a comparative risk assessment program that considers some atmospheric, human health, and fire hazards. However, it does not encompass a life cycle analysis and overlooks environmental and public health threats such as end-of-life PFAS pollution.

As described in Section 1.4.2, under the SNAP program, the EPA requires submitting information covering substitute names, applications, physicochemical properties, operational work conditions, ODP, GWP, flammability, availability, cost, human acute toxicity, carcinogenicity, and genetic toxicity. Chronic human health impacts, environmental fate, bioaccumulation, and transport are optional in the SNAP substitute submission form. While these guidelines are established to protect the stratospheric ozone layer, EPA-SNAP use approval for a refrigerant in one or more applications should not be considered a comprehensive EHS evaluation.

ASHRAE safety classifications primarily focus on flammability standards and one health hazard metric, the Occupational Exposure Limit (OEL). However, the OEL does not capture all potential health risks associated with a refrigerant. While ASHRAE and EPA-SNAP effectively address immediate safety concerns such as fire hazards or ozone depletion, their narrow focus on acute risks creates potential blind spots. This is particularly evident when evaluating novel entities such as HFOs, where a more nuanced evaluation is necessary to understand their long-term health and environmental effects comprehensively.

Alternative evaluations, such as the GreenScreen® for Safer Chemicals,[133] provide comprehensive EHS assessments by examining critical endpoints such as chronic or life-threatening health effects, acute health impacts, environmental effects on wildlife, potential physical damage, and environmental fate characteristics. However, GreenScreen relies on authoritative sources, which often take a long time to publish their information officially, and data gaps exist in their toxicology assessments, particularly in the case of the most novel refrigerants.

TURI's Pollution Prevention Options Analysis System (P2OASys) (https://p2oasys.turi.org/) offers a more comprehensive approach. It evaluates the available quantitative information and harmonized categorizations regarding acute and chronic health hazards, physical properties relevant to safety, ecotoxicity hazards, environmental fate, atmospheric hazards, and qualitative lifecycle endpoints regarding production and disposal, helping complete the EHS picture.

Beyond the limitations of hazard evaluations, key concerns require further investigation. Most fluorinated refrigerants are either PFAS under internationally accepted definitions or decompose into PFAS during their life cycle. A growing body of research highlights health hazards linked to the PFAS chemical class[62,63] and is not often explicitly addressed in current analyses. Persistence is increasingly considered enough to designate substances as xenobiotics (foreign to life; from the Greek *xenos* meaning "stranger" and *bios* meaning "life") as chemicals of concern[81,134]. High persistence indicates a substance's resistance to natural degradation processes[62], while also being "exogenous" or foreign to biological systems[81] - key characteristics of xenobiotics that can lead to environmental and health impacts.

Furthermore, EJ considerations are often overlooked. Fenceline communities near fluorinated refrigerant manufacturing facilities risk exposure to highly hazardous chemicals like carbon tetrachloride and hydrogen fluoride[135]. PFAS water and soil pollution from these processes pose an additional threat, with removal being costly and often unavailable in low-income areas. Existing analyses might not fully incorporate these EJ concerns.

2.3.1 – Standard refrigerant EHS evaluations

Table 3 summarizes the ASHRAE safety classification (A1-B3)[116] based on flammability, according to the American Society for Testing and Materials (ASTM) E681-09(2015) Standard Test Method for Concentration Limits of Flammability of Chemicals (Vapors and Gases)[136], and human exposure hazard, sorted by OELs, defined as the maximum safe human exposure level of an airborne chemical. Workplace OELs are legally enforceable by the U.S. Occupational Safety and Health Administration (OSHA) 29 CFR Part 1910.1000 ruling on air contaminants[137]. ASHRAE Standard 34 limits the amount of contained refrigerant in a piece of equipment (formally called refrigerant charge size) based on its flammability and OEL[116], and the EPA recognizes ASHRAE Standard 34 as an occupational safety guideline.

The flammability of a refrigerant is determined by the temperature at which the refrigerant will produce a flame without an external ignition source (autoignition temperature) and the minimum concentration of a combustible substance that can propagate a flame under the specified conditions of the ASTM E681-09(2015) test[136] (or Lower Flammability Limit – LFL; sometimes called the Lower Explosive Limit). The lower the autoignition temperature or LFL, the more flammable the refrigerant is. Blending refrigerants can adjust the autoignition temperature to meet safety requirements by tuning it within the range of individual component properties.

The temperature range at which vapor compression refrigeration operates depends on its intended use[138]. The optimal refrigerant properties for each application affect equipment settings. For example, ice cream makers operate at -40°C, air conditioners at +10°C, and heat pumps at +40°C. Only ASHRAE class A1 refrigerants are allowed to be used for all applications. The higher the flammability and/or toxicity of a refrigerant, the more use restrictions are placed, particularly if leakages could enter a closed environment. Systems placed outside occupied spaces, usually on the exterior of buildings, are subject to lesser restrictions.

TABLE 3

ASHRAE safety classification and some examples for each class.

LFL (g/m^3)	Heat of combustion	Burning velocity	Occupational Exposure Limit (OEL)	
			OEL > 400 ppm	OEL ≤ 400 ppm
No flame			A1: HCFCs, HFCs, CO_2, H_2O	B1: very rare
>100	<19 kJ/g	≤10 cm/s	A2L: Most HFOs, HFC-32	B2L: Ammonia
>100	<19 kJ/g	>10 cm/s	A2: HFC-152s	B2: Seldom used
≤100	≥19 kJ/g	Not specified	A3: Hydrocarbons	B3: none

Pure HFO-1234yf, HFO-1234ze(E), and HFC-32 possess noticeable flammability, placing them into the recently *ad hoc* defined ASHRAE A2L safety class. A common strategy to reduce the flammability and toxicity risks of refrigerants is blending with less flammable or toxic gases. To reduce HFO refrigerant flammability, market suppliers currently offer blends with HFC refrigerants[139]. However, no commercial HFO/HFC blend classified as A1 also complies with a GWP lower than the 450 threshold value. The GWP threshold for most applications is set at 150 in OECD countries[138]. The blending strategy can also be implemented to reduce the flammability risks of hydrocarbons by using HFCs[36,140], CO_2[141–143] or ammonia[82]. However, HC/HFC refrigerant blends contain less than 5% HC, and HC blends with CO_2 or ammonia are rare.

Recent updates to the EPA-SNAP list are focused on low-GWP substances and are in line with the latest edition of the Underwriters Laboratories Standard for Safety Household and Similar Electrical Appliances (UL Standard 60335-2-89) concerning equipment manufactured after May 1, 2023. The EPA exempted propane from the Stationary Refrigeration and Air Conditioning venting prohibition[44], encouraging its adoption for equipment containing up to 300 grams of propane refrigerant.

As of June 2024, the American Industrial Hygiene Association (AIHA) has set 8-hour Workplace Environmental Exposure Limits (WEELs) of 1,000 ppm for HFC-32, HFC-152a, and HFC-125, and 500 ppm for HFO-1234yf. While WEELs are non-mandatory recommendations, they provide valuable guidance for industrial settings and maintenance work. For HFO-1234ze(E), both the manufacturer and ASHRAE 34-2022 recommend 800 ppm. Additionally, manufacturers recommend acceptable exposure limits (AELs) for several refrigerant blends: R-454A at 690 ppm, R-454C at 615 ppm, R-455A and R-457A at 650 ppm, and R-516A at 590 ppm. OSHA has established a mandatory Permissible Exposure Limit (PEL) of 5,000 ppm for carbon dioxide[144]. Users can obtain these exposure limits from Safety Data Sheets (SDSs).

The size and location of equipment impact fluid selection. Large industrial refrigeration systems can use refrigerants like ammonia (R-717), classified as B2L, toxic, and mildly flammable. On the other hand, residential air conditioners and heat pumps follow construction codes that limit the use of toxic and flammable fluids. The OEL concentration is 25 ppm for ammonia[145], resulting in impractical indoor charge quantities for household direct air cooling applications[146]. OSHA rule 29 CFR 1910.111 and 1910.119147 must be followed by facilities holding over 10,000 pounds of ammonia. Catastrophic failures of ammonia-based refrigeration systems can lead to fatalities and environmental damage from eutrophication. Engineering approaches, such as rooftop compact low-charge designs, reduce but do not fully eliminate those risks[5]. Proper training can help improve the safe handling and maintenance of ammonia-based systems[148]. Given the small amount of refrigerant use, EPA considers that propane (HC-290) leaks from standalone refrigeration units are not expected to affect local air quality significantly through photochemical smog creation[44].

Transcritical R-744 systems operate at significantly higher pressures than legacy HFC systems, from 44 bar (638 psi) up to 170 bar (2466 psi). Equipment components, piping, gaskets, and service tools must therefore be rated for these elevated pressures. Equipment design involves pressure relief valves to ensure safe refrigerant release during malfunctions. Furthermore, low-temperature steel is crucial to maintain system integrity in case of a leak, which can cause temperatures to plummet to as low as -78°C.

The National Fire Protection Association (NFPA) standard 69[149] provides guidelines for preventing and controlling explosions in enclosures handling flammable materials. Designed for engineers, operators, and safety inspectors, it covers methods for explosion prevention (controlling oxygen or fuel levels), isolation (limiting damage using vents), and ignition control (using safe equipment). NFPA 69 offers a framework to enhance safety and ensure compliance with building and safety codes in facilities with potentially explosive materials.

Refrigerant systems must also be charged and degassed specifically to avoid condensate formation inside the refrigerant pipework. Frost burns can occur if contact is made with liquid or solid refrigerants. Appropriate Personal Protective Equipment (PPE) must be used, such as insulating gloves, safety footwear, and earplugs. The use of self-contained breathing apparatuses is mandatory whenever handling toxic gases or when there's a potential for an oxygen-deficient atmosphere.

2.3.2 – Complementary EHS evaluations

While ASHRAE and EPA standards provide valuable frameworks for a primary refrigerant evaluation, they may not fully capture the complex environmental and health implications of these substances. GreenScreen is a valuable tool that leverages authoritative data sources to assess chemicals' environmental and health impacts. However, data gaps in toxicological assessments can limit comprehensive evaluations of novel refrigerants. To address this challenge, the TURI Pollution Prevention Options Analysis System (P2OASys) offers a systems-based approach by incorporating qualitative lifecycle endpoints related to production and disposal, enabling a more holistic comparative chemical safety assessment.

2.3.2.1 – GreenScreen and Pharos

The GreenScreen for Safer Chemicals Assessment Framework[150] is used to categorize chemicals based on a comprehensive assessment involving 18 human health endpoints (carcinogenicity, mutagenicity; reproductive, developmental, and endocrine disruption; acute toxicity and effects from repeated exposure), 3 ecotoxicity hazards (acute, chronic, and terrestrial), persistence and bioaccumulation potential, chemical reactivity, flammability, and regulatory restrictions. To communicate an overall hazard level, GreenScreen profilers assign chemicals to four benchmark (BM) classes:

- BM-1 - Benchmark 1: Avoid - Chemical of High Concern. Reserved for substances with a high hazard of carcinogenesis, mutagenesis, reproductive or developmental toxicity, endocrine disruption, or PBT.
- BM-2 - Benchmark 2: Use but Search for Safer Substitutes. Not as hazardous as BM-1 but still presenting high hazards for other endpoints, such as neurotoxicity or skin and respiratory sensitization.
- BM-3 - Benchmark 3: Use but Still Opportunity for Improvement.
- BM-4 - Benchmark 4: Prefer - Safer Chemical.

GreenScreen assessments are often conducted by companies looking to evaluate safer alternatives for specific chemical uses, and therefore, not all GreenScreen assessments are publicly available. The Pharos database (https://pharos.habitablefuture.org/) collects information on human and environmental health hazards using the GreenScreen assessment alongside authoritative lists (e.g., from environmental protection agencies) to assess the safety of a chemical. The Pharos Project builds upon the GreenScreen by incorporating additional environmental impact metrics relevant to refrigerants, such as ODP, GWP, and OELs, providing a more complete picture for refrigerant assessment. Each endpoint is given a hazard level based on the highest hazard assigned by the most authoritative lists based on the Global Harmonized System (GHS) classification and labeling of chemicals. Pharos then generates a List Translation (LT) score to summarize all available data. The LT scores are:

- LT-1 (likely BM-1): The chemical meets the criteria for BM-1 with high confidence. It indicates that if a full GreenScreen assessment were conducted, the chemical would most likely be a Benchmark-1 chemical.
- LT-P1 (possible BM-1): The chemical preliminarily meets BM-1 criteria in certain flagged endpoints, but additional research is required to confirm its hazard level and overall classification.
- LT-UNK: The available information does not clearly lead to an LT-1 or LT-P1 score.
- NoGS: The chemical is not listed in GreenScreen yet.

Table 4 and Table 5 provide a comparison of the relevant EHS hazards among halogenated and non-halogenated refrigerants respectively. A comparative analysis of halogenated and non-halogenated refrigerants reveals distinct profiles across various EHS criteria. Halogenated refrigerants, including HFCs, HCFCs, and HFOs, present a complex picture. The halogenated refrigerants included in Table 4 were selected to represent a comprehensive spectrum of both current market dynamics and evolving regulatory landscape in the refrigeration industry. The selection encompasses four key categories: 1) emerging alternatives, including HFO-1234yf, HFO-1234ze(E), HFO-1132a, and HCFO-1233zd, which represent the industry's shift toward lower GWP options; 2) restricted substances due to toxicity concerns (HFC-125, HCFC-123, R-1130(E)); 3) SNAP-accepted high-GWP refrigerants (HFC-152a, HFC-32) for specific applications or for blends; and 4) traditional refrigerants (HFC-134a, HFC-143a) that dominated the market historically but are now being phased down due to climate concerns. For more information on physicochemical properties, safety classifications, and environ-

TABLE 4

P2OASys, Pharos, and ASHRAE hazard comparison among halogenated refrigerants of current relevance in the market.

Status	Emerging alternatives				Restricted substances			Accepted high GWP		Phasing down	
Denomination	HFO-1234yf	HFO-1234ze(E)	HFO-1132a	HCFO-1233zd	HCFC-123	R-1130(E)	HFC-125	HFC-152a	HFC-32	HFC -134a	HFC-143a
CAS Number	754-12-1	29118-24-9	75-38-7	102687-65-0	306-83-2	156-60-5	354-33-6	75-37-6	75-10-5	811-97-2	420-46-2
Chemical class	HFO	HFO-1234ze(E)	HFO	HCFO	HCFC	t-DCE	HFC	HFC	HFC	HFC	HFC
Acute Human Effects	7	6	10	7	8	10	8	4	3	6	7
Chronic Human Effects	6	10	10	6	9	7	8	5	5	4	8
Ecological Hazards	7	2	2	6	5	7	3	3	6	2	4
Environmental Fate & Transport	9	10	5	9	9	8	10	5	10	10	9
Atmospheric Hazard	5	7	2	2	9	2	6	2	8	5	6
Physical Properties	10	7	10	7	7	10	7	10	9	7	10
Life Cycle Factors	10	7	10	10	8	10	10	4	8	7	10
P2OASys Hazard Level	VH	H	H	H	VH	VH	H	M	H	M	VH
Pharos EHS class	LT-UNK	LT-UNK	LT-P1	NoGS	LT-P1	LT-P1	LT-UNK	LT-UNK	LT-UNK	LT-UNK	LT-UNK
SNAP Approved	Yes	Yes	No	Yes	No	No	No	Yes	Retrofit	No	No
ASHRAE class	A2L	A2L	A3	A1	B1	B2	A1	A2	A2L	A1	A1

Low   Medium   High   Very High

The data presented in this table is current as of August 2024. For the most up-to-date information, please refer to the full analysis available at https://P2OASys.turi.org.

