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The Toxics Use Reduction Institute (TURI) respectfully submits the following comments to the European Chemicals Agency as input on their PFAS restriction proposal regarding fluorinated gases (F-gases). TURI is an independent government agency established in 1989 by the Commonwealth of Massachusetts to help implement the state's Toxics Use Reduction Act, assisting businesses with the transition to safer alternatives to hazardous substances. TURI offers the following information based on research and experience around the assessment of alternatives, including their hazards, as companies in Massachusetts face potential restrictions on products containing hydrofluorocarbons (HFCs) and Per- and polyfluorinated alkyl substances (PFAS). TURI addresses F-gas concerns in Heating, Ventilation, Air Conditioning, and Refrigeration (HVACR) and shares data gathered about potential alternatives to HFCs and other F-gasses. TURI's objective is to provide holistic and objective information about available alternatives, particularly the newer generation of refrigeration options, to assist EU Member States in crafting an appropriate PFAS restriction and businesses in assessing their alternatives.

The term "regrettable substitute" is used when an industry or society goes through an effort to eliminate a problematic chemical and switches to another chemistry or technology but then finds that the alternative is no safer than the original chemical.

Given recent technological progress and proven instances of success, it is feasible to completely transition from F-gas HVACR systems to alternative, non-fluorinated refrigerants. TURI carefully evaluated the substitution of HFCs with HFO refrigerants and has concerns based on the evidence of environmental hazards, such as their effective Global Warming Potential (GWP) and the likelihood of PFAS pollution throughout the lifecycle of HFOs. TURI is pleased to share this information with ECHA to help review the EU PFAS restriction proposal.

HFOs are a potentially regrettable substitute for HFCs:

- The effective GWP of HFOs could be higher than regulatory thresholds, depending on the likelihood of them forming HFC-23.
- The concept of 'average GWP' does not account for the fact that some gases in a refrigerant blend may have a high GWP and long atmospheric lifetime.
- There is a risk that legislative measures focused exclusively on reducing the use of HFCs may defeat the purpose of other legislative objectives, such as protecting drinking water from PFAS contamination.
- The patented pathways to produce the HFO refrigerant family involve the use of known Carcinogenic, Mutagenic, and Reprotoxic (CMR) chemicals.
- To mitigate the flammability risks of HFOs, companies are commercializing blends with HFCs.
- The location of F-gas production sites in the US is strongly associated with areas with high levels of PFAS in water. A similar correlation may exist in the EU.
- The impact of refrigerant production and disposal is disproportionately higher on underserved communities exposed to harmful fluorinated pollutants released into the air, contributing to excess cancer rates and respiratory problems.
- Significant long-term economic costs are likely with the continued use of HFOs as refrigerants.

Business and governance potential non-fluorinated refrigerants:

- Newer CO₂, HC, and HC/CO₂ designs present significant operating cost savings over F-gas systems.
- There is strong evidence that Heating, Ventilation, Air Conditioning, and Refrigeration (HVACR) equipment with non-fluorinated refrigerants are available on the market today and are safer and cost-competitive against their fluorinated counterparts, including Ultra Low Temperature (ULT) refrigeration.
- The economic feasibility of non-fluorinated refrigerant based HVACR is translating into widening customer adoption.
- CO₂, HC/CO₂ cascade systems and Ultra Low Charge (ULC) ammonia systems are expected to dominate commercial and industrial refrigeration in less than 5 years in OECD countries.
- A deterrent that slows the transition to non-fluorinated refrigerants is the need for investment in suitable equipment that works with such refrigerants.
- Transitioning to low-GWP refrigerants is just one of five main engineering strategies for reducing the climate impact of vapor compression HVACR.
- The latest safety standards show a growing acceptance of flammable refrigerants for commercial and industrial applications, enabling the adoption of hydrocarbons.
- Upgrading mobile refrigeration to non-fluorinated refrigerants is within reach.
- Besides techno-economic benefits, moving away from F-gases presents opportunities for significant social benefits through enhanced environmental protection.

The effective GWP of HFOs could be higher than regulatory thresholds, depending on the likelihood of them forming HFC-23.

While the Global Warming Potential (GWP) metric does not usually contemplate the effect of degradation compounds, the effective GWP does take into account GHG gas generation during environmental fate. There is evidence suggesting that commercially available HFOs, although having a low atmospheric lifetime, could potentially decompose to HFC-23 (trifluoro methane or fluoroform; CHF₃ GWP₁₀₀ = 14800; CAS number: 75-46-7) [1]. 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 HVACR systems.

There is evidence of various HFO degradation mechanisms leading to the production of the high global warming HFC-23. There is evidence that HFO-1234ze(E) and HFO-1234ze(Z) degrade quickly and quantitatively into Trifluoro acetaldehyde (CF₃CHO; trifluoroethanal; TFE; CAS number: 75-90-1), while HFO-1336mzz(E) produces one molecule of TFE and one molecule of TFA per HFO-1336mzz(E) molecule quantitatively [2]. HFO-1234yf and HFO-1225ye produce trifluoroacetic acid (CF₃COOH; TFA; CAS number: 76-05-1) [2–5] quantitatively by oxidation in atmospheric conditions. Although TFA is well known for its chemical stability, it is not expected to remain intact and could lead to the formation of HFC-23 through diverse pathways (e.g.: [6–9]), while TFE is a well-known photochemical precursor of HFC-23 [1,10].

The concept of ‘average GWP’ does not account for the fact that some gases in a blend may have a much higher GWP and atmospheric lifetime, and it does not avoid the release of high-GWP persistent gases into the atmosphere, even having a low weighted average GWP. The ‘average GWP’ does not contemplate HFO degradation products. More careful consideration is needed to balance concerns about PFAS [11] with those of climate change [12–14].

There is a risk that legislative measures focused exclusively on reducing the use of HFCs can defeat the purpose of other legislative objectives, such as drinking water protection from PFAS.

Authorized HFOs and HFO/HFC blends are associated with halocarbon and PFAS water pollution. Currently, certain F-gases approved by the EPA Significant New Alternatives Policy (SNAP), such as HFO-1233zd, HFO-1234ze(E), HFO-1234yf, and their blends with HFCs are not listed as PFAS by US regulations, while classified as PFAS by internationally accepted definitions [15,16]. The approval of F-gases under the US Clean Air Act (CAA) could significantly undermine ongoing water resource protection from PFAS under the US Clean Water Act (CWA) among other PFAS regulatory initiatives. Effective removal of PFAS from water-polluted bodies can be as costly as 1.1 USD per cubic meter [17]. PFAS remediation costs in the US are a National Burden of almost 70 billion USD [18], while societal costs of current PFAS-polluted sites amount to several trillion USD [19].

The patented pathways to produce the HFO refrigerant family (shown in Figure 1), involve the use of known Carcinogenic, Mutagenic and Reprotoxic (CMR) chemicals [20–22].

Carbon tetrachloride (CTC) [23], perchloroethylene (PCE) [22], and HFCs [20] are precursors in the production of HFOs and PFAS as intended or unintended by-products [21]. Given that CTC and PCE, classified as known CMR chemicals, are key precursors involved in the manufacture of HFCs and HFOs, F-gas manufacturing process will inevitably have a harmful Environmental, Health and Safety (EHS) impact to workers and ‘fence line’ communities nearby production sites [24,25]. EPA determined that CTC presents unreasonable risk [26] to workers from long-term inhalation and dermal exposures and liver toxicity from short-term dermal exposure, and has proposed risk management measures including an existing chemical exposure limit (ECEL) of 0.03 ppm as an 8-hour time-weighted average (TWA) [27]. This illustrates additional concerns raised over production phase of the HFOs lifecycle.

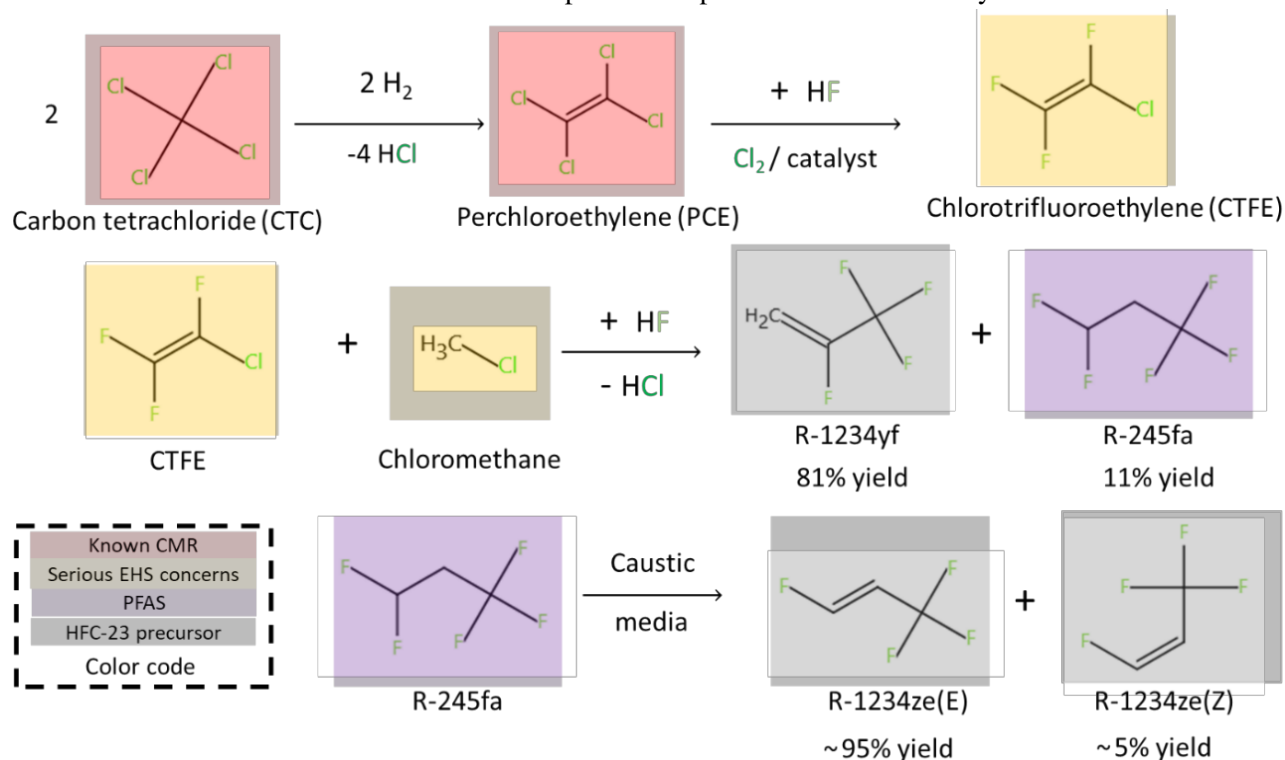


FIGURE 1: CHEMICAL PATHWAYS FOR THE PRODUCTION OF HFO REFRIGERANTS.
SOURCE: MASSACHUSETTS TOXICS USE REDUCTION INSTITUTE.
BASED ON REFERENCES [20–23,26–29]

The location of F-gas production sites in the US is strongly associated with areas where high levels of PFAS have been found in water [30–33].

