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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 CO_2, HC, and HC/CO_2 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.
- CO_2, HC/CO_2 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; CHF_3 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 (CF_3CHO; 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 (CF_3COOH; 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.

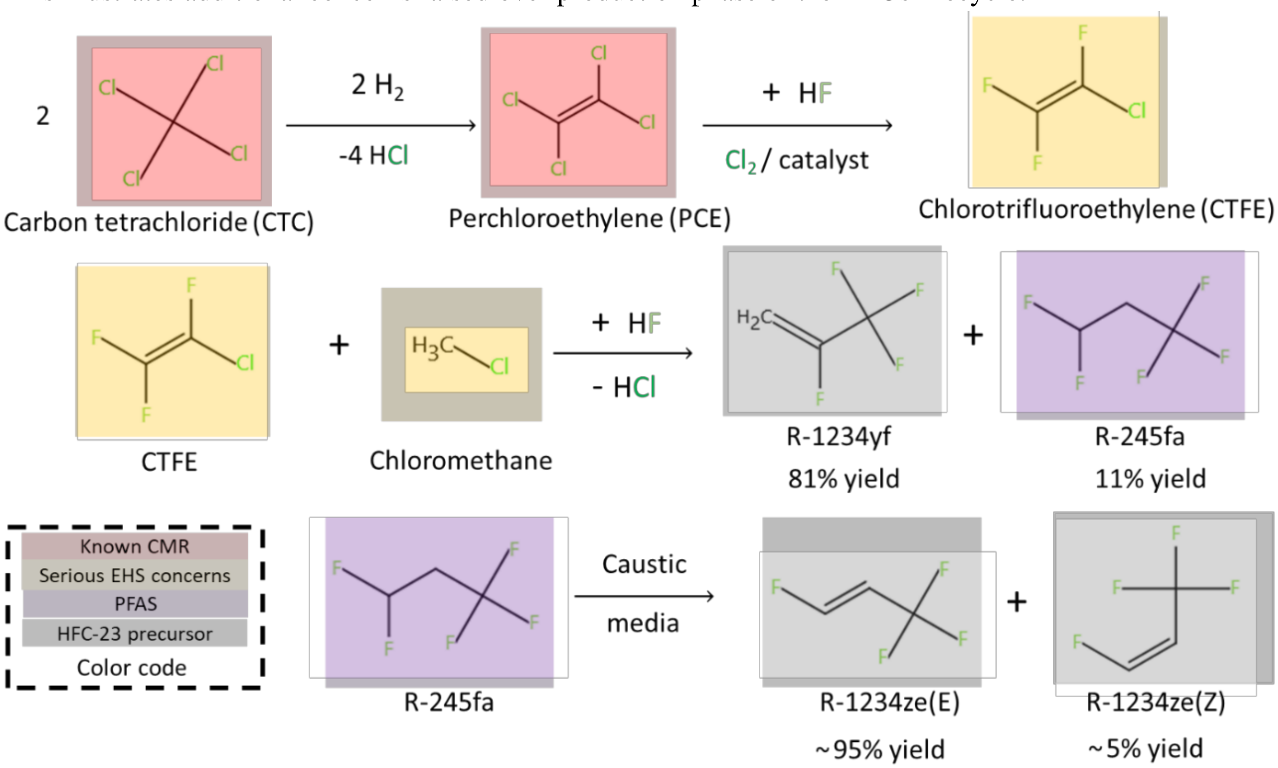

FIGURE 1: CHEMICAL PATHWAYS FOR THE PRODUCTION OF HFO REFRIGERANTS.
SOURCE: MASSACHUSETTS TOXICS USE REDUCTION INSTITUTE.
BASED ON REFERENCES [20–23,26–29]

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 CO_2, HC and HC/CO_2 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 CO_2, HCs, or HC/CO_2 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 CO_2 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 CO_2 demonstrates up to 50% annual energy savings, meaning short payback periods over the initial investment [56–58]. It is expected for CO_2 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 (CO_2), ammonia (NH_3), 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 CO_2, corrosion due to the use of CO_2 and NH_3, 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 CO_2/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 CO_2, HC, and HC/CO_2 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 CO_2 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].

CO_2; HC/CO_2 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 CO_2 (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/CO_2 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 CO_2 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 CO_2e 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 CO_2e emissions by up to 20% [80].
- The condenser transfers heat from the refrigerant to the environment. Improving efficiency can reduce the indirect CO_2e 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 CO_2 [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 (COF_2) 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 CO_2 in transport refrigeration is growing as businesses look for more sustainable alternatives to ammonia and HFCs. CO_2-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, CO_2 systems offer several advantages over traditional refrigerants [52,73,98]. CO_2/HC cascade systems are increasingly employed in food transportation [62] and storage [53,63].

CO_2 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 CO_2 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 statal 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.

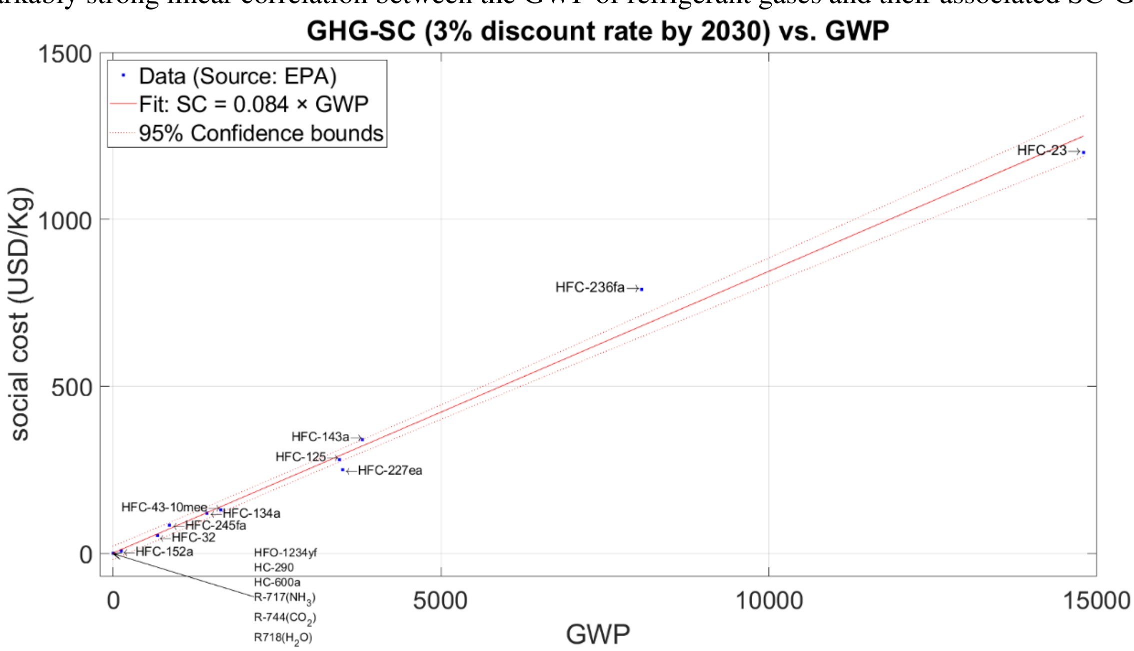

FIGURE 2: SOCIAL COST OF REFRIGERANT GASES AS A FUNCTION OF THEIR GWP. SOURCE: MASSACHUSETTS TOXICS USE REDUCTION INSTITUTE. DATA SOURCE: [25,75,76]

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 CO_2, 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.

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