TABLE 5

P2OASys, Pharos, and ASHRAE hazard comparison among non-halogenated refrigerants of current relevance in the market.

Denomination	HC-290	HC-600	HC-600a	HC-1150	R-717	R-744	R-718
CAS Number	74-98-6	106-97-8	75-28-5	75–85–1	7664-41-7	124-38-9	7732-18-5
Chemical class	HC	HC	HC	HC	NH_3	CO_2	Water
Acute Human Effects	4	5	4	7	10	7	3
Chronic Human Effects	6	5	4	6	4	2	2
Ecological Hazards	5	6	6	5	6	3	2
Environmental Fate & Transport	7	7	6	4	6	5	2
Atmospheric Hazard	2	2	2	6	5	2	2
Physical Properties	10	10	10	10	10	6	3
Life Cycle Factors	2	8	5	7	8	4	2
P2OASys Hazard Level	M	M	M	M	H	M	L
Pharos EHS class	LT-UNK	LT-1	LT-1	LT-UNK	LT-P1	LT-UNK	BM-4
SNAP Approved	Yes	No	Yes	Yes	Yes	Yes	Yes
ASHRAE class	A3	A3	A3	A3	B2L	A1	A1

Low   Medium   High   Very High

The data presented in this table is current as of August 2024. For the most up-to-date information, please refer to the full analysis available at https://P2OASys.turi.org.

mental impact data of these and additional refrigerants currently available in the market, readers are directed to Appendix I: Relevant properties of refrigerant gases on the market.

Among the halogenated refrigerants shown in Table 4, three are classified as LT-P1 (HFO-1132a, HCFC-123, and R-1130(E)) based on their inclusion on hazard lists generated by authoritative bodies, while seven are designated as LT-UNK (HFO-1234yf, HFO-1234ze(E), HFC-125, HFC-152a, HFC-32, HFC-134a, and HFC-143a), indicating uncertain toxicity levels requiring further assessment. Appendix 1 provides an extensive compilation of refrigerant gases with different status on the market, showing their ASHRAE and Pharos EHS classifications alongside physical properties. The "w/ concerns" designation, applied to substances such as HFC-227ea and HFO-1336mzz(Z), indicates chemicals that, while not meeting the criteria for a more severe classification, have raised specific health or environmental concerns during assessment. Due to the relatively recent introduction of many alternative refrigerants and the time-intensive nature of comprehensive toxicological assessments, there is limited information available for thorough GreenScreen evaluations.

2.3.2.2 - TURI Pollution Prevention Options Analysis System

TURI's P2OASys (Pollution Prevention Options Analysis System) was designed to highlight a broader set of potential environmental, worker, or public health impacts. The tool assigns scores ranging from 2 to 10 for various hazard endpoints (2-4: Low; 4-6: Medium; 6-8: High; 8-10: Very High), with a lower score indicating a lower overall EHS concern. The numeric overall P2OASys score indicates the relative hazard of the alternative being considered, and it should be referenced only within the context of specific use, not as a definitive value assigned to a chemical or product. P2OASys is a useful complement to other EHS evaluations, such as ASHRAE or Pharos, and is easy to generate, read and understand. There is also a strong correspondence between Pharos or GreenScreen categories and P2OASys evaluation summaries.

The initial step for conducting an EHS assessment using P2OASys involves gathering publicly available data on the target chemical. This can be accomplished by obtaining safety data sheets (SDSs) and technical data sheets (TDSs) from vendors or databases (e.g., EPA CompTox; PubChem), or by using predictive toxicology tools (e.g., EPI suite, QSAR toolbox) to fill in any data gaps. The assessment compares the same human health and environmental hazard endpoints as GreenScreen but is grouped into eight main categories, discussed below.

The following bullet points include information on how P2OASys assesses hazard categories, specific information on refrigerants when known, relevant information about other screening systems and limitations associated with the tool as appropriate.

- **Acute Human Health Effects:** This category assesses the authoritative information available on potential short-term health impacts resulting from refrigerant exposure. These impacts may include inhalation, ingestion, skin contact, respiratory and eye irritation. The EPA-SNAP program requires the submission of some critical acute toxicology studies (inhalation, repeated exposure, prenatal developmental studies, cardiac sensitization, and irritation assays). Refrigerants evaluated here were given P2OASys scores for Acute Human Health Effects ranging from 2 (H-600a, isobutane) to 10 (R-717, ammonia). All refrigerants cause asphyxiation if their vapors displace air in a confined space. Contact with their cold liquid forms may irritate the skin or eyes or cause frostbite. While F-gases are marketed as non-toxic, acute health effects of exposure to these substitutes include drowsiness and dizziness. By repeated exposure, F-gases may cause irregular heartbeat or cardiac arrhythmia[151,152]. Most F-gases proposed as low-GWP alternatives (HFO-141b; HCFO-1233zd; R-1130(E); HCFC-123; among others) were rejected by EPA-SNAP Rule 21 over toxicity and very high persistence concerns[44,153]. The P2OASys assessment also uses Threshold Limit Values (TLVs), which are widely recognized and regularly updated occupational exposure limits based on industrial experience and scientific studies.

- **Chronic Human Effects:** This category evaluates potential long-term health impacts associated with refrigerant exposure, including carcinogenicity, mutagenicity, reproductive toxicity, endocrine disruption, and organ system damage by repeated exposure. The P2OASys chronic human effect analysis does not include metabolite toxicity. By comparison, the SNAP program only encourages (as an option) submittal of information on Chronic Human Effects.
- **Ecological Hazards:** This category evaluates authoritative information encompassing quantitative assessments and GHS categories of their acute and chronic toxicity to fish, crustaceans, and algae. The SNAP program only encourages (as an option) submittal of information on Ecological Hazards. Refrigerants evaluated in this report receive P2OASys Ecological Hazards scores ranging from 2 (e.g., water, HFO-1234ze(E), and HFC-134a) to 10 (ammonia). The analysis does not include supply chain considerations, such as the ecological hazards of precursors or the toxicity of breakdown products.
- **Environmental Fate and Transport:** This category examines the environmental impact of refrigerants, focusing on aspects such as their persistence, degradation, and potential for bioaccumulation. The SNAP program only encourages (as an option) submittal of information on this category. Refrigerants evaluated here were given P2OASys scores for Environmental Fate and Transport ranging from 2 (water) to 10 (HFC-134a, HFC-32, HFC-365mfc, HFO-1336mzz(Z), HFO-1234ze(E)). By and large, the fluorinated gases have greater persistence due to the presence of carbon-fluorine bonds. It is important to note that this category does not include the potential hazards of breakdown products, such as TFA from HFOs. This topic is explored in more detail in Sections 2.5 and 2.6.
- **Atmospheric Hazard:** This category evaluates the environmental impact of refrigerants, encompassing their influence on greenhouse gas emissions, ozone depletion, and acid rain formation. P2OASys category scores are derived from the average of the two highest hazard subcategories. For F-gases, high GWP (score 8) combined with zero ODP or acid rain potential (score 2) results in an average atmospheric hazard score of 5. Conversely, some low-GWP gases receive higher scores due to non-zero ODP. This information is mandatory to submit a new alternative to the EPA-SNAP program. It is included in Pharos but not considered in a GreenScreen assessment.
- **Physical Properties:** This category summarizes the vapor pressure, GHS and NFPA liquid and gas flammability categorizations, flash point, reactivity, pH, corrosivity, odor, and volatility. Flammability drives higher scores in this category. This information is mandatory to submit a new alternative to the EPA-SNAP program. It is worth mentioning that all refrigerant gases operate under pressure, which is a common hazard among refrigerants.
- **Life Cycle Factors:** This category is a qualitative assessment of toxic chemical creation/elimination in the supply chain, not a full life cycle assessment. PFAS production and end-of-life concerns contribute to higher scores (up to 10) for related refrigerants. Poor implementation of reclamation systems led to the assumption that all refrigerants were non-recycled in scoring. Disproportionate harm to nearby communities and refrigerant production facilities workers due to the use of toxic chemicals is not expressly included in the Life Cycle Factors category. It is not considered a topic of submission in the EPA-SNAP program. This topic is explored in more detail in Section 2.7 – Environmental Justice.

Finally, P2OASys integrates process factors (exposure potential, operational pressure, temperature, ergonomic and psychosocial hazards, energy, and water use) as well as qualitative life cycle factors. Given the highly variable nature of process factors across specific refrigerant use conditions, process factors are not considered in this report.

Each of the categories considered may contain subcategories, resulting in a total of 150 possible assessment criteria. The assessment becomes more reliable with more information available. The ASHRAE hazard classification system primarily relies on OELs to assess refrigerant safety, focusing on a single lumped threshold for acute toxicity. In contrast, P2OASys takes a more comprehensive approach by incorporating multiple data sources, including the American Conference of Governmental Industrial Hygienists (ACGIH) TLVs, which are regularly updated based on peer-reviewed research and widely recognized in occupational health. By using TLVs alongside other indicators, P2OASys provides a more nuanced and up-to-date evaluation of acute human health effects, considering factors such as GHS categories or lethal doses from inhalation, ingestion, skin contact, and irritation. This multifaceted approach allows P2OASys to capture a broader range of potential health impacts.

2.3.2.3 – A common limitation of chemical hazard assessments

Though the P2OASys analysis attempts to consider life cycle impacts in the analysis, it does not delve into specific transportation, disposal, and reclamation approaches. While GreenScreen and P2OASys provide robust frameworks for evaluating chemical hazards, it's crucial to consider the broader implications of the PFAS class. It's important to note that Environmental Justice (EJ) is an emerging concept often not adequately captured in most hazard assessments. EJ concerns the fair treatment and meaningful involvement of all people, regardless of race, color, national origin, or income, in developing, implementing, and enforcing public health and environmental laws, regulations, and policies.

Data gaps represent a significant constraint in chemical hazard evaluation, with frameworks like GreenScreen indicating when insufficient data exists for definitive categorizations. A weight of evidence approach helps address this challenge by evaluating all available information from different sources, including in vitro studies, to comprehensively assess chemical risks. The EU's REACH regulation takes this further with its "no data, no market" principle, requiring adequate safety information before market entry and addressing gaps through data sharing, read-across methods, and new testing when necessary.

2.4 – Comparative EHS hazard evaluation

Global regulation of refrigerant gases has focused primarily on climate change and ozone depletion, reflecting the narrow objective of relevant treaties. Nevertheless, other environmental hazards should also be considered, particularly when thoroughly evaluating alternative refrigerant gases to the phasing-down HFCs and HCFCs.

Despite the limited data availability, computational toxicology consistently indicates a significant ecological impact of halogenated refrigerants, characterized by high toxicity to aquatic organisms. HFC compounds demonstrate persistence in the environment, with a tendency for long-range transport, contributing to their classification as high atmospheric hazards due to significant global warming potentials. A qualitative life cycle analysis indicates high public health and EJ concerns regarding the highly toxic raw materials required to manufacture F-gases. Particularly, novel variants exhibit unidentified levels of acute human toxicity, which raise concerns regarding their potential for chronic health consequences.

Replacements such as HFOs and HFC/HFO blends, often marketed for lower climate impact, still pose environmental challenges. HFOs degrade quickly but form the extremely persistent and mobile TFA or the super greenhouse gas HFC-23 as breakdown products[96]. Despite these drawbacks, these halogenated refrigerant alternatives are still available or recently launched on the market as drop-in replacements, possessing suitable physical properties for existing refrigeration equipment designs. HFOs present higher flammability than the incumbent HFCs to be replaced, however; therefore, they are typically blended with high-GWP HFCs to reach ASHRAE category A1.

In contrast, non-halogenated refrigerants generally present a more benign environmental profile. Except for ammonia, these substances typically exhibit lower levels of acute and chronic toxicity to humans. Their ecological impact is also less than that of the halogenated refrigerants. HCs, CO_2, and NH_3 and their degradation products have significantly lower atmospheric lifetimes. Because of the acute health risks posed by ammonia, however, various other regulatory compliance requirements (e.g., OSHA's Process Safety Management of Highly Hazardous Chemicals, standard 29 CFR 1910.119) strictly govern its use. The intense regulatory focus and treatment of ammonia as a highly hazardous substance have led to robust equipment build quality, regular leak prevention, detection, maintenance protocols, and innovative system designs such as low-charge ammonia systems, discussed in Section 3.

Although the physical properties of non-halogenated refrigerants may present certain limitations for refrigeration applications, particularly in the case of hydrocarbons and HFOs due to their flammability, their overall life cycle assessments often demonstrate reduced environmental burdens and the potential to shift towards more benign ways of production. Fluorinated SNAP-approved substances and ammonia have high to very high EHS concerns, particularly regarding acute human toxicity, ecotoxicity, and life cycle considerations. It is possible that the hazards in question were not considered during the SNAP assessment, likely due to insufficient submitted information. It is important to note that periodic updates are made to SNAP rules, and as such, new information or chemical evaluations presented under new frameworks, such as the Kigali Amendment, may supersede previous rules.

While substances in the LT-P1 and LT-1 classes are not SNAP-approved, the Pharos assessment of most HFCs and HFOs (LT-UNK or NoGS classes) indicates low confidence due to limited data. From a P2OASys perspective based on SDS and computational toxicology information, HFOs show high to very high EHS hazard scores, with the exception of HFC-152a. In contrast, SNAP-approved hydrocarbons, CO_2 and water have medium to low P2OASys hazard scores.

2.5 – Refrigerant transportation, disposal and reclamation

Transportation emissions are directly linked to the distance traveled. Large trucks are commonly used to transport refrigerants to fractionation, recycling, or disposal facilities. Minimizing refrigerant leakage during transportation is particularly significant for F-gases due to their impact on the climate[154]. Specialized containers, commonly used for transporting gaseous fuels, are necessary for flammable refrigerant transportation (DOT regulation 49 CFR Part 177.834)[155]. This includes A2L ASHRAE safety class refrigerants (HFOs) and A3 ASHRAE safety class refrigerants like propane and isobutane.

When refrigerants can no longer be recovered for reuse, they are typically incinerated in a controlled environment[156]. This process can reduce the release of harmful substances into the atmosphere[157], but it may still produce greenhouse gases. Several incineration methods exist for controlled refrigerant disposal[156,157]. For instance, liquid-injection incineration produces higher greenhouse gas emissions than superheated steam incineration due to higher operating temperatures and additional drying processes. In Europe, gaseous/fume oxidation is often favored as it allows for the recovery of certain acids[154], reducing the need for effluent treatment.

While the reclamation of refrigerants is emphasized as crucial for sustainability and is an emerging trend, it is currently a marginal practice[156]. Utilizing refillable refrigerant cylinders instead of disposable ones is a potential strategy to mitigate emissions and hazards associated with cylinder transportation, storage, disposal, and residual refrigerant (also known as "heel")[158]. This approach could potentially reduce refrigerant waste and promote resource reuse.