The Environmental Protection Agency (EPA) has confirmed this correspondence by releasing maps that show the spatial relationship between F-gas production sites and PFAS contamination hot spots [24]. On

the other hand, non-fluorinated refrigerants are anticipated to have a much lower Life Cycle Impact (LCI). Especially in the case of ammonia [34,35] and propane [36,37], most of their impact during manufacturing can be mitigated by implementing alternative production processes.

The impact of refrigerant production and disposal is disproportionately higher on underserved communities exposed to harmful fluorinated pollutants released into the air, contributing to excess cancer rates, and respiratory problems.

Studies have shown that people living near F-gas production sites have higher levels of these chemicals in their blood than those living further away [24,38]. It is expected, given that ***fluorinated gas production takes place in facilities that co-produce Poly- and Per-FluoroAlkyl Substances (PFAS)*** [39], using similar precursors.

As a result of increased public awareness [40–42] and stricter regulations [43,44], many chemical companies have been forced to take action to address the PFAS-related issues: from leaving the PFAS market altogether [45], settling multi-billion USD lawsuits [46–50] or selling their F-gas production facilities to other companies [51]. In this context, the potential use of climate change mitigation as a justification for the continued production and sale of PFAS fluorinated chemicals [12–14] is concerning.

Newer CO₂, HC and HC/CO₂ designs present significant operating cost savings over F-gas systems.

Table 1 lists the cost of implementing refrigerants for different end uses. Equipment costs depend upon 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 hypervariable nature.

Application	Refrigerant	Refrigerant charge (Kg/kW of CC)	New equipment cost (USD per kW of CC)	
			Equipment	Refrigerant
Split air conditioning	R-32	0.18	311	0.6
Split air conditioning	R-410a	0.18	153	20
Window air conditioning	R-410a	0.46	559	50
Window air conditioning	R-32/R-290	0.13	304	9.2
Centralized air conditioning	R-1234ze(E)	0.18	194	22
Mobile air conditioning	R-744	0.10	1044	0.8
Mobile air conditioning	R-134a	0.09	310	3.8
Mobile air conditioning	R-1234yf	0.04	530	21
Commercial refrigeration	R-290	0.01	124	2.4
Commercial refrigeration	R-744	0.63	1788	7.5
Household cold storage	R-600a	0.40	2810	57
Heat pumps	R-410a	0.37	321	38
Heat pumps	R-290	0.07	355	2.4
Industrial refrigeration	R-744	0.98	6240	5.7
Industrial refrigeration	R-744+R-717 (Cascade)	1.30+0.76	2911	2.9
Industrial refrigeration	R-717	2.60	2588	2.2
Industrial refrigeration	R-717 (ULC)	0.23	2170	5.7

TABLE 1: EQUIPMENT COST PER COOLING CAPACITY FOR DIFFERENT APPLICATIONS AND REFRIGERANTS. (AVERAGED VALUES, VARIABILITY IS WITHIN 40%)

Despite CO₂, HCs, or HC/CO₂ based equipment being more expensive, newer designs present significant short-term cost savings through performance monitoring digitalization and dedicated designs [52,53], such as adiabatic condensation that enables heat recovery in CO₂ based systems [54,55]. Novel equipment working with non-fluorinated refrigerants currently presents higher equipment cost per cooling capacity

than F-gas-based HVACR. Startups need to heavily invest in dedicated designs to meet cooling capacity demand, while competing with established companies that had a head start in the market, using amortized designs based on F-gas refrigerant use.

Equipment tailored to CO₂ demonstrates up to 50% annual energy savings, meaning short payback periods over the initial investment [56–58]. It is expected for CO₂ to achieve wider application in food storage (convenience stores and cold rooms) [59] and regular use in heat pumps [60], a major contributor to fully replacing HFCs before 2030.

Heating, Ventilation, Air Conditioning, and Refrigeration (HVACR) equipment with non-fluorinated refrigerants are available on the market today and are safer and cost-competitive against their fluorinated counterparts, including Ultra Low Temperature (ULT) refrigeration.

Our assessment determined that refrigerants such as carbon dioxide (CO₂), ammonia (NH₃), and hydrocarbons (HCs) have been known for a long time and can be efficiently implemented with the right technology [53,60–63]. Technological improvements have successfully addressed historical concerns, such as the cooling capacity of CO₂, corrosion due to the use of CO₂ and NH₃, and flammability of HCs. New low charge ammonia refrigeration systems are significantly more efficient and results in less acute health risks to workers than traditional ammonia systems.

EPA-SNAP authorizes new ULT equipment deployment using ethane (R-170), ethene (R-1150) and propane (R-290) for industrial ULT 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 CO₂/HC cascade systems [64]. Solid-state refrigeration, such as thermoelectric or magnetocaloric refrigeration, are emerging technologies capable of meeting ULT refrigeration [65,66] as well as refrigerated centrifugation needs.

The relative EHS hazards of low GWP refrigerants can be summarized using the TURI - Pollution Prevention Options Analysis System (TURI P2OASys) for a comprehensive evaluation comprising toxicity, flammability, and environmental impact. [TURI's P2OASys](#) can be leveraged to avoid unforeseen environmental, worker, or public health impacts. The tool assigns scores enclosing 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 hazard. The numeric value of the overall P2OASys score is an approximate evaluation of relative hazard for comparing alternatives, and it must be contemplated in their context, not as a definitive value assigned to a chemical or product. Table 2 provides a comparison of the relevant EHS hazards among various low-GWP refrigerants. R-152a and R-134a are being phased out or blended with HFOs. Next generation halogenated gases are observed having high (H) to very (VH) overall EHS hazards, while halogen free gases present low (L) to medium (M) overall EHS hazards.

Halogenated gases

ASHRAE denomination	Chemical class	CAS No	ASHRAE Safety class	Occupational Exposure Limit (ppm v/v)	P2OASys*		EPA- SNAP approved
R-141b	HFC	1717-00-6	n/a	500	6.8	H	No
R-1233zd	HCFO	102687-65-0	A1	800	6.3	H	No
R-1234ze(E)	HFO	29118-24-9	A2L	800	7.0	H	Yes
R-1234yf	HFO	754-12-1	A2L	500	8.1	VH	Yes
R-1130(E)	t-DCE	156-60-5	B2	1000	6.4	H	No
R-123	HFC	306-83-2	B1	50	6.8	H	No
R-152a	HFC	75-37-6	A2	1000	4.9	M	In blends
R-32	HFC	75-10-5	A2L	1000	7.2	H	Yes
R-134a	HFC	811-97-2	A1	1000	5.2	M	In blends

Halogen-free gases

ASHRAE denomination	Chemical class	CAS No	ASHRAE Safety class	OEL (ppm v/v)	P2OASys*		SNAP approved
R-290	HC	74-98-6	A3	1000	5.6	M	Yes
R-600	HC	106-97-8	A3	1000	5.4	M	No
R-717	NH ₃	7664-41-7	B2L	25	7.0	H	N/A
R-744	CO ₂	124-38-9	A1	5000	4.4	M	In blends
R-718	Water	7732-18-5	A1	none	2.3	L	N/A
R-1150	HC	75-85-1	A3	1000	5.3	M	Yes

TABLE 2: EHS RISK COMPARISON AMONG PURE REFRIGERANTS OF RELEVANCE IN THE MARKET.

* EHS RISK ASSESSMENT: GREEN – LOW (L); YELLOW – MEDIUM (M); ORANGE – HIGH (H); DARK ORANGE – VERY HIGH (VH).

The economic feasibility of non-fluorinated refrigerant based HVACR is translated into widening customer adoption.

Many HVACR manufacturing leaders are converting their sales portfolio to **fully non-fluorinated** by 2027 [60,62]. More specialized start-ups are successfully increasing their Market Readiness Level (MRL) to capitalize on the demand for systems using non-fluorinated refrigerants [67].

According to a recent report from ATMOSphere [68], market penetration of CO₂, HC, and HC/CO₂ based systems is steadily increasing in the US 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 CO₂ refrigeration systems in North America and Europe, respectively.

Many grocery retailers are willing to invest in non-fluorinated refrigerant-based HVACR as an effective way to achieve GHG emission goals [69,70] while avoiding corporate liabilities related to using F-gas refrigerants. 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 [68].

CO₂; HC/CO₂ cascade systems and Ultra Low Charge (ULC) ammonia systems are expected to dominate commercial and industrial refrigeration [71] in OECD countries by 2027 and in non-OECD countries by 2036. Despite the greater expense of working at higher pressure, trans critical CO₂ (R-744) has promising prospects for commercial refrigeration, including supermarkets [56,72].

Moreover, numerous manufacturers and commercial operators have successfully switched to halogen-free refrigerants, particularly HC/CO₂ cascade equipment [57], in several supermarket chains [62,73]. Peripheral measures such as heat recovery systems integrated with sanitary water heating enabled the adoption of CO₂ refrigeration systems in medium and large food retail and storage facilities [54,58].

Ammonia (R-717) is the most efficient refrigerant used in various industrial applications with typical cooling capacities above 1 MW. However, ammonia is acutely toxic, and it is important to take precautions to prevent leaks and accidents.

A new opportunity for ammonia is arising with the implementation of ULC units, paving the way for a resurgence of ammonia due to better equipment and lower chemical use [21,23]. Novel ULC 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 [42] with a charge up to 2.6 Kg/kW, minimizing the refrigerant fill costs and reducing, but not eliminating, potential liabilities related to acute toxicity and eutrophication.

A deterrent that slows the transition to non-fluorinated refrigerants is the need for investment in suitable equipment that works with such refrigerants.

Drop in substitutes for retrofitting purposes must possess very similar properties to the refrigerant to be replaced [74], which explains the market expansion of HFOs given the amount of deployed equipment currently utilizing HFCs.

While HFO refrigerants, HFO/HFC, or HFC/HC blends are currently used as a short-term workaround, recent precautionary policy trends on F-gases [60,75,76] and PFAS [43,77,78] will create more F-gas refrigerant availability limitations.

It is important to note that retrofitted HVACR equipment generally exhibits lower efficiency compared to the latest models, contributing avoidable indirect CO₂e emissions. Moreover, retrofitting has a typical payback period of 0.7 years due to low investment, while purchasing new equipment plus remodeling existing buildings can be as short as 2 years [79].