2.6 – Halocarbon and PFAS pollution

According to a study by the United States Geological Survey (USGS), the most common halocarbon pollutant in U.S. surface waters[159] is chlorodifluoromethane (HCFC-22) due to its persistent nature and its wide use as a refrigerant and PFAS/fluoropolymer precursor[34]. Given that HFO refrigerants are also utilized as PFAS synthetic precursors, it is reasonable to conclude that their environmental exposure pathways are analogous.

Per- and polyfluoroalkyl substances (PFAS) are well-known environmental pollutants, but our understanding of their environmental presence is constrained by current analytical methods primarily focusing on larger PFAS molecules. A recent article published by the Natural Resources Defense Council (NRDC)[160] pointed out that many PFAS compounds contaminate water resources in the United States, which the EPA does not currently monitor. We are just beginning to understand the extent of the PFAS problem.

A new USGS study estimates that about 45% of the tap water in the U.S. may contain PFAS[66]. This information is supported by the EPA Maximum Contaminant Levels[161,162] and the Agency for Toxic Substances and Disease Registry (ATSDR) profile[163]. While the USGS study identified 32 PFAS, the true extent of PFAS diversity in drinking water could be wider[65,128]. The extent of PFAS presence in the environment remains unidentified[164], as current environmental monitoring efforts encompass only a limited set of PFAS compounds[165]. Environmental monitoring efforts primarily focus on a small subset of molecules containing four to nine perfluorinated carbon chains[30,161] out of the thou-

Long-Term Effects of Trifluoroacetic Acid (TFA) in the Environment

Human exposure to TFA is likely widespread[128,129]. Although health effects are still under investigation, the structural similarity of TFA to other PFAS that are well characterized in their systemic toxicity raises concerns about its potential health effects. Based on animal studies, TFA can harm reproductive health and cause liver damage[166]. A study from the German Environment Agency on TFA indicates potential liver stress or damage via a dose-dependent increase in the hepatic enzyme alanine aminotransferase (ALT)[291]. Liver recovery was observed after cessation of TFA administration.

Severe refrigerant-induced acute hepatitis[292,293], characterized by fever, diarrhea, myalgia, jaundice, elevated liver enzymes, and extensive liver cell damage, is a serious complication akin to halothane hepatitis[294,295], an immune-mediated reaction that could be initiated by the oxidative metabolism of fluorinated gases containing more than one carbon. While HCFC-123 and the anesthetic 1,1,1-trifluoro-2-bromo-2 chloroethane (halothane) are well-known causes of acute hepatitis, the possibility of TFA-forming fluorinated refrigerants inducing acute hepatitis cannot be dismissed. Unstable TFA-related metabolites combine with liver proteins[296] forming TFA-protein antigens[297] that can trigger an autoimmune response[298] that leads to liver inflammation and damage[299]. The rate of refrigerant metabolic oxidation and the subsequent level of TFA-protein formation appear to be critical factors in determining the severity of the autoimmune chain of reactions[294,298], culminating in acute liver failure.

Removing PFAS from polluted water is costly, nearly doubling water treatment expenses[241]. This difficulty stems from the unique chemically resistant properties of PFAS, making it hard to remove fully within large-scale treatment systems. The effectiveness of affordable residential activated carbon drinking water filters in removing PFAS is incomplete and dependent on chain length. Long-chain PFAS are more efficiently removed (~60–70%) than short-chain PFAS (~40% removal)[300]. Attaining almost complete elimination of PFAS requires using advanced and more expensive methods[242], such as ion exchange[301], reverse osmosis[300], and nanofiltration[302]. The small size of TFA poses significant challenges to its removal from drinking water and complicates its inclusion in standard PFAS testing methods.

sands of PFAS present in the market and the environment.

Total organofluorine analysis has revealed a substantial unidentified fraction of PFAS, a portion likely dominated by trifluoroacetic acid (TFA)[166], an environmental degradation product of HFOs[96,112,125] and most commercial HFCs[167–169] (except for HFC-152a). The consensus among most experts is that TFA is not naturally occurring[101,124.] Measured TFA concentrations are approaching regulatory thresholds, such as the drinking water health guidance value of 60 μg/L[168], established by Germany in 2020. Furthermore, temporal trends of TFA levels in precipitation suggest a correlation with increased air conditioner usage during warmer months[125,170].

Well-studied PFAS, typically presenting four to nine long carbon chains and strong carbon-fluorine bonds, are widely recognized as systemic toxicants, capable of disrupting the liver, immune, endocrine, and reproductive systems[49,58,60] and exhibiting persistent bioaccumulation and resistance to chemical and biochemical degradation[62]. TFA, while structurally simpler (one perfluorinated carbon), exhibits similar concerning properties — liver toxicity, immune system disruption, environmental persistence, and resistance to chemical degradation — raising concerns about its potential for similar adverse health effects[166]. An analog to TFA having just one additional non-fluorinated carbon, 3,3,3-trifluoro propanoic acid, which is a metabolite of HFC-245fa, was identified as the causal agent of cerebellar damage in lactating female rats[171], suggesting potential neurotoxic effects of repeated TFA exposure. Moreover, the EPA has set a health toxicity value for perfluoro propanoic acid (PFPrA)[172], based on its effects on the liver. PFPrA is molecularly just one perfluorinated carbon longer than TFA. In addition, as stated in Section 2.1, there are concerns that TFA may transform under certain conditions into HFC-23[96], a super greenhouse gas with a GWP100 of 14800.

2.7 – Environmental Justice

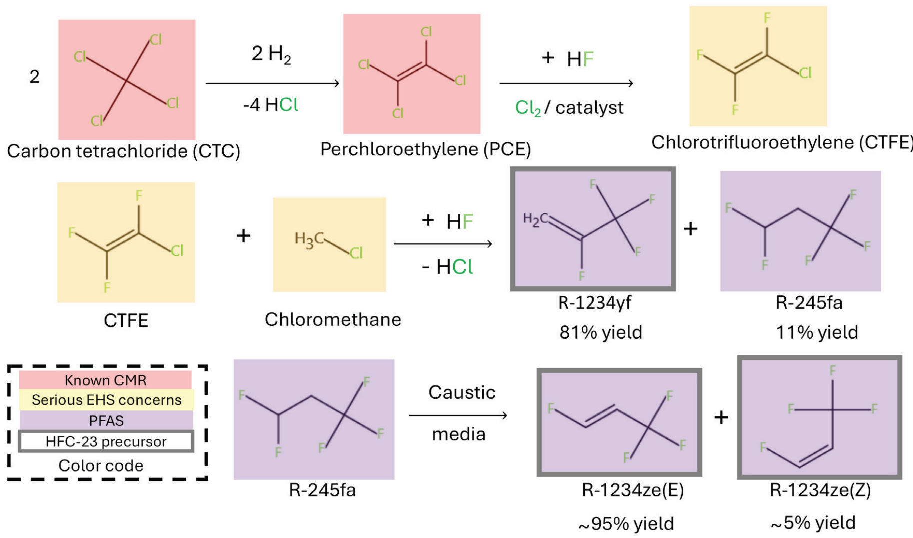
Exposure to harmful fluorinated pollutants released into the air contributes to respiratory and other health problems[135]. The health impacts of refrigerant production and disposal processes that generate air emissions are likely higher in fence line communities[10], which are disproportionately low-income minorities burdened by environmental hazards coming from nearby industrial facilities. Studies have shown that living near F-gas and PFAS production sites corresponds to higher blood levels of hazardous chemicals[71] in comparison with living further away[10,128]. In addition, fluorinated gas production takes place in facilities that co-produce other PFAS[63], using similar precursors. Chronic exposure to toxic air pollutants released from these facilities significantly elevates the risk of cancer among residents. For instance, communities within a one-mile radius of HFC production facilities show a 66% higher total cancer risk than the U.S. national average[10]. Additionally, the PFAS burden on the waterwork sector, linked upstream through the supply chain of HFCs and HFOs, is higher than the economic benefits of HFCs and HFOs[173,174] refrigerants, particularly affecting vulnerable communities with limited access to advanced PFAS removal technologies.

The production of non-halogenated refrigerants, such as propane (HC-290) and carbon dioxide (R-744), is generally considered to have a lower environmental impact compared to F-gas production[178]. Traditional ammonia (R-717) production heavily relies on natural gas and coal for the ammonia Haber synthesis process[179]. However, electrolytic ammonia production[180] offers a decarbonization pathway because renewable electricity can power the electrochemical production of the hydrogen required for ammonia synthesis[7]. Similarly, renewable propane[8] can be a direct drop-in replacement for traditional fossil-derived propane.

In recent years, public awareness of the dangers of PFAS pollution has grown significantly and has been driven by several factors, including the release of scientific studies documenting widespread pollution and the health risks associated with PFAS exposure[63], the filing of numerous lawsuits against chemical companies for their role in PFAS contamination[181–184], and the landmark passage of transformative legislation that not only restricts PFAS use[185,186] but also commits unprecedented billions in infrastructure funding to combat PFAS pollution[161,187]—marking a pivotal shift

FIGURE 3

Synthetic route for the production of SNAP-approved HFO refrigerants.



High-concern substances in HFO manufacturing processes

The pathways for the production of the HFO-1234 refrigerant family (shown in Figure 3) involve the use of hydrogen fluoride (HF), carbon tetrachloride (CTC)[175], perchloroethylene (PCE)[79], and HFCs[77] as precursors[10]. The EPA Regulatory Impact Analysis report on Phasing Down Production and Consumption also mentions the use of nickel, chromium, and antimony compounds as catalysts[10]. It is worth mentioning that HFOs are also PFAS precursors[34], often co-produced in the same facility. Given that CTC and PCE, both of which are known Carcinogenic, Mutagenic, and Reprotoxic (CMR) chemicals, are key precursors involved in the manufacture of HFCs and HFOs, the F-gas manufacturing process is more likely to negatively impact workers and communities near production sites. EPA has determined that CTC presents an unreasonable risk[177] to workers from long-term inhalation and dermal exposures and liver toxicity from short-term dermal exposure. EPA also finds PCE poses unreasonable health risks due to neurotoxicity and potential carcinogenicity[176]. The reader is referred to Appendix II to examine the spatial correspondence between U.S. F-gas production sites' activity with climate hazards (Figure A1) and public health risks, particularly respiratory diseases (Figure A2) and excess cancer cases (Figure A3).

Rethinking Refrigerant Selection Beyond ODP and GHG

The current focus on ODP and GHG emissions in standard refrigerant cycle analyses offers a limited perspective. Incorporating more comprehensive chemical hazard assessments and environmental justice considerations would ensure the selection of alternative refrigerants that minimize environmental and health impacts throughout their life cycle while protecting the well-being of the global community and communities disproportionately affected.

from awareness to decisive action. Furthermore, as a result of increased public awareness[188–190] and stricter regulations[30,191], many chemical companies have been forced to take action to address PFAS-related issues: leaving the PFAS market altogether[192], settling multi-billion dollar lawsuits[184,193–195] or selling their F-gas production facilities[196].

3. Performance assessment

This section describes the technical and economic aspects of adopting alternative refrigerants, distinguishing direct (drop-in) substitutes from those that require equipment replacement for their implementation.

3.1 – Refrigerants action and performance metrics

Refrigeration is one of the most significant engineering achievements[138], a versatile technology with a wide range of applications distributed across an interdependent network of stakeholders, including equipment manufacturers, chemical companies, distributors, end users, governments, and the biosphere. Among other uses, refrigeration efficiently preserves food and provides atmospheric controls and comfort. Manufacturers, distributors, and refrigerant producers are driven by technological advancements, profitability, and financial risk, while government regulation can play a crucial role in driving innovation to safer and more sustainable technologies.

According to the second law of thermodynamics, the vapor compression cycle cannot be 100% efficient. It experiences energy losses due to friction, mechanical vibration, noise or residual heat.

Vapor Compression Refrigeration Cycle Overview

Refrigerant gases undergo an operation called the vapor compression cycle[197] that allows them to absorb heat from a source and release it to another place, called a sink. Heat pumps can exchange their heat source and sink. For this process to happen, energy in the form of mechanical work must be invested. Figure 4 depicts this vapor compression cycle, which consists of four stages:

Stage I – Vapor compression: The refrigerant gas, initially at a temperature T1 and pressure P1, is subjected to increased pressure (P2>P1) by external mechanical work (W_{comp}) invested through a compressor device. In these conditions, the temperature of the refrigerant will also increase (T2>T1). The temperature of the refrigerant at the compressor outlet (T2) is called *Discharge Temperature* and represents the highest temperature in the cycle.

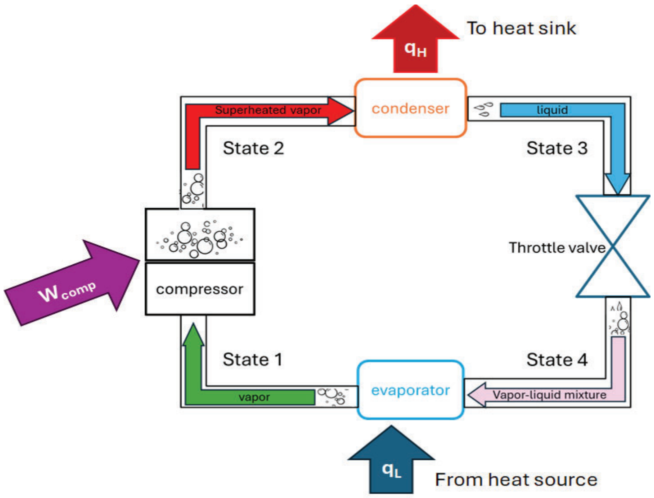
Stage II – The compressed refrigerant is transferred into a heat exchanger (condenser) and releases heat into the sink (q_H) until it becomes a liquid at a temperature T3 and pressure P3, the *Condensing Pressure*. P3 is a working pressure that must be set higher than the pressure at which the refrigerant changes phase (*Saturation Pressure*) at a given temperature.

Stage III – An expansion valve releases the liquid refrigerant, reducing its temperature (T4<T3) and pressure (P4<P3) and allowing it to enter another heat exchanger (evaporator). P4 is also called *Evaporating Pressure*.

Stage IV – The refrigerant absorbs heat from the environment (q_L) through the walls of the evaporator. The vaporized liquid refrigerant returns to its gaseous form, tending to expand, then enters the compressor again at a pressure of P1 to repeat the cycle.

FIGURE 4

Coefficient of Performance (CoP) definition and generic vapor compression cycle for refrigeration.



These unavoidable inefficiencies drive manufacturers to continuously seek ways to minimize energy losses through improved refrigerants and ongoing technological advances in HVACR and heat pump systems. A measure of efficiency for refrigerant systems is called the Coefficient of Performance (CoP): the minimum amount of external energy investment for a certain amount of useful refrigerant effect. The CoP in a vapor compression cycle expresses the heat transferred from the heat source (stage III, q_L) to the heat sink (stage II, q_H) divided by the quantity of work input to the compressor (stage I, W_{comp}):

$$\mathrm{CoP} = \frac{|q_L - q_H|}{W_{\mathrm{comp}}}$$

The properties of refrigerants impact the design of refrigeration equipment, which varies based on refrigerant identity, refrigeration cycle type, source-to-sink temperature difference, and the internal operative window of pressure and temperature. The key properties that are important to know for refrigerants include:

- **Critical temperature:** The highest temperature at which it is possible to separate a substance into two fluid phases (vapor and liquid).
- **Critical pressure:** The pressure above which a gas cannot co-exist with a liquid phase.
- **Saturation pressure:** The pressure at which a liquid will vaporize at a given temperature.
- **Saturation temperature:** The temperature at which a liquid will boil at a given pressure.
- **Specific volume:** The volume occupied by a unit mass of refrigerant.
- **Specific heat:** The amount of heat required to raise the temperature of a unit mass of a refrigerant by one degree of temperature.
- **Thermal conductivity:** The ability of a material to conduct heat.
- **Viscosity:** The resistance of a fluid to flow.

- **Cooling capacity (CC):** The amount of heat that can be removed by the refrigerant, determined by the specific heat capacity of the refrigerant in both its gas and liquid forms, equipment settings like compressor efficiency, evaporator, and condenser design, and refrigerant cycle configuration. Seasonal factors, such as ambient temperature and relative humidity, also significantly impact cooling capacity.
- **Stability:** Resistance against undesirable reactions, such as the formation of gases, solids, or corrosive substances.

Critical pressure and temperature determine the operating P-T range (or envelope). Saturation pressure and temperature determine the efficiency of a refrigerant for a given operative set point. Specific volume, specific heat, thermal conductivity, and viscosity affect the CoP of an equipment configuration and the cooling capacity per refrigerant unit mass[198].

ASHRAE classifies refrigeration applications according to their evaporator temperature requirements, which directly relate to their intended use. Low Temperature systems, operating at around -31.7°C, include freezer systems for frozen storage and ice cream. Medium Temperature systems, with evaporator temperatures near -6.7°C, are typically used in refrigerators and cold storage for fresh food preservation. Standard indoor thermal comfort systems operate at an evaporator temperature of 7.2°C, primarily designated for air conditioning and dehumidification. These standardized temperatures help engineers and technicians compare refrigerant performance across different applications.

Table 6 shows distinct operational characteristics among different refrigerants across ASHRAE temperature categories. Unlike most refrigerants, which operate in cycles transitioning between gas and liquid phases, CO_2 (R-744) predominantly works in transcritical conditions, transitioning between supercritical fluid and gas states. This behavior explains why CO_2 operates at notably higher pressures across all temperature categories. Other refrigerants can operate in transcritical conditions, but CO_2 dominates the market segment. Ammonia (R-717) functions at relatively low evaporator pressures, and both HFCs and HFOs maintain moderate pressure levels throughout their operation.

Net Refrigeration Effect (NRE): Actual Cooling Power

The Net Refrigeration Effect (NRE) represents the heat absorption potential per unit mass of refrigerant, measured in kJ/kg. NRE inherently depends on the thermodynamic properties of the refrigerant gas and the operating P-T envelope of the refrigeration system. This property directly influences the cooling capacity (CC), quantifying the actual heat removal rate from a system in kW or BTU/hr. The equipment design, particularly the compressor sizing and heat exchanger configurations, determines the achievable mass flow rate and, thus, the final CC. The following relationship combines the heat absorption capability of a refrigerant with its circulation rate to determine actual cooling power:

$$\mathrm{CC} = \dot{m} \cdot \mathrm{NRE}$$

(Where $\dot{m}$ is the mass flow rate of the refrigerant). Drop-in refrigerant substitutes for use in existing equipment must function within a similar P-T envelope and with comparable CoP and CC. The second law of thermodynamics and the CoP calculation applies to all refrigeration technologies and heat pump cycles. CoP and CC are valuable metrics for screening refrigerants by performance. However, CoP and CC results may vary with the base thermodynamic cycle, the temperature difference between the heat sink and source, and the specific equipment design, making it difficult to compare results from one equipment configuration to another.

TABLE 6

Thermodynamic performance metrics of various refrigerants under ASHRAE standard application categories.

Refrigerant	Chemical Name	Evaporator Pressure (MPa)	Condenser Pressure (MPa)	NRE (kJ/kg)	Refrigerant Circulated (g/s)	Power Consumption (kW)	CoP	Discharge Temperature (°C)
Standard Low Temperature (LT) refrigeration: Evaporator -31.7°C/Condenser 30°C								
R-717	Ammonia	0.110	1.167	1079	0.93	0.3327	3.007	140.9
R-744	Carbon dioxide	1.349	7.213	132.1	7.57	0.5892	1.698	91.3
HC-170	Ethane	1.012	4.655	153.6	6.51	0.5947	1.681	57.9
HC-1270	Propylene	0.199	1.305	269.1	3.72	0.3471	2.880	49.1
HCFC-22	Chlorodifluoromethane	0.152	1.192	155.3	6.44	0.3369	2.967	65.4
Standard Medium Temperature (MT) refrigeration: Evaporator -6.7°C/Condenser 30°C								
R-717	Ammonia	0.332	1.167	1113	0.90	0.1599	6.254	82.1
R-744	Carbon dioxide	2.909	7.213	129.5	7.72	0.2845	3.514	61.3
HC-170	Ethane	2.024	4.655	163.1	6.13	0.2786	3.588	46.2
HFC-32	Difluoromethane	0.653	1.928	258.6	3.87	0.1690	5.924	59.7
HC-290	Propane	0.385	1.079	288.6	3.47	0.1669	5.987	34.9
HC-600a	Isobutane	0.123	0.405	278.0	3.60	0.1620	6.171	30.0
HFO-1234yf	2,3,3,3-Tetrafluoropropene	0.250	0.783	120.5	8.30	0.1715	5.835	30.0
HFO-1234ze(E)	trans-1,3,3,3-Tetrafluoropropene	0.168	0.578	139.6	7.16	0.1658	6.030	30.0
HFC-134a	1,1,1,2-Tetrafluoroethane	0.228	0.770	153.0	6.54	0.1650	6.063	34.8
Standard indoor thermal comfort: Evaporator 7.2°C/Condenser 30°C								
R-717	Ammonia	0.558	1.167	1128	0.89	0.0893	11.19	58.6
HC-600a	Isobutane	0.201	0.405	296.3	3.37	0.0901	11.08	30.0
HC-600	Butane	0.134	0.283	326.9	3.06	0.0899	11.23	30.0
HC-290	Propane	0.588	1.079	303.9	3.29	0.0931	10.74	32.6
HFO-1234yf	2,3,3,3-Tetrafluoropropene	0.401	0.783	129.0	7.75	0.0941	10.62	30.0
HFO-1234ze(E)	trans-1,3,3,3-Tetrafluoropropene	0.280	0.578	149.1	6.71	0.0918	10.90	30.0
HFC-32	Difluoromethane	1.018	1.928	261.1	3.83	0.0944	10.60	46.9
HFC-134a	1,1,1,2-Tetrafluoroethane	0.377	0.770	161.0	6.21	0.0918	10.90	32.6

Data includes ammonia, CO_2, hydrocarbons, HFCs, HCFCs, and HFOs operating at low temperature (LT, -31.7°C), medium temperature (MT, -6.7°C), and high temperature (HT, 7.2°C) applications with a standard 30°C condenser temperature. Performance parameters include operating pressures, Net Refrigerating Effect (NRE), mass flow rates, power consumption, Coefficient of Performance (CoP), and compressor discharge temperatures.[116]

CoP improves as evaporator temperatures increase for all refrigerants. Ammonia exhibits the highest CoP values in every temperature range. HFCs and HFOs display similar performance characteristics. The data presented in Table 6 indicates that CO_2 has lower CoP values, especially in low-temperature applications. However, it's crucial to understand that these standardized test conditions do not reflect the optimized operating conditions commonly found in actual CO_2 systems.

The discharge temperature patterns show significant variation, with ammonia operating at higher discharge temperatures, while F-gases maintain consistently lower discharge temperatures and CO_2 exhibits moderate discharge temperatures. Regarding intrinsic refrigeration capabilities, ammonia demonstrates a substantially higher NRE than other refrigerants, while CO_2, HFCs, and HFOs exhibit lower but comparable refrigeration effects. These characteristics highlight the importance of matching refrigerant selection to specific application requirements and operating conditions.

3.2 – Technical feasibility of drop-in substitutes

Correct drop-in substitutes for retrofitting purposes must possess very similar properties to the refrigerant to be replaced[198,199]. HFOs share many similar physical and chemical properties to HFCs. This physical similarity explains the sudden market expansion of HFOs, given the amount of equipment deployed currently utilizing HFCs.

For replacing HFCs, halogen-free gases, with very few exceptions, require a major equipment overhaul or purchase of new HVACR systems. HFO-1234yf serves as a component in refrigerant mixtures with HFCs to reduce the "average GWP." These mixtures can substitute for the R134a refrigerant in both existing and new systems for mobile and heat pump applications. Hydrocarbons exhibit high flammability but have a comparable CoP to HFCs, low GWP, low toxicity, and moderate biodegradability, and have thus been accepted by EPA-SNAP as drop-in substitutes for HFCs for certain uses. Three main strategies facilitate the use of hydrocarbon-based refrigerants as drop-in substitutes for HFCs:

- **Blending with low flammability refrigerants (usually HFCs) for fire retardancy:** The blend might still contain high GWP gases, but its "average GWP" is tailored to comply with regulatory thresholds without compromising, and occasionally improving, performance. However, the composition of SNAP-approved HFC/HC blends is currently less than 5% of the hydrocarbon content[36], suggesting that no meaningful HFC mitigation, only phase down, can be achieved by using blends.
- **Overhauling of existing equipment:** Equipment modifications must be made to work safely with HCs in existing HFC-based HVACR systems. The main concern regarding flammability is in the compressor. Electrotechnical standards dictate that HCs must work with an enclosed compressor, with proper electrical wiring protection against dust and water jets and clearly labeled "Attention Fire Hazard"[24]. Choosing the right lubricants and gasket materials is essential to sealing the system and preventing leakage through the tubing and mobile parts.
- **Equipment commissioning and planned maintenance:** This should be performed by certified HVACR technicians. Devices must be installed in suitable areas as directed on their tags.

3.3 – Limitations of retrofitting

Retrofitting an HFC-based HVAC system can offer a relatively inexpensive alternative to purchasing new equipment, potentially reducing energy bills by up to 20% while enhancing the efficiency of existing equipment by incorporating improved mechanical parts and sensors to monitor refrigerant leaking and control the performance. The cost of retrofitting an existing system varies depending on the extent of the required upgrades[200]. While not all situations warrant expensive retrofits, it's important to note that retrofitted HVACR equipment generally exhibits lower efficiency compared to the latest HVACR models, thereby contributing to avoidable CO2 emissions[32].

The Hidden Economics of HVACR Upgrades

Considering the average lifespan (15 to 20 years) for HVACR systems, replacement at 10-year old systems is advisable, as older systems typically experience performance deterioration over time[303,304]. Enhancing performance through retrofitting has a typical payback period of 0.7 years due to low investment, while a major investment in purchasing new equipment plus remodeling existing buildings can be as short as 2 years[200]. While HFO refrigerants, HFO/HFC or HFC/HC blends are currently used as a short-term workaround, recent precautionary policy trends on F-gases[1,27,28] and PFAS[29,30,31] will likely create more limitations on F-gas refrigerant availability. Recycling refrigerants, though promising for reducing F-gas environmental impact and addressing availability, remains impractical for most suppliers due to economic and logistic challenges. Also, HC and HFO flammability require blending with high-GWP HFC refrigerants to match existing building standards.

3.4 – SNAP-approved alternatives to HFC refrigerants

F-gases currently represent over 80% of the refrigerant market[201]. U.S.-based companies are leaders in intellectual property and production of new-generation F-gas refrigerants: HFOs and HFO/HFC blends[25,201]. Table 7 lists the refrigerants produced in the U.S. and approved by the latest SNAP rules. This includes HC-600a (isobutane), accepted in SNAP Rule 22 for its outstanding market penetration since it has SNAP approval for household refrigeration.

The EPA is continuously considering submissions of potential substitutes when listing acceptable and unacceptable products and releasing new rules. The EPA modified the use conditions for wider adoption of HC-600a and HC-290 (propane) in certain end-uses[23], including household refrigerators, self-contained commercial ice machines, stand-alone equipment, and refrigerated food processing and dispensing equipment. EPA-SNAP rule 26 also lists ethene for special applications.

SNAP Rule 26 lists nine halogenated gases, many of which could soon be affected by proposed ECHA PFAS restrictions[49] for PFAS that meet the OECD definition[202]. However, the EPA PFAS definition[75] excludes F-gases approved under SNAP. SNAP also approved HCFO-1233zd for cold storage warehouses, ice rinks, and industrial process air conditioning (new equipment only). Ammonia is SNAP-approved as a substitute for CFC-12 and HCFC-22 in refrigeration and AC. Water (R-718) is only contemplated under EPA-SNAP as a foam-blowing agent and heat transfer fluid[23].

TABLE 7

Examples of refrigerants produced in the U.S. approved by the latest SNAP rules.

SNAP—approved refrigerant	Main U.S. Producers	Composition			GWP	ODP	Contains PFAS*	Applications
		Chemical name	CAS No	% w/w				
HFC-32	Chemours; Arkema; Daikin	Difluoromethane	75-10-5	100	675	0	No	Retrofitting of industrial process chillers (GWP<700).
HCFO-1233zd	Honeywell; Arkema	1-Chloro-3,3,3-trifluoropropene	2730-43-0	100	6	3.10^{-4}	Yes	New cold storage warehouses, industrial HVACR and ice rink
HFO-1234ze(E)	Arkema	1,3,3,3-tetrafluoro-(1E)-propene	29118-24-9	100	6	0	Yes	Commercial; residential; replaces HFC-134a
HFO-1234yf	Chemours; Honeywell	2,3,3,3-Tetrafluoropropene	754-12-1	100	4	0	Yes	Mobile air conditioning; replaces HFC-134a
R-454A (blend)	Chemours; Daikin	2,3,3,3-Tetrafluoropropene (HFO-1234yf)	754-12-1	65	4	0	Yes	Chillers <90 Kg of charge and cascade systems.
		Difluoromethane (HFC-32)	75-10-5	35	675	0		
R-454B (blend)	Chemours	2,3,3,3-Tetrafluoropropene (HFO-1234yf)	754-12-1	67	4	0	Yes	Industrial chillers; replaces R-410a blend
		Difluoromethane (HFC-32)	75-10-5	32	675	0		
R-454C (blend)	Chemours; Daikin	2,3,3,3-Tetrafluoropropene (HFO-1234yf)	754-12-1	78.5	4	0	Yes	Commercial; residential; heat pumps
		Difluoromethane (HFC-32)	75-10-5	21.5	675	0		
R-455A (blend)	Honeywell	2,3,3,3-Tetrafluoropropene (HFO-1234yf)	754-12-1	75.5	4	0	Yes	Commercial; residential; mobile; replaces HFC-134a
		Difluoromethane (HFC-32)	75-10-5	21.5	675	0		
		Carbon dioxide (R-744)	124-38-9	3	1	0		
R-457A (blend)	Arkema	2,3,3,3-Tetrafluoropropene (HFO-1234yf)	754-12-1	70	4	0	Yes	Commercial; residential
		Difluoromethane (HFC-32)	75-10-5	18	675	0		
		1,1-difluoro ethane (HFC-152a)	75-37-6	12	124	0.07		
R-516A (blend)	Arkema	2,3,3,3-Tetrafluoropropene (HFO-1234yf)	754-12-1	77.5	4	0	Yes	Commercial; residential; replaces HFC-134a
		1,1-difluoro ethane (HFC-152a)	75-37-6	14	124	0.07		
		1,1,1,2-tetrafluoroethane (HFC-134a)	811-97-2	8.5	1430	0		
HC-600a	National Refrigerants	Isobutane	75-28-5	100	6	0	No	Commercial; residential (new equipment)
HC-290	National Refrigerants	Propane	74-98-6	100	3	0	No	New self-contained ice machines and stand-alone equipment.
HC-1150	National Refrigerants	Ethene	75–85–1	100	4	0	No	Very low-temperature refrigeration

HFC   HFO or HCFO   HFC/HFO blend   Hydrocarbon   Red text = Concerning EHS features

* PFAS understood as chemicals that contain at least one fully (per) or (poly) fluorinated carbon.[202]

3.5 – Performance improvement opportunities

Transitioning to low-GWP refrigerants is just one of the five main engineering strategies for improving the climate impact of vapor compression systems. Other important strategies that can be employed include:

- Low GWP drop-in substitutes can reduce the system's indirect carbon emissions by up to 50%.
- A more efficient compressor, the heart of a vapor compression cycle, can reduce the indirect GHG emissions of the system by up to 20%[203]. Screw or scroll compressors are usually more efficient than reciprocating compressors due to reduced friction and noise.
- Efficient condensers, which transfer heat from the refrigerant to the environment, can reduce the indirect carbon emissions of the system by up to 15%[90].
- A more efficient evaporator, which extracts heat from the environment, can increase the CoP of the system by up to 10%[204].
- Integrating heat recovery systems can reduce heating costs and space demand in commercial buildings[17,205].