Transitioning to low-GWP refrigerants is just one of five main engineering strategies for reducing the climate impact of HVACR based on vapor compression.

State-of-the-art equipment development is focused on dedicated designs optimizing the critical stages of vapor compression. Enablers for safer and more efficient non-fluorinated refrigerant implementation include:

- Screw or scroll compressors present less friction and noise than reciprocating compressors. A more efficient compression can reduce indirect CO₂e emissions by up to 20% [80].
- The condenser transfers heat from the refrigerant to the environment. Improving efficiency can reduce the indirect CO₂e emissions of the system by up to 15% [81].
- The evaporator is the part of the system that extracts heat from the environment. A more efficient evaporator can increase the CoP of the system by up to 10% [82].
- Integrating heat recovery systems reduce heating costs and space demand [54,83].
- Reducing the amount of refrigerant (or charge) inside the refrigeration loop [63,84].

The latest safety standards show a growing acceptance of flammable refrigerants for commercial and industrial applications, enabling the adoption of hydrocarbons.

Due to flame propagation and ignition probability, HC refrigerants are classified as A3 according to ASHRAE. Extensive testing results have shown that the increased risk of using A3 refrigerants in mobile refrigeration can be significantly reduced if the refrigeration system is improved using suitable constructive measures [85], such as sealed control units and leaking sensors connected to feedback loop compressor controls. HVACR installations must comply with all flammability and safety requirements for installation. No indoor HVACR equipment can hold more than 150 grams of hydrocarbon charge in the US [86], while that charge limit is being uplifted to 500 grams in Europe [53] in light of novel approaches to equipment design and electrical housing standards[87]. Ductless technology already in the market can mitigate flammability risks [62] of A3 refrigerant use.

To mitigate the flammability risks of HFOs, companies are commercializing blends with high-GWP refrigerants. HFO-1234yf, R-1234ze(E), and HFC-32 possess noticeable flammability, placing them into the A2L safety class. A common strategy to reduce flammability risks is blending. To reduce HFO refrigerant flammability, suppliers currently offer blends with high-GWP HFCs [88–90]. The blending strategy can also be implemented to reduce the flammability risks of HCs by using mostly CO₂ [91–93] or, in some cases, ammonia [94].

However, no commercial HFO/HFC blend classified as A1 also complies with a GWP lower than 450 [95], while the GWP threshold for most applications is set at 150. HFOs such as R-1234yf are just slightly less flammable (A2L) than HCs [96] and produce highly toxic hydrogen fluoride (HF) and carbonyl fluoride (COF₂) when burned [85,90,97], posing a serious risk to fire rescue teams.

Upgrading mobile refrigeration into using non-fluorinated refrigerants is within reach, considering that transportation has a long history of leveraging pressurized gases. Moreover, the use of CO₂ in transport refrigeration is growing as businesses look for more sustainable alternatives to ammonia and HFCs. CO₂-based transport refrigeration in Europe is expected to grow from 1% in 2018 to 20% by 2030 [52]. Particularly for global food transportation and fishing vessels, CO₂ systems offer several advantages over traditional refrigerants [52,73,98]. CO₂/HC cascade systems are increasingly employed in food transportation [62] and storage [53,63].

CO₂ based Mobile Air Conditioning (MAC) systems debut in the 2023 European market. Most car makers now use the R-1234yf refrigerant in their vehicles, implementing additional leaking and fire safety measures, as a pivotal advancement towards CO₂ based MAC.

HFOs can be deemed a regrettable substitute from the economic perspective.

In addition to their environmental impact, HFOs are more expensive than HFCs, and they are not as widely available, while businesses are looking for cost-effective and reliable refrigerants. In some instances, corporate liabilities can exceed profits by several orders of magnitude. PFAS-producing companies are facing several lawsuits [40,42,99–102] regarding the consequences of the pollution around their production sites, taking a toll on their market value [103,104] and threatening product availability. Nationwide PFAS compliance costs far exceed the profits from producing PFAS-containing products [19]. Water utilities experience difficulty covering the PFAS removal expenses, so they often pass these costs on to users/taxpayers [18], so the long-term sustainability of HFOs as refrigerant gases is uncertain.

Besides techno-economic benefits, moving away from F-gases greatly contributes to social well-being and governance through environmental protection. The US EPA recently defined and reported a comparison of climate-related social costs of different HFC refrigerants and their potential drop-in replacements [24,25]. The social cost of GHGs (SC-GHG) is a quantitative estimate of climate impact compensation that federal and state agencies are considering for rulemaking [75,76,105], including 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, risk of conflict, etc. The SC-GHG reflects the societal value of policies and initiatives preventing GHG emissions. Figure 2 shows a remarkably strong linear correlation between the GWP of refrigerant gases and their associated SC-GHG.

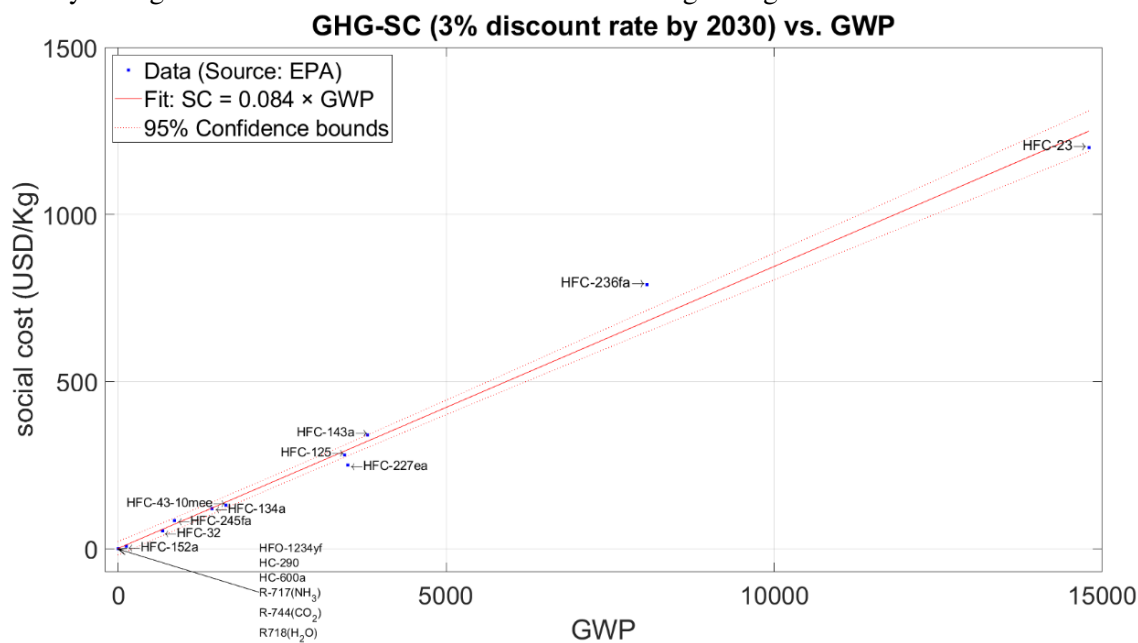


FIGURE 2: SOCIAL COST OF REFRIGERANT GASES AS A FUNCTION OF THEIR GWP.
SOURCE: MASSACHUSETTS TOXICS USE REDUCTION INSTITUTE. DATA SOURCE: [25,75,76]

The SC-GHG measures only one of the societal damages related to refrigerant gas emissions. However, the climate benefits of phasing down HFCs are found to be substantial, providing \$37 trillion (2020 USD) in social benefits over the lifetime of current international agreements, while expediting the phasedown of HFCs could increase the estimated climate benefits to \$41 trillion (2020 USD) [25]. Table 3 summarizes key points of the LCI associated with the available families of refrigerant gases. The GHG-SCs of HFCs, HFOs, and their blends are already significantly higher than their market price.

Moreover, there is consensus that chemical reactions introduce uncertainties that are difficult to quantify in a way that can be modeled [24], so current GHG social cost models are limited to describing climate impact without considering chemical transformations during environmental fate. Even if refrigerant reclaim and recycling would be implemented, their climate benefits based on reductions in current HFC emissions (GWP between 500 and 4000) could be outweighed by HFO fugitive emissions depending on the likelihood of HFO degradation into HFC-23 (GWP = 14800) [1].

Despite the known EHS risks and increasing binding corporate liabilities related to the manufacturing and disposal of F-gas refrigerants, a key marketing strategy is to frame HFOs as helping to reduce GHG emissions by keeping the efficiency of retrofitted equipment and working in novel improved heat pumps. However, HFOs present PFAS-related impacts on public health among other social costs, as well as flammability issues that can require the use of high-GWP HFCs to mitigate. On the other hand, HVACR equipment working with CO₂, HCs or ammonia is available, cost effective, safe, and present lower LCI.

Refrigerant family	Raw materials	Manufacturing	Use (GHG-SC; USD/Kg) *	Management hazards	Mitigation measures
HFCs	Fluorspar mineral. Petrochemicals. Catalysts.	Hydrogen fluoride reaction with CFCs and HCFCs.	120 – 1200	Long-lasting GHG releases. Water pollution. PFAS cleanup burden.	Phasing out and reclaiming policy implementation.
HFOs	Fluorspar mineral. Petrochemicals. Catalysts.	Hydrogen fluoride reaction with perchloroethylene and HFCs.	0.13 – 85	Long-lasting GHG releases. Flammables. Water pollution. PFAS cleanup burden.	Essential use and recycling policy implementation.
HFO/HFC blends	Fluorspar mineral. Petrochemicals. Catalysts.	HFOs and HFCs mixing.	12 – 60	Long-lasting GHGs. Water pollution. PFAS cleanup burden.	Essential use and recycling policy implementation.
HCs	Petrochemicals.	Hydrocarbon purification.	0.26 – 0.78	Flammables. Photochemical smog.	Safety standards. Dedicated design. Biobased HCs.
HCs/HFC blends	Petrochemicals.	HCs and HFCs mixing.	100 - 1000	Long-lasting GHGs. Water pollution. PFAS cleanup burden.	Essential use and recycling policy implementation.
Carbon dioxide	Carbon dioxide.	Carbon dioxide purification.	0.13	Climate impact through inefficiency.	Efficiency standards. Dedicated design.
Ammonia	Hydrogen, nitrogen, and catalysts.	Haber process. Nitrogen electrolysis.	0	Eutrophication. Catastrophic toxicity.	Safety standards. Low charge design. Cleaner NH ₃ production.

TABLE 3: QUALITATIVE LIFE CYCLE IMPACT COMPARISON AND MITIGATION ANALYSIS OF REFRIGERANT GASES.