Table 8 lists common approaches implemented by state-of-the-art equipment for safer and more efficient operation, including reducing the amount of refrigerant (or charge) inside the refrigeration loop[206], leak monitoring, and dedicated designs such as enclosed compressors and cascade systems[207].

TABLE 8
Modern approaches to common issues in vapor compression equipment.

Issues	Solutions	Enabling the use of
Leakage into confined spaces	Reduced refrigerant charge by compact heat exchangers	Flammables (HFO, HC)
	Gas removal by forced ventilation	Flammables (HFO, HC)
	Smart sensors, alarms and shut down by feedback loop	Flammables (HFO, HC); toxic (NH_3)
	Outdoor placement of compressor and condenser	Flammables (HFO, HC); toxic (NH_3)
	Ultra-low charge systems	Flammables (HC); toxic (NH_3)
Low CoP	Cascade equipment design Heat recovery	Carbon dioxide and water
	High pressure transcritical cycle	Carbon dioxide
Loud noise	Scroll or screw compressors	Any refrigerant

Flammability and toxicity concerns cannot be overlooked for any application. It is worth noting that modifying building safety standards for adopting new equipment that works with low acute toxicity / mildly flammable (ASHRAE A2L safety class) HFOs can function as an enabler for low acute toxicity / flammable (ASHRAE A3 safety class) HCs refrigerants implementation.

The US-EPA ENERGY STAR program provides federal tax credits and deductions[208] to homeowners and businesses that make energy-efficient upgrades to their homes and buildings. Savings for homeowners include up to $3200 in annual tax credits for energy-efficient home upgrades. Builders of energy-efficient new homes can receive a tax credit that is specifically tied to ENERGY STAR requirements. Tax deductions for commercial buildings can be claimed for energy efficiency increases of at least 25%. These incentives favor buying new equipment over retrofits.

3.5.1 – Residential air conditioning

Indoor safety codes restrict flammable and toxic gases; HVACR installations must comply with all flammability and safety requirements for installation. No indoor HVACR equipment in the U.S. can hold more than 300 grams of hydrocarbon charge[23]. That charge limit increased to 500 grams in Europe[209] in light of novel approaches to equipment design, permanent magnet synchronous (brushless) motors, and electrical housing standards[24].

Split technology already in the market can mitigate flammability risks[210]. Split units have two parts: One is installed outside and contains the compressor and condenser, while the other is installed inside and contains the evaporator. The compressor and condenser are the most likely to leak refrigerant, so it is safer to install them outside, while the indoor evaporator removes heat from the room that needs to be cooled.

3.5.2 – Residential refrigeration

The use of isobutane (HC-600a) as a refrigerant in residential refrigerators has increased significantly since the EPA-SNAP approved its use in 2015. This is due to the high CoP and low GWP of isobutane and its compatibility with existing equipment manufacturing. Updated safety standards to increase the allowable refrigerant charge of HCs enabled HC-600a use. More than 600 different models of household refrigerator running with the hydrocarbon HC-600a are considered more efficient than the U.S. federal standard, according to the US-EPA ENERGY STAR program[211]. Ammonia is not considered suitable for domestic refrigerators or air conditioners because of low admissible exposure thresholds and material compatibility (e.g., corrosion, particularly when copper or brass fittings are in confined spaces).

3.5.3 – Commercial refrigeration

Propane (HC-290) is listed in EPA-SNAP Rule 26 as acceptable[23] for commercial refrigeration; it can be used only in new self-contained or standalone equipment that meets the appliance safety standard UL 60335-2-89. The EPA proposes to allow propane as a refrigerant in new refrigerated food processing and dispensing equipment and exempts propane from the venting prohibition under CAA section 608, applicable to equipment manufactured after the effective date of the final rule (May 2023). With the modification of SNAP Rule 26 (June 2024)[23] to allow propane charges up to 300g in closed case refrigerators and 500g in open case refrigerators, the EPA has harmonized its regulations with UL and ASHRAE standards, thereby establishing a unified regulatory framework for higher-capacity propane refrigeration systems across self-contained commercial cases, ice makers, and food processing equipment.

Ammonia remains a refrigerant of choice for many industrial and commercial applications, particularly with the advent of low-charge technologies. Ammonia is safe for use in centralized Ultra Low Charge (ULC) chillers where the chilled water is pumped to air handling units[209]. Ammonia leaks are contained in the water instead of being released to the environment.

Despite the greater expense associated with its higher pressure operational requirements, transcritical CO_2 (R-744) has promising prospects for commercial refrigeration, including supermarkets[15,16]. Moreover, numerous manufacturers and commercial operators have successfully switched to halogen-free refrigerants, particularly HC/CO_2 cascade equipment[20,209], in several supermarket chains[12,21]. Peripheral measures such as heat recovery systems integrated with sanitary water heating enabled the adoption of CO_2 refrigeration systems in medium and large food retail and storage facilities[17,18]. CO_2 and HC/CO_2 cascade systems are expected to dominate commercial refrigeration in OECD countries by 2027 and in non-OECD countries by 2036[1].

3.5.4 – Mobile refrigeration and air conditioning

AAddressing flammability concerns in mobile refrigeration and air conditioning (cars, food transportation, etc.) is especially important. Most car makers now use the HFO-1234yf refrigerant or its blends in new models, implementing additional leak prevention and fire safety measures. Other than in automobile air conditioning, pure HFO-1234yf has limited standalone applications. HFO-1234yf is slightly less flammable (A2L) than HCs[116,212] and can produce highly toxic hydrogen fluoride (HF) and carbonyl fluoride (COF_2) in a scenario of accidental fire[213], posing a serious risk to rescue teams dealing with dealing with burning cars.

Due to flame propagation and ignition probability, HC refrigerants are classified as A3 according to ASHRAE. Extensive testing results have shown that the flammability hazard of A3 refrigerants in mobile refrigeration can be mitigated if the refrigeration system is improved using suitable constructive measures[214,215], such as sealed units, hermetic compressors, adapting capillary tubes, brushless fan motors, and feedback loop controls[216].

Performance testing of HC refrigerants in a conventional F-gas based Mobile Air Conditioning (MAC) system[217] showed that HC-290 (propane), HC-600a (isobutane), and an HC-290/HC-600a mixture could provide acceptable cooling capacity and lower GWP than HFC-134a or HFC-152a. The results of this study emphasize that hydrocarbons are viable alternatives for the widely used HFC-134a and that retrofitting for safety is feasible.

Since transportation has a long history of leveraging pressurized gases, upgrading mobile refrigeration and MAC into non-fluorinated gases should be within reach. In 2023, at least one European car and bus company debuted the use of CO_2 in MAC systems. Although the principle had been known for several decades, introducing CO_2 MAC systems into current mass-produced vehicles required significant development of new components, circuitry, and controls[218]. The higher operating pressures of CO_2 systems require thicker component walls, but the components are smaller than HFC-134a systems[219,220]. Additionally, the smaller and more efficient components of CO_2 systems are expected to reduce fuel consumption[218,220] and related TEWI[221]. As in stationary systems, integrating heat recovery eliminates the need for supplemental heating devices.

The use of CO_2 in transport refrigeration is growing as businesses look for safer and more sustainable alternatives to ammonia and HFC-based systems. Particularly for global food freights and fishing vessels, CO_2 systems offer several advantages over traditional refrigerants[4,21,222]. Schemes that unlock transcritical CO_2 capabilities include:

Two-stage systems: Using two compressors, one for the high-pressure side of the system and one for the low-pressure side.

- Single-stage systems: Using a single compressor to circulate the refrigerant.
- Cascade systems: Using two different refrigerants working in different conditions, connected by a heat exchanger. CO_2/HC cascade systems are increasingly employed in food transportation[12] and storage[5,209].
- Materials improvement in manufacturing technologies based on aluminum alloys have also reduced the diameter, weight, and cost of piping and heat exchangers[220].

3.5.5 – Industrial refrigeration

With the exception of water, carbon dioxide (R-744) is the chemically safest refrigerant, becoming widely used in industrial facilities, water chillers, and heat pumps in recent years since key components for CO_2 refrigeration systems have been developed, along with dedicated designs able to work in transcritical conditions to improve safety, efficiency, and capacity[4,18,216,222].

Ammonia (R-717) is the most efficient refrigerant for various industrial applications. Despite its toxicity and corrosivity, the availability, low price, high efficiency, and warning pungent odor of ammonia have made it an attractive option for large industries with typical cooling capacities requirements above one megawatt. The use of ultra-low charge (ULC) units allows for reconsideration of ammonia as a safer refrigerant[5,209], leading to consider ULC as favorable alternatives. However, it is crucial to recognize that acute toxicity and eutrophication hazards persist. Thus, ULC ammonia systems still require robust process safety and engineering controls to prevent leaks and accidents. Facilities containing more than 10,000 pounds of ammonia must adhere strictly to OSHA 29 CFR regulations[147]. The potential for catastrophic failures in ammonia-based refrigeration systems cannot be ignored, as they seriously threaten human life and the environment.

Ammonia may be replaced by carbon dioxide in some traditional industrial refrigeration applications. Carbon dioxide is more efficient than ammonia when the evaporating temperature is lower than −40 °C[142,146]. Ammonia may still be used in many applications, such as the CO_2/NH_3 cascade system[5]. However, due to the pressure and charge requirements for industrial-scale refrigeration, it is important to take precautions to prevent accidents.

Regulation (EU) 2024/573 introduces GWP limits for refrigerants in Ultra Low Temperature (ULT) refrigeration[47] operating below −50°C, setting a maximum GWP threshold of 2,500. Under the Kigali Amendment to the Montreal Protocol, OECD nations must implement quota systems[223] that progressively reduce the production and consumption of high-GWP F-gas refrigerants. These combined regulatory pressures mean industrial users will need to proactively identify and transition to lower-GWP alternatives for ULT applications.

HFC-23 and perfluorocarbon-containing blends are no longer acceptable for ULT refrigeration systems under SNAP. On the other hand, EPA-SNAP authorizes using ethane (HC-170) and ethene (HC-1150) only for new ULT equipment deployment for industrial refrigeration. There are more than 700 available ENERGY STAR Certified Lab Grade refrigerators and industrial-scale ultra-freezer models based on pure HCs, HC blends, and CO_2/HC cascade systems[224]. Thermoelectric or magnetocaloric refrigeration are emerging solid-state refrigerant-free technologies capable of meeting ULT refrigeration needs[225] as well as refrigerated centrifuges[226] where flammable refrigerants or high working pressures could compromise operational safety.

4. Economic assessment

A practical energy efficiency metric for refrigerants is the Coefficient of Performance (CoP), defined in Section 3, which allows the comparison of intrinsic energy use efficiency among refrigerant gases in a defined operation setting. When choosing direct substitutes, candidates are sorted by CoP similarity with the refrigerant gas that must be replaced. Other aspects, such as equipment cost, material compatibility, and safety, are considered afterward.

Section 4.2 provides performance and cost information solely for comparison purposes. The rising cost of new F-gas refrigerants is challenging the HVACR industry. HFOs are more expensive than HFCs[1]. Handling flammable substances like HFOs and HCs can significantly impact the supply chain. Businesses must purchase more expensive insurance, hire additional safety personnel, and implement more stringent safety procedures to comply with various regulations. In addition, flammable substances may require special storage and transportation facilities, which can add to costs. These costs would be distributed throughout the supply chain, potentially resulting in a substantial increase in refrigerant prices[25]. However, high GWP refrigerants are capped for production and import in OECD countries, which caused a rise in their prices, explaining the current competitiveness of HFOs and HFO/HFC blends. HFC-32 is the only SNAP-approved HFC in Rule 26, being among the lowest-priced refrigerants on the market. It is important to note that HFC-32's GWP is higher than most of the proposed regulatory thresholds, and its use is limited to retrofitting industrial equipment that is difficult or costly to replace on short notice.

Table 9 presents key refrigerant alternatives, including efficiency metrics, market pricing, regulatory status, and application suitability across different sectors. Several important considerations should frame the interpretation of these data:

- The economic data represents a market snapshot during the compilation of this alternatives assessment, and pricing dynamics in the refrigerant market are volatile and can change rapidly.
- While the CoPs provide a standardized efficiency metric, these values should be interpreted cautiously, as they may not reflect the actual performance of modern HVACR systems. This is particularly relevant for CO_2 (R-744) systems, where field performance typically exceeds the standardized test conditions presented here.
- Direct CoP comparisons between non-drop-in alternatives may be misleading, as different refrigerants operate with specialized equipment designs and the temperature difference between the heat sink and source. The table also highlights the evolving regulatory landscape, indicating which refrigerants are facing phase-down periods and which alternatives are gaining approval for specific applications.

TABLE 9
Efficiency and pricing information of common refrigerants (as of July 2023).

Refrigerant	Chemical Class	CoP*	Price ($/Kg)	SNAP / Market status	Applicability			
					Residential	Commercial	Mobile	Industrial
HFO-1234ze(E)	HFO	6.03	120	Approved for air conditioning	Yes	Yes	Limited	Limited
HFO-1234yf	HFO	5.84	211	Approved for mobile refrigeration	Yes	Yes	Yes	Limited
HFC-32	HFC	5.92	2.8	Approved for industrial retrofitting only	No	No	No	Limited
HFC-32/HC-290	HFC/HC blend	5.35	90	Approved with use conditions	Limited	Yes	No	Yes
HC-290	HC	5.99	173	Approved with use conditions	Limited	Yes	No	Yes
HC-600a	HC	6.17	123	Approved for fridges and freezers	Limited	Yes	No	Yes
R-744	CO_2	3.51**	8	Emerging for cold storage units	Limited	Yes	Yes	Yes
R-717	Ammonia	6.25	2.2	Consolidated for large industrial HVACR	No	Limited	Limited	Highly
HCFC-22	HCFC	6.11	162	Phasing out, bans on new equipment	Yes	Yes	Yes	Yes
R-410a	HFC-32/HFC-125 (50/50)	5.78	111	Phasing out, bans on new equipment	Yes	Yes	Yes	Yes
HFC-134a	HFC	6.06	32	Phasing out, bans on new equipment	Yes	Yes	Yes	Yes

* Tabulated CoP for a standard MT refrigeration cycle:[116] condensation at -7.2°C/evaporation 30°C.

** Field performance of CO_2 equipment differs from tabulated CoP values.

Commercial refrigeration equipment manufacturing based on propane (HC-290) has reached economy of scale[209]. CO_2 (R-744) is the safest refrigerant gas offered at a reasonable cost. Ammonia is the lowest priced and most abundant refrigerant, a main driver for its industrial applications. Ammonia is a commonly employed refrigerant in animal meat processing, dairy and ice cream plants, beverage processing facilities, ice rinks, warehouses, shipboard seafood processing, and petrochemical facilities[5].

The economic feasibility of environmentally sound refrigerants is translated into widening customer adoption. According to a recent report from ATMOsphere[19], market penetration of CO_2, HC, and HC/CO_2-based systems for cold storage is steadily increasing in the U.S. at an annual pace of 2.2%, while Europe is witnessing exponential growth with an expected increase of about 100% in cold storage revenue with respect to pre-pandemic levels, mainly due to online grocery shopping. By December 2022, there were 1,895 and 57,000 sites with transcritical CO_2 refrigeration systems in North America and Europe, respectively[19].

4.1 – Economics of Heat Pumps

Electric heat pumps that use refrigerant gases are being adopted at a high rate for home heating purposes because they have a higher energy efficiency and safety than traditional gas furnaces[2,227]. Moreover, heat pumps can deliver both heating and cooling functions, whereas furnaces can provide only heat Electric heat pumps present higher equipment costs but lower installation and operating costs[228] while providing positive climate governance outcomes.

The U.S. Inflation Reduction Act updated the Enhanced Use of Defense Production Act, authorizing US $250 million in funding[229] to accelerate the adoption of heat pumps, water heaters, heat pump system components, and renovation of existing production facilities to transition away from direct fossil energy use[230]. The government of Canada provides up to 5,600 CAD in grants[231] to individual homeowners to heat pumps.[232] The grants cover home evaluations, new equipment costs, electrical upgrades, and fuel tank removal, and are available to homeowners whose annual earnings are at or below the median household income after taxes.

The British Department for Business, Energy & Industrial Strategy experimented with a living heat pump lab[233], called the Electrification of Heat (EoH) demonstration project, funded by the UK government, to test the feasibility of a large-scale rollout of heat pumps in existing British homes. The project ran from July 2020 to October 2021 and involved the installation of 742 heat pumps in a broad spectrum of housing types and socio-economic groups. Refrigerants covered in this trial were HC-290 (propane) and HFC-32 (moderated GWP, difluoromethane) for newly installed units and R-410a (phasing out HFC blend) for previously installed HVAC units.

For the EoH project, three contractors installed various heat pumps, including air-source heat pumps (able to work with propane), ground-source heat pumps, and hybrid heat pumps, ranging from £10,000 to £45,000. The cost of improving the insulation of older homes was between 10 and 30% of the total renovation cost. No property type or architectural era is unsuitable for a heat pump deployment. However, propane heat pumps require placement away from drains, creating potential layout issues in existing properties. Scaling up this £14M living lab nationwide in the UK could create 9,700 direct, indirect, and induced jobs and a gain of almost 15:1 over ten years[234].

4.2 – Economic comparison of options

Table 10 lists the cost of implementing refrigerants that are widely used in the market for different applications. Equipment costs depend upon various factors, such as design, parts, operation settings, construction materials, space usage, or the temperature difference between the heat sink and the heat source. Installation and indirect costs are omitted from the analysis due to their highly variable nature.

Novel equipment working with non-halogenated refrigerants currently presents a higher equipment cost per cooling capacity than F-gas-based HVACR. The price of refrigerant-grade HCs is comparable with novel HFOs, but the equipment that works with HCs is designed to minimize the required refrigerant charge[235]. Startups face significant investment challenges in developing dedicated cooling solutions to compete with established companies that leverage existing F-gas refrigerant designs. While incumbent firms benefit from their amortized F-gas-based designs, new entrants must commit substantial resources to market alternative systems despite delivering equivalent cooling capacity.

Despite CO_2, HCs, or HC/CO_2-based equipment being more expensive, newer designs present significant cost savings through performance monitoring digitalization and dedicated designs[209,222], such as adiabatic condensation that enables heat recovery in CO_2-based systems[17,236,237]. Many grocery retailers are willing to invest in HVACR systems based on non-halogenated gases as an effective way to achieve GHG emission goals[13,14] while avoiding corporate liabilities related to using F-gas refrigerants. Equipment tailored to CO_2 demonstrates up to 50% annual energy savings, meaning short payback

TABLE 10

Equipment cost per cooling capacity for different applications and refrigerants.

Application	Refrigerant	Class	Refrigerant charge (Kg/kW of CC)	New equipment cost ($ per kW of CC)					
				Equipment			Refrigerant		
Split air conditioning	HFC-32	HFC	0.18	311	±	73	0.6	±	0.2
Split air conditioning	R-410a	HFC blend	0.18	153	±	34	20	±	5.0
Window air conditioning	R-410a	HFC blend	0.46	559	±	54	50	±	2.8
Window air conditioning	HFC-32/HC-290	HFC/HC blend	0.13	304	±	63	9.2	±	1.2
Centralized air conditioning	HFO-1234ze(E)	HFO	0.18	194	±	0	22	±	5.0
Mobile air conditioning	R-744	CO_2	0.10	1044	±	0	0.8	±	0.0
Mobile air conditioning	HFC-134a	HFC	0.09	310	±	137	3.8	±	0.9
Mobile air conditioning	HFO-1234yf	HFO	0.04	530	±	230	21	±	0.0
Commercial refrigeration	HC-290	HC	0.01	124	±	43	2.4	±	0.8
Commercial refrigeration	R-744	CO_2	0.63	1788	±	324	7.5	±	3.1
Household cold storage	HC-600a	HC	0.40	2810	±	1590	57	±	26
Heat pumps	R-410a	HFC blend	0.37	321	±	57	38	±	5.0
Heat pumps	HC-290	HC	0.07	355	±	142	2.4	±	0.4
Industrial refrigeration	R-744	CO_2	0.98	6240	±	3048	5.7	±	3.3
Industrial refrigeration	R-744+R-717 (Cascade)	CO_2+NH_3 working in tandem	1.30+0.76	2911	±	422	2.9	±	0.0
Industrial refrigeration	R-717	Ammonia, NH_3	2.60	2588	±	872	2.2	±	0.8
Industrial refrigeration	R-717 (ULC)	Ammonia, NH_3	0.23	2170	±	1886	5.7	±	0.0

*Averaged values, variability is within 40%.

periods for the initial investment[16,18]. It is expected that CO_2 will achieve wider application in food storage (convenience stores and cold rooms)[17,209] and regular use in heat pumps[1], a major contributor to fully replacing HFCs before 2030. The number of self-contained HC-based refrigeration cabinets in U.S. stores was estimated to be 919,000 in December 2022, a 12% annual increase[19].

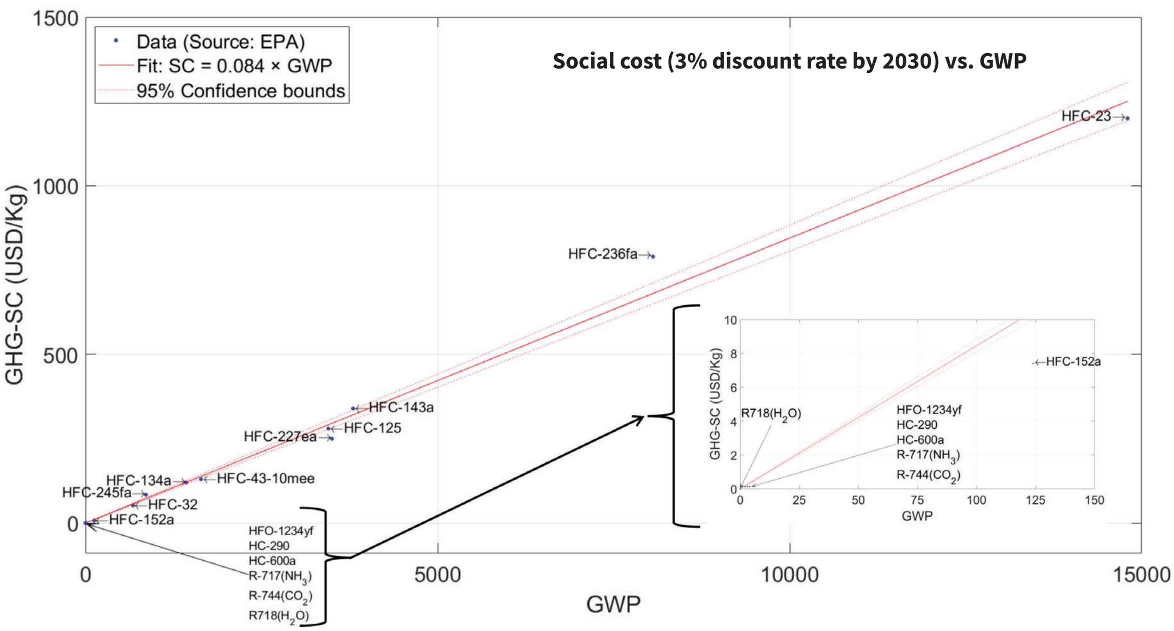
The widespread adoption of cascade ammonia/CO_2 systems within OECD countries is largely attributed to incentives offered to industrial users to transition away from outdated HCFC-22 technology[5,209]. Additionally, novel designs meet cooling capacity demands with lower ammonia charges. ULC ammonia systems have a specific charge that could go as low as 0.018 Kg/kW, representing a stark contrast to direct expansion systems[22] with a charge of up to 2.6 Kg/kW, minimizing refrigerant fill costs and potential liabilities related to acute toxicity and eutrophication.

4.3 – Socioeconomic impact considerations

Besides techno-economic benefits, moving away from F-gases greatly contributes to social well-being. The U.S. EPA recently defined and reported a comparison of climate-related social costs of different HFC refrigerants and their potential drop-in replacements. The GHG social cost (GHG-SC) is a quantitative estimate of climate impact compensation that federal and state agencies are considering for rulemaking[27,28,238]. The GHG-SC considers all climate change impacts, such as changes in the net value of ecosystem services, EHS hazards, property damage from increasing natural disasters, disruption of energy systems, and risk of conflict. The GHG-SC reflects the societal value of policies and initiatives preventing GHG emissions. Figure 5 shows a remarkably strong linear correlation between the GWP of refrigerant gases and their associated GHG-SC reported by the EPA[10].

According to a 2020 EPA National Center for Environmental Economics report, phasing down HFCs could provide US $37 trillion in climate benefits following current international agreements, with even greater benefits (US $41 trillion) if the phasedown is expedited[11]. However, it's important to note that the EPA Office of Air and Radiation subsequently reviewed these findings and established an official value between US $265 and $270 billion in net benefits[9], considering both the climate benefits and the compliance costs associated with phasing down HFCs.

FIGURE 5
The social costs of refrigerant gases rise linearly with their GWP.



Socioeconomic impacts of PFAS water pollution in the U.S.

The locations of F-gas production sites in the U.S. are strongly associated with areas where high levels of PFAS have been found in water and people[128,135,239,240]. The U.S. EPA has confirmed this geographical relationship between F-gas production sites and PFAS contamination hot spots[10]. The EPA recently proposed a PFAS National Primary Drinking Water Regulation[161] expected to impact around 66,000 water systems[162]. The estimated cost for implementation and treatment is between US $772 million and US $1.2 billion annually, potentially rising an additional US $30-60 million annually if stricter waste disposal regulations are enforced[162].

The American Water Works Association estimates that the PFAS remediation costs in the U.S. represent a national burden of US $10 to $70 billion[173] when considering only the removal of long-chain PFAS. Effective removal of short-chain PFAS, such as TFA, HFCs and HFOs, from polluted water bodies can be as costly as $1 to $3.50 per cubic meter[241,242]. While societal costs of current PFAS-polluted sites amount to several trillion USD[174,243], most optimistic market value prospects for HFOs are between two and three billion USD[244,245].

On the other hand, carbon dioxide, ammonia, and hydrocarbon refrigerants are anticipated to have a much lower end-of-life cycle impact; at the same time, most of their impact during manufacturing can be mitigated by implementing alternative production processes, especially in the case of ammonia[6,7] and propane[246].

5. Overall Alternatives Assessment of Refrigerant Gases

Refrigerant alternatives to HFCs include HFOs, ammonia, hydrocarbons, and carbon dioxide. Table 11 summarizes the different refrigerant families' benefits, drawbacks, and relevant LCI aspects, including potential mitigation measures. Based on this analysis, avoiding the use of F-gases in HVACR is feasible.

While businesses are looking for cost-effective and reliable refrigerants, corporate liabilities associated with possible litigation or enhanced regulation associated with HFCs can potentially exceed profits by several orders of magnitude. In recent years, PFAS-producing companies have faced several lawsuits[181–183,188,190,247] regarding the consequences of the pollution at their production sites, taking a toll on their market value[248,249] and threatening F-gas availability. Moreover, HFOs are more expensive than HFCs and do not ensure better energy performance[250,251].

While manufacturers recognize the EHS and potential corporate liability challenges associated with F-gas refrigerants, ongoing market dynamics continue to drive the development and promotion of certain PFAS-based refrigerant technologies[252]. The main argument is that HFOs can help reduce GHG emissions by maintaining the efficiency of retrofitted equipment and working in novel, improved heat pumps. However, HFOs present flammability issues, hidden GHG-SC related to their environmental fate, and PFAS-related impacts on public health.

Moreover, retrofitting outdated refrigeration systems with newer fluorinated chemicals is a common short-term solution, but it is not sustainable given the associated avoidable GHG emissions. The potential for the eventual transformation of HFOs to HFC-23, with its very high GWP, undermines the climate change mitigation objective of phasing down HFC use globally under the Kigali Amendment of the Montreal Protocol. Therefore, HFOs may potentially be considered a regrettable substitute for mitigating the climate impact of HFC-based refrigeration systems.

On the other hand, HVACR equipment with safer refrigerants is available today and is cost-competitive with its F-gases counterparts. Many industries are shifting focus to non-halogenated refrigerants, and specialized manufacturing companies are committed to scaling up production to meet market demand and policy targets. Companies specialized in manufacturing equipment working with non-halogenated refrigerants for other applications are also crowding into the heat pump space[2], seeing the market opportunity[253]. Small and medium end users are future-proofing their refrigeration systems to avoid continuous refrigerant changes, and several market leaders are converting their sales portfolio to fully non-halogenated by 2027[1,12,209].