References

1. UNITED NATIONS ENVIRONMENT PROGRAMME (UNEP) Environmental Effects of Stratospheric Ozone Depletion, UV Radiation, and Interactions with Climate Change - 2022 Assessment Report 2023. <https://ozone.unep.org/system/files/documents/EEAP-2022-Assessment-Report-May2023.pdf>

2. Burkholder, J.B.; Cox, R.A.; Ravishankara, A.R. Atmospheric Degradation of Ozone Depleting Substances, Their Substitutes, and Related Species. *Chem. Rev.* 2015, 115, 3704–3759, <https://doi.org/10.1021/cr5006759>
3. Holland, R.; Khan, M.A.H.; Driscoll, I.; Chhantyal-Pun, R.; Derwent, R.G.; Taatjes, C.A.; Orr-Ewing, A.J.; Percival, C.J.; Shallcross, D.E. Investigation of the Production of Trifluoroacetic Acid from Two Halocarbons HFC-134a and HFO-1234yf and Its Fates Using a Global Three-Dimensional Chemical Transport Model. US Office of Scientific and Technical Information 2021. <https://www.osti.gov/servlets/purl/1772952>
4. Joudan, S.; Silva, A.O.D.; Young, C.J. Insufficient Evidence for the Existence of Natural Trifluoroacetic Acid. *Environ. Sci.: Processes Impacts* 2021, 23, 1641–1649, <https://doi.org/10.1039/D1EM00306B>
5. Russell, M.H.; Hoogeweg, G.; Webster, E.M.; Ellis, D.A.; Waterland, R.L.; Hoke, R.A. TFA from HFO-1234yf: Accumulation and Aquatic Risk in Terminal Water Bodies. *Environmental Toxicology and Chemistry* 2012, 31, 1957–1965, <https://doi.org/10.1002/etc.1925>
6. Castro, P.; Franco, A.; Ramos, M.; Cravo, S.; Afonso, C. Potential of Ectomycorrhizal Fungus *Pisolithus Tinctorius* to Tolerate and to Degrade Trifluoroacetate into Fluoroform. *New Biotechnology* 2014, 31, S65, <https://doi.org/10.1016/j.nbt.2014.05.1760>
7. Reynard, L.M.; Donaldson, D.J. Overtone-Induced Chemistry of Trifluoroacetic Acid: An Experimental and Theoretical Study. *J. Phys. Chem. A* 2002, 106, 8651–8657, <https://doi.org/10.1021/jp021084w>
8. Visscher, P.T.; Culbertson, C.W.; Oremland, R.S. Degradation of Trifluoroacetate in Oxic and Anoxic Sediments. *Nature* 1994, 369, 729–731, <https://doi.org/10.1038/369729a0>
9. Auerbach, I.; Verhoek, F.H.; Henne, A.L. Kinetic Studies on the Decarboxylation of Sodium Trifluoroacetate in Ethylene Glycol. *J. Am. Chem. Soc.* 1950, 72, 299–300, <https://doi.org/10.1021/ja01157a079>
10. Campbell, J. A Detailed Investigation into CF₃CHO Photolysis, UNSW Sydney, 2022. <https://10.26190/UNSWORKS/24197>
11. Le Monde.fr Revealed: The Massive Contamination of Europe by PFAS “Forever Chemicals.” Le Monde.fr 2023. https://www.lemonde.fr/en/les-decodeurs/article/2023/02/23/revealed-the-massive-contamination-of-europe-by-pfas-forever-chemicals_6016906_8.html
12. Chemours Now Taking Orders in North America for Opteon™ XL41 Zero ODP, Low GWP Refrigerant Available online: <https://investors.chemours.com/news-releases/news-releases-details/2023/Chemours-Now-Taking-Orders-in-North-America-for-Opteon-XL41-Zero-ODP-Low-GWP-Refrigerant/default.aspx>
13. Daikin Daikin’s Policy and Comprehensive Actions on the Environmental Impact of Refrigerants Refrigerants 2023. https://www.daikin.com/-/media/Project/Daikin/daikin_com/csr/information/influence/daikin_policy-en-pdf.pdf
14. Arkema SOCIAL RESPONSIBILITY 2021 COMMUNICATION ON PROGRESS Extract from 2021 Universal Registration Document 2022. https://www.arkema.com/files/live/sites/shared_arkema/files/downloads/socialresponsability/2021-arkema-social-responsibility-cop.pdf
15. ECHA ECHA Publishes PFAS Restriction Proposal Available online: <https://echa.europa.eu/-/echa-publishes-pfas-restriction-proposal>
16. La Merrill, M.A.; Vandenberg, L.N.; Smith, M.T.; Goodson, W.; Browne, P.; Patisaul, H.B.; Guyton, K.Z.; Kortenkamp, A.; Coglian, V.J.; Woodruff, T.J.; et al. Consensus on the Key Characteristics of Endocrine-Disrupting Chemicals as a Basis for Hazard Identification. *Nat Rev Endocrinol* 2020, 16, 45–57, <https://doi.org/10.1038/s41574-019-0273-8>

17. SETAC Europe 2022 Keynote- Hans Peter H. Arp: Reducing Pollution of PMT Substances to Protect Water; 2022; https://www.youtube.com/watch?v=s6_O6MBpE8k
18. American Water Works Association WITAF 56 TECHNICAL MEMORANDUM PFAS National Cost Model Report 2023. <https://www.awwa.org/Portals/0/AWWA/Government/2023030756BVFfinalTechnicalMemorandum.pdf>
19. U.S. Chamber of Commerce PFOS and PFOA Private Cleanup Costs at Non-Federal Superfund Sites Available online: <https://www.uschamber.com/environment/pfos-and-pfoa-private-cleanup-costs-at-non-federal-superfund-sites>
20. Cottrell, S.A.; Tung, H.S.; Wang, H.; Chiu, Y.; Cerri, G. Manufacturing Process for HFO-1234ZE 2016. <https://patentimages.storage.googleapis.com/69/9d/83/8c030c75c4a235/US9255046.pdf>
21. Van Der Puy, M. Process for the Preparation of 2,3,3,3-Tetrafluoropropene (HFO-1234yf) 2011. <https://patentimages.storage.googleapis.com/41/8b/fc/1a9e0670838f53/US8071826.pdf>
22. Baral, A.; Urban, R. Upstream Climate Impacts from Production of R-134a and R-1234yf Refrigerants Used in Mobile Air Conditioning Systems 2013. https://theicct.org/sites/default/files/publications/ICCT_RefrigerantsImpacts_20130909.pdf
23. Petrosky, J.T. Manufacture of Perchloroethylene from Carbon Tetrachloride in the Presence of Hydrogen 1994. <https://patentimages.storage.googleapis.com/11/35/c1/f47508a8d72ae9/US5315050.pdf>
24. US EPA Regulatory Impact Analysis for Phasing Down Production and Consumption of Hydrofluorocarbons (HFCs) 2022. <https://www.epa.gov/system/files/documents/2022-07/RIA%20for%20Phasing%20Down%20Production%20and%20Consumption%20of%20Hydrofluorocarbons%20%28HFCs%29.pdf>
25. US EPA, O. The Social Costs of Hydrofluorocarbons and the Large Climate Benefits from Their Expedited Phasedown Available online: https://www.epa.gov/system/files/documents/2023-05/2023-05_0.pdf
26. US EPA, O. Final Risk Evaluation for Carbon Tetrachloride Available online: <https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/final-risk-evaluation-carbon-tetrachloride>
27. US EPA Carbon Tetrachloride (CTC); Regulation Under the Toxic Substances Control Act (TSCA) Available online: <https://www.regulations.gov/document/EPA-HQ-OPPT-2020-0592-0008>
28. Pharos Project TETRACHLOROETHYLENE Available online: <https://pharosproject.net/chemicals/2010523>
29. Pharos Project CARBON TETRACHLORIDE Available online: <https://pharosproject.net/chemicals/2007105>
30. EWG PFAS Contamination in the U.S. 2022. https://www.ewg.org/interactive-maps/pfas_contamination/map/
31. Material Research Global Map MATERIAL RESEARCH ATLAS OF TOXIC CHEMICAL PRODUCTION 2023. <https://materialresearch.world/the-atlas>
32. US EPA EJScreen - EPA's Environmental Justice Screening and Mapping Tool (Version 2.11) 2023. <https://ejscreen.epa.gov/mapper/>
33. Newton, S.; McMahan, R.; Stoeckel, J.A.; Chislock, M.; Lindstrom, A.; Strynar, M. Novel Polyfluorinated Compounds Identified Using High Resolution Mass Spectrometry Downstream of Manufacturing Facilities near Decatur, Alabama. Environ. Sci. Technol. 2017, 51, 1544–1552, <https://doi.org/10.1021/acs.est.6b05330>
34. Soloveichik, G. Electrochemical Synthesis of Ammonia as a Potential Alternative to the Haber–Bosch Process. Nat Catal 2019, 2, 377–380, <https://doi.org/10.1038/s41929-019-0280-0>
35. Atmonia Technology – Atmonia. <https://atmonia.com/technology/>
36. Delparish, A.; Uslu, A.; Cao, Y.; de Groot, T.; van der Schaaf, J.; Noël, T.; Fernanda Neira d'Angelo, M. Boosting the Valorization of Biomass and Green Electrons to Chemical Building Blocks: A