5.1 – Conclusions

There is no universal solution for the wide variety of refrigeration systems and applications. Nonetheless, with proper technological advancements in place, carbon dioxide, ammonia, and other non-halogenated organic compounds are replacing the role of F-gas refrigerants. Innovative iterations of these alternatives have been proven effective and safe in cooling systems while presenting reduced EHS hazards[82,217,254]. We currently have feasible opportunities to switch to safer refrigerants and protect workers, public health, and the environment.

The choice of a refrigerant depends on the specific application. Important factors to consider for a drop-in substitute are safety, cost, performance, and the ability to retrofit existing equipment, particularly for systems currently using the most widely used refrigerants that will likely be phased out[255]. Despite the short-term benefits of retrofitting, purchasing modern equipment presents a more compelling case regarding safety and performance improvements. Retrofitting outdated equipment may increase the likelihood of leakage and reduce energy efficiency, which can result in higher indirect GHG emissions. In contrast to older HVACR generations, safer and viable non-halogenated alternatives to HFCs are widely available now.

Equipment design deeply influences refrigerant performance. Historically, comparing performance under standardized conditions has, in some cases, perpetuated the use of F-gases. This approach can overlook the potential of non-halogenated refrigerants when paired with equipment specifically designed for F-gas properties. Refrigerant gases work within a dedicated vapor compression cycle with specific machinery and materials. Equipment configuration determines the efficiency and safety of a refrigerant, and it is worth revisiting available equipment options that now enable the use of refrigerants discarded in previous generations.

The impacts of the extraordinary persistence of PFAS on public health and the environment, discussed in Section 2.6 and 4.1, prompt a critical reassessment of the use of PFAS. The trend is toward a more judicious approach, minimizing nonessential applications of PFAS[256]. Under the proposed ECHA PFAS restriction[49], some refrigerant uses would be given time-limited derogations of 5 or 12 years for further alternatives to be developed or for new designs and processes to be implemented. A transition to non-halogenated refrigerants is technically achievable and has already been implemented in various sectors[48].

Table 11 offers a summarized comparison among refrigerant families. Novel technologies fulfill current refrigeration requirements using CO_2, HCs, or ammonia. Efficient compression[257], pressure control[258], and heat recovery features[1] enabled the application of transcritical CO_2 for commercial applications such as supermarkets. The latest hermetic systems and electric safety standards[259] allowed the expansion of the hydrocarbon refrigerant market into commercial and residential applications. There are a variety of additional solutions that can also be implemented to reduce the environmental impact of refrigeration systems. These include building insulation upgrades and renewable energy use[260]. While traditional ammonia systems pose latent liabilities due to requiring large quantities of refrigerant, low-charge ammonia designs[5] drastically reduce human exposure and eutrophication potential in the event of a leak. However, proper training and safety protocols are still essential for all facilities using ammonia to help protect worker safety and handle potential leaks effectively. Although some trade-offs may be necessary, the long-term environmental and financial advantages of these alternatives outweigh the short-term challenges.

The flammability of HFOs is only slightly lower than that of HCs. Recognizing the importance of addressing fire hazard concerns, refrigerant manufacturers are introducing blends containing high-GWP refrigerants as fire suppressants to mitigate HFO and HC flammability. The latest ASHRAE safety standards imply a growing acceptance of flammable refrigerants for commercial and industrial applications. This significant shift in perspective fosters innovation and encourages the adoption of HCs. Therefore, blends containing high-GWP HFCs are a regrettable option due to their unnecessary climate or PFAS hazard tradeoff for a safety concern already addressed by equipment and building design.

The US-EPA ENERGY STAR program incentivizes energy-efficient upgrades for homes and buildings with tax credits and deductions. Over 600 HC-based household refrigerators and 700 lab-grade freezers are ENERGY STAR certified. However, a lack of incentives for purchasing non-fluorinated equipment remains a barrier to faster transition.

The development of innovative HVACR technologies based on safer refrigerant gases is driven by new environmental regulations, changing preferences and needs of diverse stakeholders, and public awareness of environmental issues regarding and beyond climate change. Recent technologies (heat pumps, smart sensors, dedicated design, etc.), regulatory GWP thresholds, and PFAS restric-

TABLE 11

Comparative qualitative analysis of the different refrigerant gas families.

Name(s)	Applications	Technology	Cost*	Manufacturing	Benefits	Hazards / Drawbacks	Mitigation measures
Ammonia (NH_3) R-717	Industrial refrigeration and large-scale food storage. Retrofitting of R-22-based HVACR equipment in non-residential buildings.	High efficiency, well established. Mostly used for industrial cooling.	Inexpensive (1 $/kW CC)	Haber process or electrolysis of hydrogen and nitrogen	Non toxic for soil. Zero GWP and ODP.	Highly Toxic for humans (acute respiratory). Elevated risk of immediate death in leaking events. High eutrophication. Corrosive (when wet) to copper, brass, and zinc.	Enforcement of safety standards. Low charge designs.
Carbon dioxide (CO_2) R-744	Motor vehicle air conditioning systems. Refrigerated transport. Commercial HVACR.	High-pressure equipment with heat recovery.	Inexpensive (2-4 $/kW CC)	CO_2 purification	Non-toxic. GWP=1. No water crystallization problems.	Might require the use of ammonia or HCs to increase efficiency. High initial investment.	Enforcement of efficiency standards. Enhance efficiency from equipment design.
Hydrocarbons (HCs)	New household refrigerators and freezers: HC-290; HC-600a. SNAP approved for ULT refrigeration: HC-1170.	Safe use under UL 60335-2-24 equipment standard.	Low to high (3-25 $/kW CC) depending on the application	Hydrocarbon purification	Non-toxic Low-GWP Zero ODP.	Flammability reduction by HFC or CO2 blending reduces efficiency.	Safety standards. Flammability mitigated by equipment design
Hydrocarbons + CO_2	Large-scale food storage and commercial refrigeration.	Cascade systems with heat recovery. Higher efficiencies than CO_2.	Lower cost than pure HCs.	Same as CO_2 and HC	Non-toxic Low GWP	Fire hazard (lower than HCs). High initial investment.	Driving design innovation
Chlorofluorocarbons (CFCs)	Phased out by enforcement of Montreal protocol.				High efficiency. Low corrosion.	High ODP; very high GWP.	Enforcement of Montreal Protocol
Hydrofluorocarbons (HFCs)	80% of currently installed HVACR equipment for residential, mobile, and commercial applications	High efficiency	Low to high (5-31 $/kW CC) depending on the application	Hydrogen Fluoride + chlorinated chemicals.	Zero ozone depletion potential (ODP).	High to very high GWP.	Enforcement of the Kigali Amendment of the Montreal Protocol. GWP>150 F-gases are banned.
Hydrofluoroolefins (HFOs)	Mobile air conditioning (HFO-1234yf); HFO-1336mzz(Z) in refrigeration and air conditioning R-513A in food refrigeration.	Similar efficiency as HFCs, drop-in available	High (19-23 $/kW CC)	Hydrogen fluoride + HFCs. Requires carbon tetrachloride and CFCs for precursor manufacturing.	Low GWP.	PFAS-related pollution HFC-23 (GWP=14800) decomposition products. Moderated flammability.	Essential use and recycling policy
Hydrochlorofluoro-olefins (HCFOs): R-1233zd(E)	Cold storage, ice rinks, and industrial air conditioning (new equipment only); industrial refrigeration (new and retrofit)	Similar efficiency as HFCs, drop-in available	High (23-44 $/kW CC)		Lowest GHG potential halogenated alternative.	Toxicity concerns and moderated flammability. Water crystallization pipe clogging. Very persistent pollutant.	Essential use and recycling policy
Water (R-718)	Large scale HVACR equipment.	Still under development.		Water purification	Non-toxic. GWP=0.	Expensive equipment.	Driving design innovation

■ Safer alternative ■ Feasible, but finding an alternative is recommended
■ Seldom used or mostly unfeasible at the moment ■ Avoid use, phasing out

* Costs are shown in $/kW cooling capacity, including refrigerant charge and power consumption.
See Table 10 above for equipment prices across domestic (<20kW), commercial (20-350kW), and industrial (>350kW) applications.

tions will shift the market toward CO_2, NH_3, and HCs. Moreover, EPA-SNAP already allows propane and isobutane in new refrigerated food preservation equipment and ethene for ULT applications, while adoption trends of HC-based heat pumps are strong in the EU and the UK.

The Clean Air Act, the Safe Drinking Water Act, and the Clean Water Act are benchmark environmental laws in the United States. However, without a robust and holistic hazard study, efforts to achieve the objectives of one law may undermine the other. Environmental regulation agencies such as ECHA utilize the OECD definition of PFAS[261] that includes HFCs and HFOs. This is different from the US-EPA PFAS definition[162], only applied in the U.S., which excludes commercially available HFCs and HFOs. It is worth recalling that HFCs and HFOs are also utilized as precursors in PFAS production. As of November 2024, some PFAS restrictions on manufacture, distribution, and/or use have been adopted in 30 U.S. states[186]. While the new generation of F-gas refrigerants is currently accepted as alternative refrigerants, increasing regulatory pressure on the production and use of F-gases[1,27,28] and PFAS[30,31,49] will likely result in limitations of HFO and HFC availability.

The nationwide costs of PFAS water compliance far exceed the profits from producing PFAS-containing products[174.] Water treatment facilities are unable to cover these expenses, so they will likely pass them on to taxpayers[262]. As stated in Section 4.3, the costs to society from PFAS-related damage associated with HFO production are several orders of magnitude higher than the economic value of HFOs[174,242]. Additionally, because HFOs may potentially produce HFC-23 during their environmental degradation, their effective GWP could be higher than regulatory thresholds. These findings suggest that using HFOs is not economically or environmentally sustainable. Considering their significant environmental impact, HFOs are likely regrettable substitutes for HFCs due to their associated PFAS pollution and potential degradation to HFC-23.

GWP and ODP are static metrics that do not capture the full range of the impacts of refrigerant gases in the environment. Several commercially available products are blended with high-GWP HFCs to fit within GWP regulatory thresholds. Moreover, HFO production involves CMRs as precursors[77–79] and PFAS as by-products[263]. HFOs degrade into TFA[100,166] and also potentially generate the very high-GWP HFC-23 as a derivative during their environmental fate[96,109].

Some industry concerns regarding non-halogenated refrigerants focus on compatibility with existing equipment. However, a comprehensive evaluation should also consider the environmental benefits of non-halogenated options and the economic benefits of acquiring newer generations of HVACR equipment against retrofitting. Due to supply chain risks and recent technological advances, CO_2, ammonia, and HCs are expected to dominate industrial refrigeration in OECD countries by 2027[1,3], except in military equipment. Ammonia, HCs, and CO_2 can be obtained from cleaner manufacturing processes promoting sustainable and responsible production practices. On the other hand, viable eco-conscious manufacturing for HFOs remains a distant and largely theoretical prospect, with substantial technological and environmental challenges still standing in the way of practical implementation.

Non-fluorinated refrigerants reduce greenhouse gas emissions compared to F-gas systems and avoid the issue of PFAS pollution associated with some HFOs. Policy can be a main driver for shifting away from F-gas-based systems. Stringent regulations on F-gas production and use will limit their availability in the future. The market adoption of non-halogenated refrigerants is rising.

In summary, non-fluorinated refrigerant options are not just emerging, they're rapidly transforming the market landscape. The economic tide is decisively turning against F-gases, with rising costs and production constraints rendering them increasingly unviable. Hydrocarbon (HC) refrigerants and CO_2 systems are now delivering cost-competitive solutions that go beyond mere alternatives, offering breakthrough operational efficiencies. Cutting-edge designs are unlocking unprecedented heat recovery capabilities, while the substantial energy savings from next-generation equipment dramatically compress investment payback periods, making the transition not just environmentally responsible, but financially compelling. Modern equipment offers faster payback periods and delivers greater indirect carbon emission reductions. Overall, non-fluorinated HVACR systems offer a compelling alternative to traditional F-gas-based technology.

The rapid growth of the global refrigerant market demands nuanced decision-making that balances climate concerns with comprehensive environmental, technological, and socioeconomic implications, recognizing that narrow climate-centric approaches may inadvertently create broader systemic challenges. There is no single solution for all refrigeration systems, but transitioning to safer refrigerants is feasible and necessary. Innovative compact HVACR systems and solid-state heat pumps based on cutting-edge technologies like the thermoelectric effect or magnetic refrigeration, briefly referred to in the next section, are emerging as viable cooling alternatives to eliminate refrigerant gas use. We can usher in a new era of sustainable cooling practices by adopting these breakthrough solutions.

5.2 – Research needs for safer refrigeration

Table 12 summarizes the challenges for research and innovation toward safer refrigeration systems.

TABLE 12
Research and development directions towards safer refrigeration.

Topic	Developing targets	Disciplines	References
Corrosion protection	• Corrosion-resistant materials and composites. • Wear resistant protective polymeric or ceramic coatings. • Extending lifetime of CO_2, NH_3 and water-based equipment.	• Material science • Chemistry • Physics	264–266
Safety by design	• Lowering refrigerant charges, especially toxic and flammable. • Safer, non-toxic refrigerants. • Smaller equipment, compact stages. • Heat exchanger geometry for process intensification. • Extended material compatibility tests for parts and lubricants. • Policy incentives to implement HVACR systems using future-proof refrigerants. • Refrigeration systems that do not require refrigerants (see Peltier refrigeration below).	• Physics • Chemistry • Engineering	210,267–269
Alternative vapor compression cycles	• Dedicated design for CoP augmentation. • Organic Rankine Cycle (ORC). • Reverse Brayton cycle – Can use air or CO_2 and direct solar energy. • High-temperature heat pumps fit for H2O and CO_2. • Absorption-compression cycles. • Indirect evaporation: Water-air.	• Physics • Chemistry • Engineering	32,204,270–278
Integration with renewable energy	• Engineering optimization to increase Market Readiness Level (MRL). • Energy policies and green building incentives.	• Physics • Engineering • Architecture	279,280
Peltier refrigeration	• Increasing MRL of portable cooling devices. • Scale up (material availability, costs, design). • High theoretical CoP; low actual CoP; R&D focused on reaching theoretical CoP. • Liquid coolant for heat transfer. • Reducing reliance on bismuth, tin, and telluride for commercial devices.	• Materials science • Solid State Physics • Engineering	281–283
Magnetic refrigeration	• Materials based on widely available elements (iron, manganese, silicon, aluminum). • Improve MRL through scaling down to portable devices. • Corrosion protection. • Increasing efficiency.	• Materials science • Solid State Physics • Engineering	226,284
Elastocaloric refrigeration	• Latest developments could achieve similar cooling capacities as other solid-state refrigeration technologies, using inexpensive elements (Fe, Ni, Ti). • Experimental phase, enhancing Technology Readiness Level required.	• Materials science • Solid State Physics • Engineering	285

Appendix I: Relevant properties of refrigerant gases on the market

Tables in this appendix are adapted from sources: 10,85–87,99,138,146,205,271,286–290.

TABLE A1

Comparison of EHS properties, atmospheric lifetime, and safety classifications of HFCs and HCFCs.

Commercial Name	CAS #	Chemical Name	GWP	ODP	POCP	Atm. Life Time (days)	CoP	Safety Class	LFL (g/m³)	OEL (ppm v/v)	Pharos EHS Class
HCFC-141b	1717-00-6	1,1-dichloro-1-fluoroethane	0.14	0.11	0.1	3,650	N/A	N/A	287	500	LT-UNK
R-1130(E)	156-60-5	trans-Dichloroethylene	25	0	34	12.7	N/A	B2	258	1,000	LT-P1
HCFC-123	306-83-2	2,2-dichloro-1,1,1-trifluoroethane	77	0.04	0.3	475	4.64	B1	none	50	LT-P1
HFC-152a	75-37-6	1,1-difluoro ethane	124	0.07	N/A	548	6.00	A2	130	1,000	LT-UNK
HCFC-124	2837-89-0	2-chloro-1,1,1,2-tetrafluoroethane	470	0.02	N/A	2,154	N/A	A1	none	1,000	LT-UNK
HFC-32	75-10-5	Difluoromethane	675	0	N/A	1,898	5.92	A2L	306	1,000	LT-UNK
HFC-134a	811-97-2	1,1,1,2-Tetrafluoroethane	1,430	0	0.1	4,891	6.06	A1	none	1,000	LT-UNK
HCFC-22	75-45-6	Chloro difluoromethane	1,810	0.055	0.1	4,344	6.11	A1	none	1,000	LT-UNK
HCFC-142b	75-68-3	1-chloro-1,1-difluoroethane	1,980	0.07	0.1	6,278	N/A	N/A	329	1,000	LT-UNK
HCFC-124	2837-89-0	2-chloro-1,1,2,2-tetrafluoroethane	3,450	0	0.2	7,000+	N/A	A1	none	N/A	LT-UNK
HFC-125	354-33-6	Pentafluoroethane	3,450	0	0	10,257	4.16	A1	none	1,000	LT-UNK
HFC-227ea	431-89-0	1,1,1,2,3,3,3-heptafluoropropane	3,500	0	0	14,199	N/A	A1	none	1,000	LT-UNK w/ concerns
HFC-143a	420-46-2	1,1,1-trifluoroethane	3,800	0	0	17,192	N/A	A2L	282	1,000	LT-UNK
HFC-23	75-46-7	Trifluoromethane	14,800	0	0	98,550	N/A	A1	none	1,000	LT-UNK

ABBREVIATIONS

Atm. Lifetime — The average amount of time a chemical substance remains in the atmosphere before it is removed through natural processes;

CAS — CAS registry number is used to uniquely identify chemical substances

CoP — Coefficient of Performance

EHS — Environment, Health and Safety

GWP — Global Warming Potential (100 years)

HC — Hydrocarbon

HCFC — Hydrochlorofluorocarbon

HFC — Hydrofluorocarbon

HFO — Hydrofluoroolefin

LFL — Lower Flammability Limit

ODP — Ozone Depletion Potential

OEL — Occupational Exposure Limit

POCP — Photochemical Ozone Creation Potential

Safety class — ASHRAE standard to classify refrigerants based on toxicity in terms of:

- **OEL** — A: lower toxicity, OEL > 400 ppm; B: higher toxicity, OEL ≤ 400 ppm
- **Flammability** — Ranking from lower to higher: 1; 2L; 2; 3

TABLE A2

EHS characteristics of hydrofluoroolefins (HFOs) and hydrochlorofluoroolefins (HCFOs).

Commercial name	CAS #	Chemical name	GWP	ODP	POCP	Atm. Life Time (days)	CoP	Safety class	LFL (g/m^3)	OEL (ppm v/v)	Pharos EHS class
HFO-1225ye(E)	5528-43-8	(E)-1,2,3,3,3-pentafluoro-1-propene	0	0	N/A	N/A	N/A	N/A	N/A	N/A	NoGS
HFO-1225ye(Z)	5595-10-8	(Z)-1,2,3,3,3-pentafluoro-1-propene	0	0	N/A	N/A	N/A	N/A	N/A	N/A	NoGS
HCFO-1233zd	102687-65-0	(E)-1-chloro-3,3,3-trifluoropropene	1	$3 \cdot 10^{-4}$	N/A	46	N/A	A1	None	800	NoGS w/concerns
HFO-1234ze(E)	29118-24-9	trans-1,3,3,3-tetrafluoropropene	1	0	5.6	16	6.03	A2L	303	800	LT-UNK
HFO-1336mzz(E)	66711-86-2	(E)-1,1,1-4,4,4-hexafluoro-2-butene	2	0	N/A	26	4.40	A1	None	400	NoGS
HFO-1234yf	754-12-1	2,3,3,3-tetrafluoro-1-propene	4	0	7	11	5.84	A2L	289	500	LT-UNK
HFO-1336mzz(Z)	692-49-9	(Z)-1,1,1,4,4,4-Hexafluoro-2-butene	2	0	N/A	26	6.50	A1	none	500	NoGS w/ concerns

ABBREVIATIONS

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POCP — Photochemical Ozone Creation Potential

Safety class — ASHRAE standard to classify refrigerants based on toxicity in terms of:

- **OEL** — A: lower toxicity, OEL > 400 ppm; B: higher toxicity, OEL ≤ 400 ppm
- **Flammability** — Ranking from lower to higher: 1; 2L; 2; 3

TABLE A3

Key EHS properties of non-halogenated refrigerant alternatives.

Commercial name	CAS #	Chemical name	GWP	ODP	POCP	Atm. Life Time (days)	CoP	Safety class	LFL (g/m^3)	OEL (ppm v/v)	Pharos EHS class
HC-170	74-84-0	Ethane	6	0	9	10	3.59	A3	38	1000	LT-UNK
HC-1150	75–85–1	Ethene	4	0	100	7	N/A	A3	36	1000	LT-UNK w/concerns
HC-1270	115-07-1	Propene	2	0	160	0	5.98	A3	46	1000	LT-P1
HC-290	74-98-6	Propane	3	0	13	12	5.99	A3	38	1000	LT-UNK
HC-600	106-97-8	Butane	7	0	30	20	6.25	A3	48	1000	LT-1
HC-600a	75-28-5	Isobutane	3	0	28	6	6.17	A3	38	1000	LT-1
R-717	7664-41-7	Ammonia	0	0	0	0	6.25	B2L	116	25	LT-P1
R-744	124-38-9	Carbon dioxide	1	0	0	300	3.51	A1	none	5000	LT-UNK
R-718	7732-18-5	Water	0	0	0	0	N/A	A1	none	none	BM-4
R-E170	115-10-6	Dimethyl ether	1	0	17	6	N/A	A3	64	1000	LT-UNK

ABBREVIATIONS

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HC — Hydrocarbon

HCFC — Hydrochlorofluorocarbon

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Safety class — ASHRAE standard to classify refrigerants based on toxicity in terms of:

- **OEL** — A: lower toxicity, OEL > 400 ppm; B: higher toxicity, OEL ≤ 400 ppm
- **Flammability** — Ranking from lower to higher: 1; 2L; 2; 3

Appendix II: U.S. F-Gas sites spatial correspondence with climate and health hazards

Source: Ref. 10: US EPA. Regulatory Impact Analysis for Phasing Down Production and Consumption of Hydrofluorocarbons (HFCs), 2022.

FIGURE A1

GHG emissions of F-gas production sites in the U.S. (metric tons CO_2 equivalent).

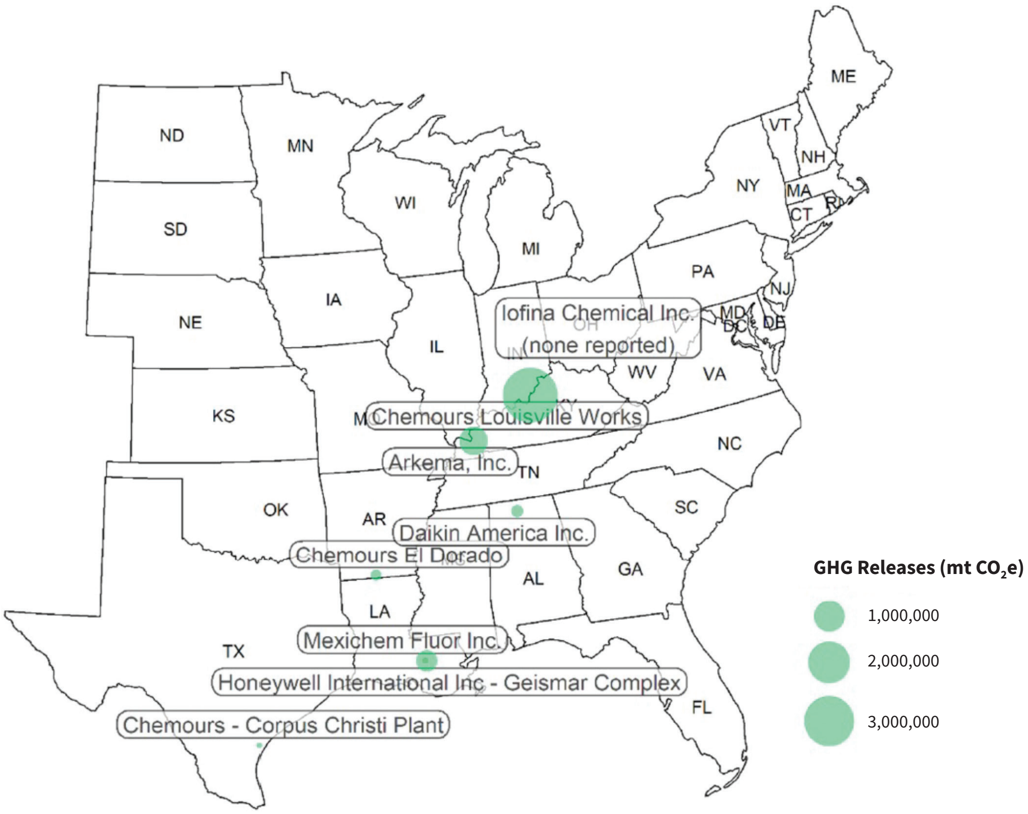


FIGURE A2

Relative respiratory risk of communities within 1 mile of HFC facilities to state averages.

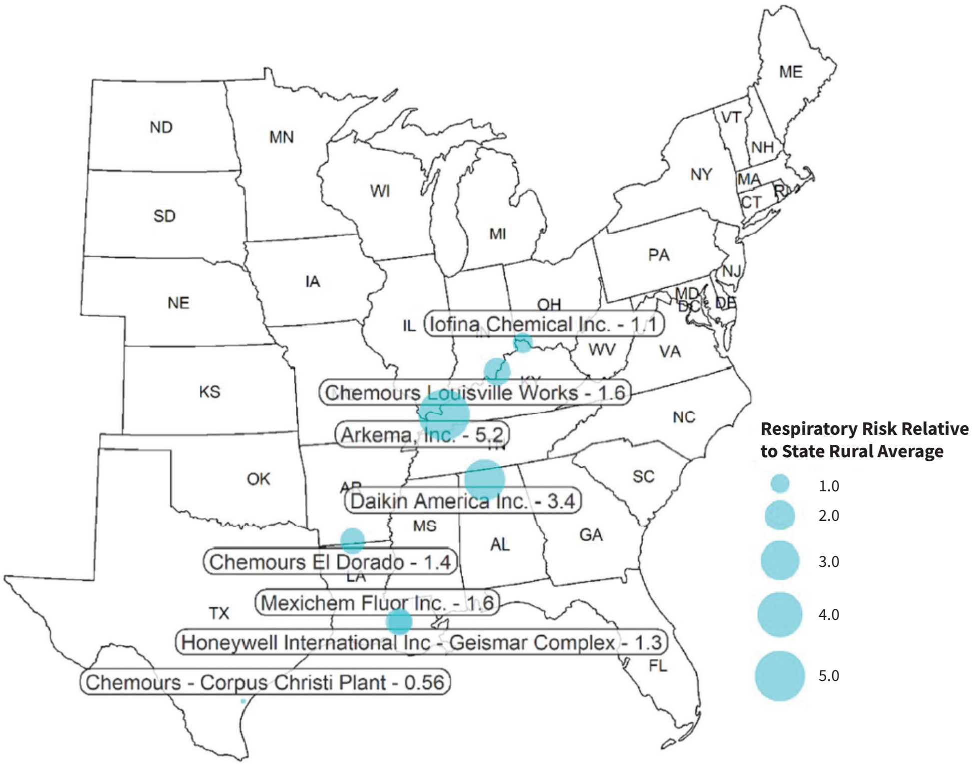
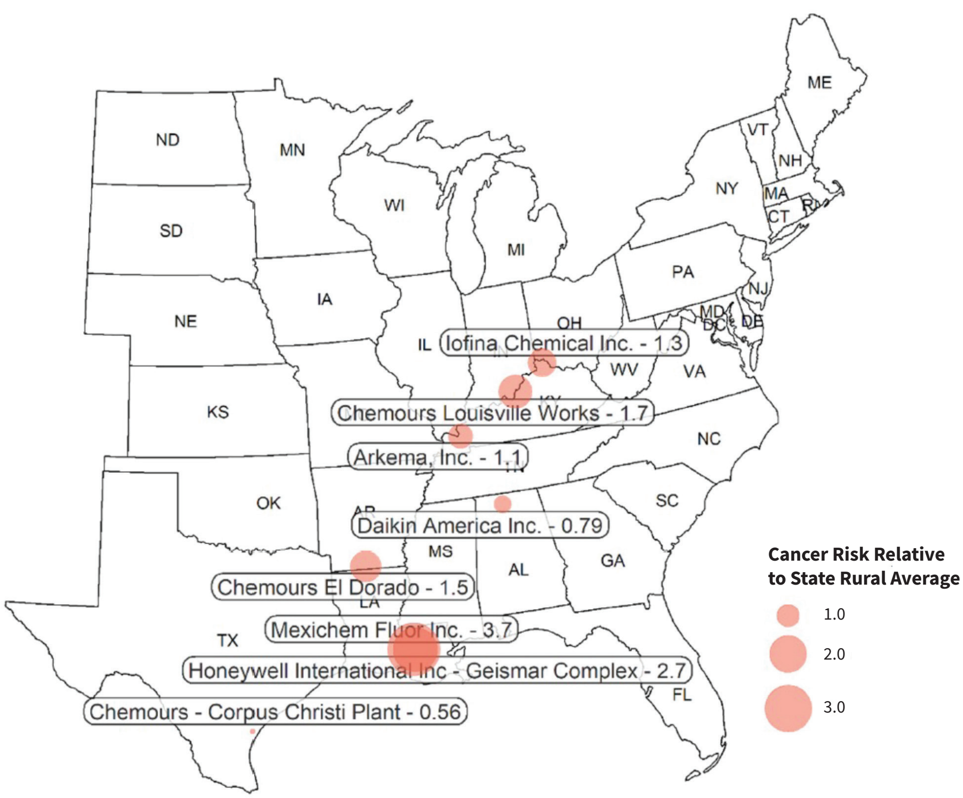


FIGURE A3

Cancer risk of communities within 1 mile of HFC facilities relative to state averages.



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