- Study on the Kinetics and Mass Transfer during the Electrochemical Conversion of HMF to FDCA in a Microreactor. Chemical Engineering Journal 2022, 135393, <https://doi.org/10.1016/j.cej.2022.135393>
37. Neste The Latest Addition to the List of Renewable Fuels – Biopropane – Will Soon Be Available Available online: <https://www.neste.com/latest-addition-list-renewable-fuels-%E2%80%93-biopropane-%E2%80%93-will-soon-be-available>
38. Zhang, L.; Louie, A.; Rigutto, G.; Guo, H.; Zhao, Y.; Ahn, S.; Dahlberg, S.; Sholinbeck, M.; Smith, M.T. A Systematic Evidence Map of Chronic Inflammation and Immunosuppression Related to Per- and Polyfluoroalkyl Substance (PFAS) Exposure. Environmental Research 2023, 220, 115188, <https://doi.org/10.1016/j.envres.2022.115188>
39. Kwiatkowski, C.F.; Andrews, D.Q.; Birnbaum, L.S.; Bruton, T.A.; DeWitt, J.C.; Knappe, D.R.U.; Maffini, M.V.; Miller, M.F.; Pelch, K.E.; Reade, A.; et al. Scientific Basis for Managing PFAS as a Chemical Class. Environ. Sci. Technol. Lett. 2020, 7, 532–543, <https://doi.org/10.1021/acs.estlett.0c00255>
40. Bright, Z. DuPont, Chemours, 3M Sued by N.C. Attorney General Over PFAS Available online: <https://news.bloomberglaw.com/environment-and-energy/dupont-chemours-3m-sued-by-n-c-attorney-general-over-pfas>
41. C&EN Solvay and Arkema Sued for PFAS Cleanup. C&EN Global Enterp 2020, 98, 15–15, <https://doi.org/10.1021/cen-09845-polcon2>
42. Perkins, T. US Agency Takes Unprecedented Action to Tackle PFAS Water Pollution | US News | The Guardian Available online: <https://amp.theguardian.com/us-news/2023/may/06/us-epa-pfas-drinking-water-pollution-ohio-river>
43. Erickson, B. EPA Targets 6 PFAS in Drinking Water Available online: <https://cen.acs.org/environment/persistent-pollutants/EPA-targets-6-PFAS-drinking/101/web/2023/03>
44. NRDC Historic PFAS Drinking Water Regulations Proposed by EPA Available online: <https://www.nrdc.org/press-releases/historic-pfas-drinking-water-regulations-proposed-epa>
45. 3M News Center 3M to Exit PFAS Manufacturing by the End of 2025 Available online: <https://news.3m.com/2022-12-20-3M-to-Exit-PFAS-Manufacturing-by-the-End-of-2025>
46. Mandard, S.; Horel, S. Arkema Faces Criminal Charges for Forever Chemical Contamination in Lyon Region. Le Monde.fr 2023. https://www.lemonde.fr/en/france/article/2023/06/05/arkema-faces-criminal-charges-for-forever-chemical-contamination-in-lyon-region_6029191_7.html
47. BASF BASF Online Report 2020 (24) Available online: <https://report.basf.com/2020/en/financial-statements/notes/notes-to-the-balance-sheet/risks-from-litigation.html>
48. Feeley, J.; Beene, R. 3M Heads to Trial in ‘Existential’ \$143 Billion PFAS Litigation Available online: <https://news.bloomberglaw.com/environment-and-energy/3m-heads-to-trial-in-existential-143-billion-pfas-litigation>
49. Casselman, B.; Penn, I.; Goldstein, M. Three ‘Forever Chemicals’ Makers Settle Public Water Lawsuits - The New York Times Available online: <https://www.nytimes.com/2023/06/02/business/pfas-pollution-settlement.html>
50. Bonta, R. Attorney General Bonta Leads Coalition in Calling for DuPont to Pay More for Contaminating Americans’ Drinking Water Supply with Toxic PFAS Available online: <https://oag.ca.gov/news/press-releases/attorney-general-bonta-leads-coalition-calling-dupont-pay-more-contaminating>
51. Daikin Daikin Acquires Refrigerant Business from Solvay S.A. | DAIKIN Chemical Europe GmbH Available online: <https://www.daikinchem.de/daikin-acquires-refrigerant-business-solvay-sa>
52. Minetto, S.; Fabris, F.; Marinetti, S.; Rossetti, A. A Review on Present and Forthcoming Opportunities with Natural Working Fluids in Transport Refrigeration. International Journal of Refrigeration 2023, <https://doi.org/10.1016/j.jirefrig.2023.04.015>

53. ATMOsphere ATMO Market Report 2022 Available online:
<https://atmosphere.cool/marketreport-2022/>
54. Danfoss HRU - Heat Recovery Unit Available online:
<https://www.danfoss.com/en/products/dhs/stations-and-domestic-hot-water/hru-heat-recovery-unit/>
55. How Does the PX G1300 Work? - CO2 System Efficiency; 2023;
<https://www.youtube.com/watch?v=VGW0c08XdKo>
56. Tsimpoukis, D.; Syngounas, E.; Bellos, E.; Koukou, M.; Tzivanidis, C.; Anagnostatos, S.; Gr. Vrachopoulos, M. Thermodynamic and Economic Analysis of a Supermarket Transcritical CO2 Refrigeration System Coupled with Solar-Fed Supercritical CO2 Brayton and Organic Rankine Cycles. Energy Conversion and Management: X 2023, 18, 100351, <https://doi.org/10.1016/j.ecmx.2023.100351>
57. Garry, M. ATMOsphere: 55,000 Stores Using Transcritical CO2 in Europe. R744 2022.
<https://r744.com/atmosphere-estimates-55000-stores-using-transcritical-co2-in-europe/>
58. ATMOsphere America Summit DAY 1 – REFRIGERATION CASE STUDIES Available online:
<https://atmo.org/announcement/day-1-refrigeration-case-studies-part-1/>
59. Godwin, D.S.; Ferenchiak, R. The Implications of Residential Air Conditioning Refrigerant Choice on Future Hydrofluorocarbon Consumption in the United States. Journal of Integrative Environmental Sciences 2020, 17, 29–44, <https://doi.org/10.1080/1943815X.2020.1768551>
60. Danfoss Refrigerant Options Now and in the Future 2022.
<https://assets.danfoss.com/documents/latest/211728/AD224586434178en-001001.pdf>
61. Li, P.; Chen, J.J.J.; Norris, S. Review of Flow Condensation of CO2 as a Refrigerant. International Journal of Refrigeration 2016, 72, 53–73, <https://doi.org/10.1016/j.ijrefrig.2016.07.022>
62. EIA Sectors Refrigeration : Cool Technologies Available online:
<https://cooltechnologies.org/sector/refrigeration/>
63. Skačánová, K. World GUIDE to Low-Charge Ammonia - Complete Report Available online:
<http://publication.shecco.com/publications/view/226>
64. ENERGY STAR Product Finder — ENERGY STAR Certified Lab Grade Refrigerators and Freezers Available online: <https://www.energystar.gov/productfinder/product/certified-lab-grade-refrigeration/results>
65. Shi, L.; Abed, A.M.; Fayed, M.; Abdulghani, Z.R.; Anqi, A.E.; Khadimallah, M.A.; Moria, H.; Wae-hayee, M. Economic Cost Analysis of Air-Cooling Process Using Different Numbers of Peltier Modules; Experimental Case Study. Case Studies in Thermal Engineering 2023, 41, 102627, <https://doi.org/10.1016/j.csite.2022.102627>
66. Zhang, Y.; Wu, J.; He, J.; Wang, K.; Yu, G. Solutions to Obstacles in the Commercialization of Room-Temperature Magnetic Refrigeration. Renewable and Sustainable Energy Reviews 2021, 143, 110933, <https://doi.org/10.1016/j.rser.2021.110933>
67. ATMOsphere America Summit DAY 1 – HEAT PUMP CASE STUDIES Available online:
<https://atmo.org/announcement/day-1-heat-pump-case-studies/>
68. ATMOsphere Commercial and Industrial Refrigeration in Europe, North America and Japan, 2022 Edition Available online: <https://atmosphere.cool/marketreport-2022/>
69. Hayes, C. ATMO America: Hannaford Equips Fifth Store with R290 Freezers. Hydrocarbons21 2022. <https://hydrocarbons21.com/atmo-america-hannaford-equips-fifth-store-with-r290-cases-for-frozen-food-line-up/>
70. US DoE Whole Foods Market: Brooklyn Third and 3rd | Better Buildings Initiative Available online: <https://betterbuildingssolutioncenter.energy.gov/showcase-projects/whole-foods-market-brooklyn-third-and-3rd>
71. Cao, T.; Hwang, Y. IEA Heat Pumping Technologies ANNEX 54: Heat Pump Systems with Low Global Warming Potential (GWP) Refrigerants Available online:
<https://heatpumpingtechnologies.org/annex54/>

72. Gullo, P. Innovative Fully Integrated Transcritical R744 Refrigeration Systems for a HFC-Free Future of Supermarkets in Warm and Hot Climates. *International Journal of Refrigeration* 2019, 108, 283–310, <https://doi.org/10.1016/j.ijrefrig.2019.09.001>
73. Azzolin, M.; Cattelan, G.; Dugaria, S.; Minetto, S.; Calabrese, L.; Del Col, D. Integrated CO₂ Systems for Supermarkets: Field Measurements and Assessment for Alternative Solutions in Hot Climate. *Applied Thermal Engineering* 2021, 187, 116560, <https://doi.org/10.1016/j.applthermaleng.2021.116560>
74. Walker, I.S. OSTI.GOV: Technical Report: Best Practices Guide for Residential HVAC Retrofits; 2003; p. LBNL--53592, 824856; <https://doi.org/10.2172/824856>
75. US EPA, O. EPA Draft “Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances” Available online: <https://www.epa.gov/environmental-economics/scghg>
76. New York State, D. of E.C. Express Terms - Adopted Part 494 - NYS Dept. of Environmental Conservation Available online: <https://www.dec.ny.gov/regulations/119032.html>
77. ECHA Per- and Polyfluoroalkyl Substances (PFAS) - ECHA Available online: <https://echa.europa.eu/hot-topics/perfluoroalkyl-chemicals-pfas>
78. Bălan, S.A.; Mathrani, V.C.; Guo, D.F.; Algazi, A.M. Regulating PFAS as a Chemical Class under the California Safer Consumer Products Program. *Environ Health Perspect* 2021, 129, 025001, <https://doi.org/10.1289/EHP7431>
79. US-EPA State and Local Climate and Energy Program - Rules of Thumb 2016 https://www.epa.gov/sites/default/files/2016-03/documents/table_rules_of_thumb.pdf
80. Hundy, G.F.; Trott, A.R.; Welch, T.C. Efficiency, Running Cost and Carbon Footprint. In *Refrigeration, Air Conditioning and Heat Pumps*; Elsevier, 2016; pp. 435–446 ISBN 978-0-08-100647-4 <https://doi.org/10.1016/B978-075068519-1.00030-X>
81. Lee, H.; Troch, S.; Hwang, Y.; Radermacher, R. LCCP Evaluation on Various Vapor Compression Cycle Options and Low GWP Refrigerants. *International Journal of Refrigeration* 2016, 70, 128–137, <https://doi.org/10.1016/j.ijrefrig.2016.07.003>
82. Murthy, A.A.; Subiantoro, A.; Norris, S.; Fukuta, M. A Review on Expanders and Their Performance in Vapour Compression Refrigeration Systems. *International Journal of Refrigeration* 2019, 106, 427–446, <https://doi.org/10.1016/j.ijrefrig.2019.06.019>
83. Yang, Z.; Feng, B.; Ma, H.; Zhang, L.; Duan, C.; Liu, B.; Zhang, Y.; Chen, S.; Yang, Z. Analysis of Lower GWP and Flammable Alternative Refrigerants. *International Journal of Refrigeration* 2021, 126, 12–22, <https://doi.org/10.1016/j.ijrefrig.2021.01.022>
84. Palm, B. Hydrocarbons as Refrigerants in Small Heat Pump and Refrigeration Systems – A Review. *International Journal of Refrigeration* 2008, 31, 552–563, <https://doi.org/10.1016/j.ijrefrig.2007.11.016>
85. Hsieh, H.-K.; Teng, T.-P. Retrofit Assessment of Automobile Air Conditioners Using Hydrocarbon Refrigerants. *Applied Thermal Engineering* 2022, 214, 118781, <https://doi.org/10.1016/j.applthermaleng.2022.118781>
86. Chemours Applications & Industries for Opteon™ Available online: <https://www.opteon.com/en/industries-applications>
87. Mota-Babiloni, A.; Fernández-Moreno, A.; Giménez-Prades, P.; Udrioiu, C.-M.; Navarro-Esbrí, J. Ternary Refrigerant Blends for Ultra-Low Temperature Refrigeration. *International Journal of Refrigeration* 2023, 148, 108–116, <https://doi.org/10.1016/j.ijrefrig.2023.01.006>
88. Feng, B.; Yang, Z.; Liu, H. Research on Inhibition of Flame Retardants on Flammability of R1234yf. *International Journal of Refrigeration* 2020, 118, 302–310, <https://doi.org/10.1016/j.ijrefrig.2020.06.031>
89. Mazyan, W.I.; Ahmadi, A.; Ahmed, H.; Hoorfar, M. Increasing the COP of a Refrigeration Cycle in Natural Gas Liquefaction Process Using Refrigerant Blends of Propane-NH₃, Propane-SO₂ and Propane-CO₂. *Heliyon* 2020, 6, e04750, <https://doi.org/10.1016/j.heliyon.2020.e04750>

90. Pearson, A. Carbon Dioxide—New Uses for an Old Refrigerant. *International Journal of Refrigeration* 2005, 28, 1140–1148, <https://doi.org/10.1016/j.ijrefrig.2005.09.005>
91. Yelishala, S.C.; Kannaiyan, K.; Sadr, R.; Wang, Z.; Levendis, Y.A.; Metghalchi, H. Performance Maximization by Temperature Glide Matching in Energy Exchangers of Cooling Systems Operating with Natural Hydrocarbon/CO₂ Refrigerants. *International Journal of Refrigeration* 2020, 119, 294–304, <https://doi.org/10.1016/j.ijrefrig.2020.08.006>
92. Roy, Z.; Halder, G. Replacement of Halogenated Refrigerants towards Sustainable Cooling System: A Review. *Chemical Engineering Journal Advances* 2020, 3, 100027, <https://doi.org/10.1016/j.cej.2020.100027>
93. McLinden, M.O.; Huber, M.L. (R)Evolution of Refrigerants. *J. Chem. Eng. Data* 2020, 65, 4176–4193, <https://doi.org/10.1021/acs.jced.0c00338>
94. Wu, X.; Dang, C.; Xu, S.; Hihara, E. State of the Art on the Flammability of Hydrofluoroolefin (HFO) Refrigerants. *International Journal of Refrigeration* 2019, 108, 209–223, <https://doi.org/10.1016/j.ijrefrig.2019.08.025>
95. BAM Final Test Report - Ignition Behaviour of HFO1234yf 2010.
96. Söylemez, E.; Widell, K.N.; Gabrieli, C.H.; Ladam, Y.; Lund, T.; Hafner, A. Overview of the Development and Status of Carbon Dioxide (R-744) Refrigeration Systems Onboard Fishing Vessels. *International Journal of Refrigeration* 2022, 140, 198–212, <https://doi.org/10.1016/j.ijrefrig.2022.05.007>
97. Ebert, A. DuPont Must Fight North Carolina Forever Chemical Suit (1) Available online: <https://news.bloomberglaw.com/environment-and-energy/dupont-chemours-must-fight-north-carolina-forever-chemical-suit>
98. Nayak, M. DuPont, 3M Sued by California Over ‘Staggering’ Pollution Available online: <https://news.bloomberglaw.com/environment-and-energy/dupont-3m-sued-by-california-over-toxic-forever-chemicals>
99. Tullo, A. Chemours Sues DuPont over Environmental Liabilities Available online: <https://cen.acs.org/environment/pollution/Chemours-sues-DuPont-over-environmental/97/i27>
100. Earls, M. Daikin America Denied Appeals Court Look at PFAS Pollution Suit Available online: <https://news.bloomberglaw.com/litigation/daikin-america-denied-appeals-court-look-at-pfas-pollution-suit>
101. Deep Value Ideas 2 Reasons To Sell 3M Stock Despite The “Good” News (NYSE:MMM) | Seeking Alpha Available online: <https://seekingalpha.com/article/4610996-2-reasons-to-sell-3m-stock-despite-the-good-news>, <https://seekingalpha.com/article/4610996-2-reasons-to-sell-3m-stock-despite-the-good-news>
102. Feeley, J. 3M Said to Be in at Least \$10 Billion PFAS Pollution Accord Available online: <https://news.bloomberglaw.com/environment-and-energy/3m-said-to-be-in-at-least-10-billion-pfas-pollution-settlement-1>
103. Just, R. Social Cost of Greenhouse Gas Estimates - Environmental & Energy Law Program Available online: <https://eelp.law.harvard.edu/2022/10/social-cost-of-greenhouse-gas-estimates/>
1. UNITED NATIONS ENVIRONMENT PROGRAMME (UNEP) Environmental Effects of Stratospheric Ozone Depletion, UV Radiation, and Interactions with Climate Change - 2022 Assessment Report 2023. <https://ozone.unep.org/system/files/documents/EEAP-2022-Assessment-Report-May2023.pdf>
2. Burkholder, J.B.; Cox, R.A.; Ravishankara, A.R. Atmospheric Degradation of Ozone Depleting Substances, Their Substitutes, and Related Species. *Chem. Rev.* 2015, 115, 3704–3759, <https://doi.org/10.1021/cr5006759>
3. Holland, R.; Khan, M.A.H.; Driscoll, I.; Chhantyal-Pun, R.; Derwent, R.G.; Taatjes, C.A.; Orr-Ewing, A.J.; Percival, C.J.; Shallcross, D.E. Investigation of the Production of Trifluoroacetic Acid from

Two Halocarbons HFC-134a and HFO-1234yf and Its Fates Using a Global Three-Dimensional Chemical Transport Model. US Office of Scientific and Technical Information 2021.

<https://www.osti.gov/servlets/purl/1772952>

4. Joudan, S.; Silva, A.O.D.; Young, C.J. Insufficient Evidence for the Existence of Natural Trifluoroacetic Acid. *Environ. Sci.: Processes Impacts* 2021, 23, 1641–1649, <https://doi.org/10.1039/D1EM00306B>
5. Russell, M.H.; Hoogeweg, G.; Webster, E.M.; Ellis, D.A.; Waterland, R.L.; Hoke, R.A. TFA from HFO-1234yf: Accumulation and Aquatic Risk in Terminal Water Bodies. *Environmental Toxicology and Chemistry* 2012, 31, 1957–1965, <https://doi.org/10.1002/etc.1925>
6. Castro, P.; Franco, A.; Ramos, M.; Cravo, S.; Afonso, C. Potential of Ectomycorrhizal Fungus *Pisolithus Tinctorius* to Tolerate and to Degrade Trifluoroacetate into Fluoroform. *New Biotechnology* 2014, 31, S65, <https://doi.org/10.1016/j.nbt.2014.05.1760>
7. Reynard, L.M.; Donaldson, D.J. Overtone-Induced Chemistry of Trifluoroacetic Acid: An Experimental and Theoretical Study. *J. Phys. Chem. A* 2002, 106, 8651–8657, <https://doi.org/10.1021/jp021084w>
8. Visscher, P.T.; Culbertson, C.W.; Oremland, R.S. Degradation of Trifluoroacetate in Oxic and Anoxic Sediments. *Nature* 1994, 369, 729–731, <https://doi.org/10.1038/369729a0>
9. Auerbach, I.; Verhoeck, F.H.; Henne, A.L. Kinetic Studies on the Decarboxylation of Sodium Trifluoroacetate in Ethylene Glycol. *J. Am. Chem. Soc.* 1950, 72, 299–300, <https://doi.org/10.1021/ja01157a079>
10. Campbell, J. A Detailed Investigation into CF₃CHO Photolysis, UNSW Sydney, 2022. <https://10.26190/UNSWORKS/24197>
11. Le Monde.fr Revealed: The Massive Contamination of Europe by PFAS “Forever Chemicals.” *Le Monde.fr* 2023. https://www.lemonde.fr/en/les-decodeurs/article/2023/02/23/revealed-the-massive-contamination-of-europe-by-pfas-forever-chemicals_6016906_8.html
12. Chemours Now Taking Orders in North America for Opteon™ XL41 Zero ODP, Low GWP Refrigerant Available online: <https://investors.chemours.com/news-releases/news-releases-details/2023/Chemours-Now-Taking-Orders-in-North-America-for-Opteon-XL41-Zero-ODP-Low-GWP-Refrigerant/default.aspx>
13. Daikin Daikin’s Policy and Comprehensive Actions on the Environmental Impact of Refrigerants Refrigerants 2023. https://www.daikin.com/-/media/Project/Daikin/daikin_com/csr/information/influence/daikin_policy-en-pdf.pdf
14. Arkema SOCIAL RESPONSIBILITY 2021 COMMUNICATION ON PROGRESS Extract from 2021 Universal Registration Document 2022. https://www.arkema.com/files/live/sites/shared_arkema/files/downloads/socialresponsability/2021-arkema-social-responsibility-cop.pdf
15. ECHA ECHA Publishes PFAS Restriction Proposal Available online: <https://echa.europa.eu/-/echa-publishes-pfas-restriction-proposal>
16. La Merrill, M.A.; Vandenberg, L.N.; Smith, M.T.; Goodson, W.; Browne, P.; Patisaul, H.B.; Guyton, K.Z.; Kortenkamp, A.; Coglian, V.J.; Woodruff, T.J.; et al. Consensus on the Key Characteristics of Endocrine-Disrupting Chemicals as a Basis for Hazard Identification. *Nat Rev Endocrinol* 2020, 16, 45–57, <https://doi.org/10.1038/s41574-019-0273-8>
17. SETAC Europe 2022 Keynote- Hans Peter H. Arp: Reducing Pollution of PMT Substances to Protect Water; 2022; https://www.youtube.com/watch?v=s6_O6MBpE8k
18. American Water Works Association WITAF 56 TECHNICAL MEMORANDUM PFAS National Cost Model Report 2023. <https://www.awwa.org/Portals/0/AWWA/Government/2023030756BVFfinalTechnicalMemorandum.pdf>

19. U.S. Chamber of Commerce PFOS and PFOA Private Cleanup Costs at Non-Federal Superfund Sites Available online: <https://www.uschamber.com/environment/pfos-and-pfoa-private-cleanup-costs-at-non-federal-superfund-sites>
20. Cottrell, S.A.; Tung, H.S.; Wang, H.; Chiu, Y.; Cerri, G. Manufacturing Process for HFO-1234ZE 2016. <https://patentimages.storage.googleapis.com/69/9d/83/8c030c75c4a235/US9255046.pdf>
21. Van Der Puy, M. Process for the Preparation of 2,3,3,3-Tetrafluoropropene (HFO-1234yf) 2011. <https://patentimages.storage.googleapis.com/41/8b/fc/1a9e0670838f53/US8071826.pdf>
22. Baral, A.; Urban, R. Upstream Climate Impacts from Production of R-134a and R-1234yf Refrigerants Used in Mobile Air Conditioning Systems 2013. https://theicct.org/sites/default/files/publications/ICCT_RefrigerantsImpacts_20130909.pdf
23. Petrosky, J.T. Manufacture of Perchloroethylene from Carbon Tetrachloride in the Presence of Hydrogen 1994. <https://patentimages.storage.googleapis.com/11/35/c1/f47508a8d72ae9/US5315050.pdf>
24. US EPA Regulatory Impact Analysis for Phasing Down Production and Consumption of Hydrofluorocarbons (HFCs) 2022. <https://www.epa.gov/system/files/documents/2022-07/RIA%20for%20Phasing%20Down%20Production%20and%20Consumption%20of%20Hydrofluorocarbons%20%28HFCs%29.pdf>
25. US EPA, O. The Social Costs of Hydrofluorocarbons and the Large Climate Benefits from Their Expedited Phasedown Available online: https://www.epa.gov/system/files/documents/2023-05/2023-05_0.pdf
26. US EPA, O. Final Risk Evaluation for Carbon Tetrachloride Available online: <https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/final-risk-evaluation-carbon-tetrachloride>
27. US EPA Carbon Tetrachloride (CTC); Regulation Under the Toxic Substances Control Act (TSCA) Available online: <https://www.regulations.gov/document/EPA-HQ-OPPT-2020-0592-0008>
28. Pharos Project TETRACHLOROETHYLENE. <https://pharosproject.net/chemicals/2010523>
29. Pharos Project CARBON TETRACHLORIDE. <https://pharosproject.net/chemicals/2007105>
30. EWG PFAS Contamination in the U.S. 2022. https://www.ewg.org/interactive-maps/pfas_contamination/map/
31. Material Research Global Map MATERIAL RESEARCH ATLAS OF TOXIC CHEMICAL PRODUCTION 2023. <https://materialresearch.world/the-atlas>
32. US EPA EJScreen - EPA's Environmental Justice Screening and Mapping Tool (Version 2.11) 2023. <https://ejscreen.epa.gov/mapper/>
33. Newton, S.; McMahan, R.; Stoeckel, J.A.; Chislock, M.; Lindstrom, A.; Strynar, M. Novel Polyfluorinated Compounds Identified Using High Resolution Mass Spectrometry Downstream of Manufacturing Facilities near Decatur, Alabama. *Environ. Sci. Technol.* 2017, 51, 1544–1552, <https://doi.org/10.1021/acs.est.6b05330>
34. Soloveichik, G. Electrochemical Synthesis of Ammonia as a Potential Alternative to the Haber–Bosch Process. *Nat Catal* 2019, 2, 377–380, <https://doi.org/10.1038/s41929-019-0280-0>
35. Atmonia Technology – Atmonia. <https://atmonia.com/technology/>
36. Delparish, A.; Uslu, A.; Cao, Y.; de Groot, T.; van der Schaaf, J.; Noël, T.; Fernanda Neira d'Angelo, M. Boosting the Valorization of Biomass and Green Electrons to Chemical Building Blocks: A Study on the Kinetics and Mass Transfer during the Electrochemical Conversion of HMF to FDCA in a Microreactor. *Chemical Engineering Journal* 2022, 135393, <https://doi.org/10.1016/j.cej.2022.135393>
37. Neste The Latest Addition to the List of Renewable Fuels – Biopropane – Will Soon Be Available Available online: <https://www.neste.com/latest-addition-list-renewable-fuels-%E2%80%93-biopropane-%E2%80%93-will-soon-be-available>
38. Zhang, L.; Louie, A.; Rigutto, G.; Guo, H.; Zhao, Y.; Ahn, S.; Dahlberg, S.; Sholinbeck, M.; Smith, M.T. A Systematic Evidence Map of Chronic Inflammation and Immunosuppression Related to

- Per- and Polyfluoroalkyl Substance (PFAS) Exposure. *Environmental Research* 2023, 220, 115188, <https://doi.org/10.1016/j.envres.2022.115188>
39. Kwiatkowski, C.F.; Andrews, D.Q.; Birnbaum, L.S.; Bruton, T.A.; DeWitt, J.C.; Knappe, D.R.U.; Maffini, M.V.; Miller, M.F.; Pelch, K.E.; Reade, A.; et al. Scientific Basis for Managing PFAS as a Chemical Class. *Environ. Sci. Technol. Lett.* 2020, 7, 532–543, <https://doi.org/10.1021/acs.estlett.0c00255>
40. Bright, Z. DuPont, Chemours, 3M Sued by N.C. Attorney General Over PFAS Available online: <https://news.bloomberglaw.com/environment-and-energy/dupont-chemours-3m-sued-by-n-c-attorney-general-over-pfas>
41. C&EN Solvay and Arkema Sued for PFAS Cleanup. *C&EN Global Enterp* 2020, 98, 15–15, <https://doi.org/10.1021/cen-09845-polcon2>
42. Perkins, T. US Agency Takes Unprecedented Action to Tackle PFAS Water Pollution | US News | The Guardian Available online: <https://amp.theguardian.com/us-news/2023/may/06/us-epa-pfas-drinking-water-pollution-ohio-river>
43. Erickson, B. EPA Targets 6 PFAS in Drinking Water Available online: <https://cen.acs.org/environment/persistent-pollutants/EPA-targets-6-PFAS-drinking/101/web/2023/03>
44. NRDC Historic PFAS Drinking Water Regulations Proposed by EPA Available online: <https://www.nrdc.org/press-releases/historic-pfas-drinking-water-regulations-proposed-epa>
45. 3M News Center 3M to Exit PFAS Manufacturing by the End of 2025 Available online: <https://news.3m.com/2022-12-20-3M-to-Exit-PFAS-Manufacturing-by-the-End-of-2025>
46. Mandard, S.; Horel, S. Arkema Faces Criminal Charges for Forever Chemical Contamination in Lyon Region. *Le Monde.fr* 2023. https://www.lemonde.fr/en/france/article/2023/06/05/arkema-faces-criminal-charges-for-forever-chemical-contamination-in-lyon-region_6029191_7.html
47. BASF BASF Online Report 2020 (24): <https://report.basf.com/2020/en/financial-statements/notes/notes-to-the-balance-sheet/risks-from-litigation.html>
48. Feeley, J.; Beene, R. 3M Heads to Trial in ‘Existential’ \$143 Billion PFAS Litigation Available online: <https://news.bloomberglaw.com/environment-and-energy/3m-heads-to-trial-in-existential-143-billion-pfas-litigation>
49. Casselman, B.; Penn, I.; Goldstein, M. Three ‘Forever Chemicals’ Makers Settle Public Water Lawsuits - The New York Times Available online: <https://www.nytimes.com/2023/06/02/business/pfas-pollution-settlement.html>
50. Bonta, R. Attorney General Bonta Leads Coalition in Calling for DuPont to Pay More for Contaminating Americans’ Drinking Water Supply with Toxic PFAS Available online: <https://oag.ca.gov/news/press-releases/attorney-general-bonta-leads-coalition-calling-dupont-pay-more-contaminating>
51. Daikin Daikin Acquires Refrigerant Business from Solvay S.A. | DAIKIN Chemical Europe GmbH Available online: <https://www.daikinchem.de/daikin-acquires-refrigerant-business-solvay-sa>
52. Minetto, S.; Fabris, F.; Marinetti, S.; Rossetti, A. A Review on Present and Forthcoming Opportunities with Natural Working Fluids in Transport Refrigeration. *International Journal of Refrigeration* 2023, <https://doi.org/10.1016/j.ijrefrig.2023.04.015>
53. ATMosphere ATMO Market Report 2022 Available online: <https://atmosphere.cool/marketreport-2022/>
54. Danfoss HRU - Heat Recovery Unit Available online: <https://www.danfoss.com/en/products/dhs/stations-and-domestic-hot-water/hru-heat-recovery-unit/>
55. How Does the PX G1300 Work? - CO2 System Efficiency; 2023; <https://www.youtube.com/watch?v=VGW0c08XdKo>
56. Tsimpoukis, D.; Syngounas, E.; Bellos, E.; Koukou, M.; Tzivanidis, C.; Anagnostatos, S.; Gr. Vrachopoulos, M. Thermodynamic and Economic Analysis of a Supermarket Transcritical CO2

- Refrigeration System Coupled with Solar-Fed Supercritical CO₂ Brayton and Organic Rankine Cycles. Energy Conversion and Management: X 2023, 18, 100351, <https://doi.org/10.1016/j.ecmx.2023.100351>
57. Garry, M. ATMOsphere: 55,000 Stores Using Transcritical CO₂ in Europe. R744 2022.
58. ATMOsphere America Summit DAY 1 – REFRIGERATION CASE STUDIES Available online: <https://atmo.org/announcement/day-1-refrigeration-case-studies-part-1/>
59. Godwin, D.S.; Ferenchiak, R. The Implications of Residential Air Conditioning Refrigerant Choice on Future Hydrofluorocarbon Consumption in the United States. Journal of Integrative Environmental Sciences 2020, 17, 29–44, <https://doi.org/10.1080/1943815X.2020.1768551>
60. Danfoss Refrigerant Options Now and in the Future 2022. <https://assets.danfoss.com/documents/latest/211728/AD224586434178en-001001.pdf>
61. Li, P.; Chen, J.J.J.; Norris, S. Review of Flow Condensation of CO₂ as a Refrigerant. International Journal of Refrigeration 2016, 72, 53–73, <https://doi.org/10.1016/j.ijrefrig.2016.07.022>
62. EIA Sectors Refrigeration : Cool Technologies Available online: <https://cooltechnologies.org/sector/refrigeration/>
63. Skačánová, K. World GUIDE to Low-Charge Ammonia - Complete Report Available online: <http://publication.shecco.com/publications/view/226>
64. ENERGY STAR Product Finder — ENERGY STAR Certified Lab Grade Refrigerators and Freezers Available online: <https://www.energystar.gov/productfinder/product/certified-lab-grade-refrigeration/results>
65. Shi, L.; Abed, A.M.; Fayed, M.; Abdulghani, Z.R.; Anqi, A.E.; Khadimallah, M.A.; Moria, H.; Wae-hayee, M. Economic Cost Analysis of Air-Cooling Process Using Different Numbers of Peltier Modules; Experimental Case Study. Case Studies in Thermal Engineering 2023, 41, 102627, <https://doi.org/10.1016/j.csite.2022.102627>
66. Zhang, Y.; Wu, J.; He, J.; Wang, K.; Yu, G. Solutions to Obstacles in the Commercialization of Room-Temperature Magnetic Refrigeration. Renewable and Sustainable Energy Reviews 2021, 143, 110933, <https://doi.org/10.1016/j.rser.2021.110933>
67. ATMOsphere America Summit DAY 1 – HEAT PUMP CASE STUDIES Available online: <https://atmo.org/announcement/day-1-heat-pump-case-studies/>
68. ATMOsphere Commercial and Industrial Refrigeration in Europe, North America and Japan, 2022 Edition Available online: <https://atmosphere.cool/marketreport-2022/>
69. Hayes, C. ATMO America: Hannaford Equips Fifth Store with R290 Freezers. Hydrocarbons21 2022. <https://hydrocarbons21.com/atmo-america-hannaford-equips-fifth-store-with-r290-cases-for-frozen-food-line-up/>
70. US DoE Whole Foods Market: Brooklyn Third and 3rd | Better Buildings Initiative Available online: <https://betterbuildingssolutioncenter.energy.gov/showcase-projects/whole-foods-market-brooklyn-third-and-3rd>
71. Cao, T.; Hwang, Y. IEA Heat Pumping Technologies ANNEX 54: Heat Pump Systems with Low Global Warming Potential (GWP) Refrigerants Available online: <https://heatpumpingtechnologies.org/annex54/>
72. Gullo, P. Innovative Fully Integrated Transcritical R744 Refrigeration Systems for a HFC-Free Future of Supermarkets in Warm and Hot Climates. International Journal of Refrigeration 2019, 108, 283–310, <https://doi.org/10.1016/j.ijrefrig.2019.09.001>
73. Azzolin, M.; Cattelan, G.; Dugaria, S.; Minetto, S.; Calabrese, L.; Del Col, D. Integrated CO₂ Systems for Supermarkets: Field Measurements and Assessment for Alternative Solutions in Hot Climate. Applied Thermal Engineering 2021, 187, 116560, <https://doi.org/10.1016/j.applthermaleng.2021.116560>
74. Walker, I.S. OSTI.GOV: Technical Report: Best Practices Guide for Residential HVAC Retrofits; 2003; p. LBNL--53592, 824856; <https://doi.org/10.2172/824856>

75. US EPA, O. EPA Draft “Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances” Available online: <https://www.epa.gov/environmental-economics/scghg>
76. New York State, D. of E.C. Express Terms - Adopted Part 494 - NYS Dept. of Environmental Conservation Available online: <https://www.dec.ny.gov/regulations/119032.html>
77. ECHA Per- and Polyfluoroalkyl Substances (PFAS) - ECHA Available online: <https://echa.europa.eu/hot-topics/perfluoroalkyl-chemicals-pfas>
78. Bălan, S.A.; Mathrani, V.C.; Guo, D.F.; Algazi, A.M. Regulating PFAS as a Chemical Class under the California Safer Consumer Products Program. *Environ Health Perspect* 2021, 129, 025001, <https://doi.org/10.1289/EHP7431>
79. US-EPA State and Local Climate and Energy Program - Rules of Thumb 2016. https://www.epa.gov/sites/default/files/2016-03/documents/table_rules_of_thumb.pdf
80. Hundy, G.F.; Trott, A.R.; Welch, T.C. Efficiency, Running Cost and Carbon Footprint. In *Refrigeration, Air Conditioning and Heat Pumps*; Elsevier, 2016; pp. 435–446 ISBN 978-0-08-100647-4. <https://doi.org/10.1016/B978-075068519-1.00030-X>
81. Lee, H.; Troch, S.; Hwang, Y.; Radermacher, R. LCCP Evaluation on Various Vapor Compression Cycle Options and Low GWP Refrigerants. *International Journal of Refrigeration* 2016, 70, 128–137, <https://doi.org/10.1016/j.ijrefrig.2016.07.003>
82. Murthy, A.A.; Subiantoro, A.; Norris, S.; Fukuta, M. A Review on Expanders and Their Performance in Vapour Compression Refrigeration Systems. *International Journal of Refrigeration* 2019, 106, 427–446, <https://doi.org/10.1016/j.ijrefrig.2019.06.019>
83. Yang, Z.; Feng, B.; Ma, H.; Zhang, L.; Duan, C.; Liu, B.; Zhang, Y.; Chen, S.; Yang, Z. Analysis of Lower GWP and Flammable Alternative Refrigerants. *International Journal of Refrigeration* 2021, 126, 12–22, <https://doi.org/10.1016/j.ijrefrig.2021.01.022>
84. Palm, B. Hydrocarbons as Refrigerants in Small Heat Pump and Refrigeration Systems – A Review. *International Journal of Refrigeration* 2008, 31, 552–563, <https://doi.org/10.1016/j.ijrefrig.2007.11.016>
85. Hsieh, H.-K.; Teng, T.-P. Retrofit Assessment of Automobile Air Conditioners Using Hydrocarbon Refrigerants. *Applied Thermal Engineering* 2022, 214, 118781, <https://doi.org/10.1016/j.applthermaleng.2022.118781>
86. DESCRIPTION 2023 ASHRAE HANDBOOK—HVAC APPLICATIONS. <https://www.ashrae.org/technical-resources/ashrae-handbook/description-2023-ashrae-handbook-hvac-applications>
87. International Electrotechnical Commission IP Ratings | IEC Available online: <https://www.iec.ch/ip-ratings>
88. Chemours Applications & Industries for Opteon™ Available online: <https://www.opteon.com/en/industries-applications>
89. Mota-Babiloni, A.; Fernández-Moreno, A.; Giménez-Prades, P.; Udriou, C.-M.; Navarro-Esbrí, J. Ternary Refrigerant Blends for Ultra-Low Temperature Refrigeration. *International Journal of Refrigeration* 2023, 148, 108–116, <https://doi.org/10.1016/j.ijrefrig.2023.01.006>
90. Feng, B.; Yang, Z.; Liu, H. Research on Inhibition of Flame Retardants on Flammability of R1234yf. *International Journal of Refrigeration* 2020, 118, 302–310, <https://doi.org/10.1016/j.ijrefrig.2020.06.031>
91. Mazyan, W.I.; Ahmadi, A.; Ahmed, H.; Hoorfar, M. Increasing the COP of a Refrigeration Cycle in Natural Gas Liquefaction Process Using Refrigerant Blends of Propane-NH₃, Propane-SO₂ and Propane-CO₂. *Heliyon* 2020, 6, e04750, <https://doi.org/10.1016/j.heliyon.2020.e04750>
92. Pearson, A. Carbon Dioxide—New Uses for an Old Refrigerant. *International Journal of Refrigeration* 2005, 28, 1140–1148, <https://doi.org/10.1016/j.ijrefrig.2005.09.005>

93. Yelishala, S.C.; Kannaiyan, K.; Sadr, R.; Wang, Z.; Levendis, Y.A.; Metghalchi, H. Performance Maximization by Temperature Glide Matching in Energy Exchangers of Cooling Systems Operating with Natural Hydrocarbon/CO₂ Refrigerants. *International Journal of Refrigeration* 2020, 119, 294–304, <https://doi.org/10.1016/j.ijrefrig.2020.08.006>
94. Roy, Z.; Halder, G. Replacement of Halogenated Refrigerants towards Sustainable Cooling System: A Review. *Chemical Engineering Journal Advances* 2020, 3, 100027, <https://doi.org/10.1016/j.cej.2020.100027>
95. McLinden, M.O.; Huber, M.L. (R)Evolution of Refrigerants. *J. Chem. Eng. Data* 2020, 65, 4176–4193, <https://doi.org/10.1021/acs.jced.0c00338>
96. Wu, X.; Dang, C.; Xu, S.; Hihara, E. State of the Art on the Flammability of Hydrofluoroolefin (HFO) Refrigerants. *International Journal of Refrigeration* 2019, 108, 209–223, <https://doi.org/10.1016/j.ijrefrig.2019.08.025>
97. BAM Final Test Report - Ignition Behaviour of HFO1234yf 2010. https://www.umweltbundesamt.de/sites/default/files/medien/419/dokumente/test_report_hfo1234yf_2010_06.pdf
98. Söylemez, E.; Widell, K.N.; Gabriell, C.H.; Ladam, Y.; Lund, T.; Hafner, A. Overview of the Development and Status of Carbon Dioxide (R-744) Refrigeration Systems Onboard Fishing Vessels. *International Journal of Refrigeration* 2022, 140, 198–212, <https://doi.org/10.1016/j.ijrefrig.2022.05.007>
99. Ebert, A. DuPont Must Fight North Carolina Forever Chemical Suit (1) Available online: <https://news.bloomberglaw.com/environment-and-energy/dupont-chemours-must-fight-north-carolina-forever-chemical-suit>
100. Nayak, M. DuPont, 3M Sued by California Over ‘Staggering’ Pollution Available online: <https://news.bloomberglaw.com/environment-and-energy/dupont-3m-sued-by-california-over-toxic-forever-chemicals>
101. Tullo, A. Chemours Sues DuPont over Environmental Liabilities Available online: <https://cen.acs.org/environment/pollution/Chemours-sues-DuPont-over-environmental/97/i27>
102. Earls, M. Daikin America Denied Appeals Court Look at PFAS Pollution Suit Available online: <https://news.bloomberglaw.com/litigation/daikin-america-denied-appeals-court-look-at-pfas-pollution-suit>
103. Deep Value Ideas 2 Reasons To Sell 3M Stock Despite The “Good” News (NYSE:MMM) | Seeking Alpha: <https://seekingalpha.com/article/4610996-2-reasons-to-sell-3m-stock-despite-the-good-news>
104. Feeley, J. 3M Said to Be in at Least \$10 Billion PFAS Pollution Accord Available online: <https://news.bloomberglaw.com/environment-and-energy/3m-said-to-be-in-at-least-10-billion-pfas-pollution-settlement-1>
105. Just, R. Social Cost of Greenhouse Gas Estimates - Environmental & Energy Law Program Available online: <https://eelp.law.harvard.edu/2022/10/social-cost-of-greenhouse-gas-estimates/>