Report summary F-gas uses

Heating, ventilation, and air conditioning and refrigeration (HVACR), foam-blowing agents, solvents, propellants, cover gases and fire suppressants

Contents

1. Uses / Applications

F-gases are a group of industrial chemicals used for heating, ventilation, air conditioning and refrigeration (HVACR), and as foam blowing agents, propellants, solvents, cover gases in magnesium industry and fire suppressants. These major sectors may be further divided into sub-applications. There are also a number of niche applications (e.g. for leak detection) that are not specifically addressed in the current assessment. F-gases used for the mentioned applications include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), hydrochlorofluorocarbons (HCFCs), unsaturated hydro(chloro)fluorocarbons (HFOs and HCFOs), hydrofluoroethers (HFEs), fluoroketones (FKs) and other fluorinated compounds. F-gases may be used either alone or in blends.

2. Main PFAS substances

The current assessment covers substances that are both F-gases and coverd by the PFAS-definition. A list of the specific F-gas substances (which are also PFAS) identified in commercial use in this assessment is found in **Appendix I**.

There are 10 different HFCs currently being used. In addition, 11 HFOs were identified (several of which are isomers), two fluoroketones, four hydrofluoroethers (HFE), 12 HFC & HFC/non-F-gas blends and nine HFC/HFO blends.

3. Tonnage band

Market data on F-gases filled into new products and in stocks each year have primarily been derived from data collated by the European Union (EU) /European Economic Area (EEA) Governments (the Greenhouse Gas (GHG) Inventory data) in their annual reporting to the UNFCCC (EU, 2020a). Tonnages of F-gases from manufacturing to decommissioning is available at the subapplication level, and is indicated in the material flow diagram in Figure 1. Data is not available at the substances level.

In 2018 in total, **30,671** tonnes**/a F-gases are filled into new products** for the first time during their manufacturing process, while **492,173** tonnes**/a are found in operating systems** (Annual stocks in operating systems refers to products that already contain F-gases and are in operation) used in EU-27 & the United Kingdom (UK) & Iceland (IS) & Norway (NO) (EU, 2020a). Remaining in products at decommissioning is 19,724 tonnes/a F-gases. From the GHG Inventory data for 2018, refrigeration and air conditioning account for 78% (24,093 tonnes /a) of the total amount of these F-gases filled into new manufactured products and 82% (404,315 tonnes /a) of the F-gases in stocks.

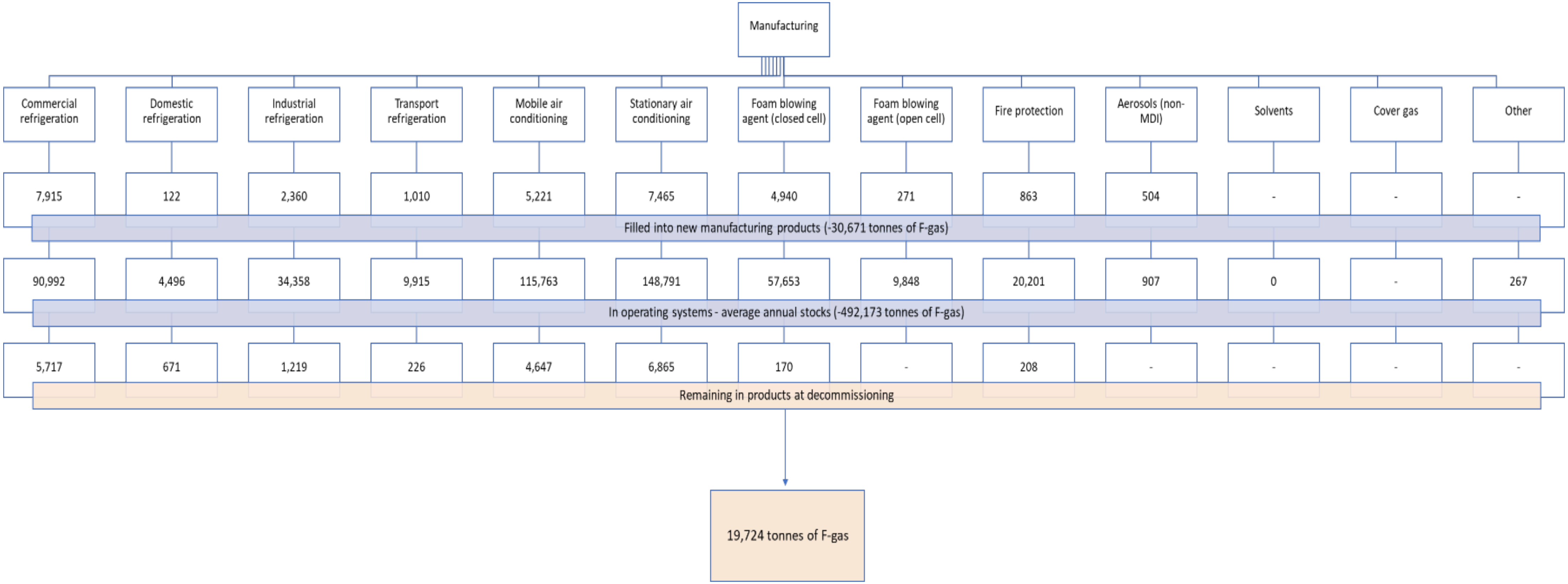

Figure 1. Material Flow diagram – F-gases from Product Manufacturing Until Decommissioning, 2018.

The European Environment Agency collects and publishes F-gas data reported by industry according to the obligations under Regulation (EC) No 517/2014 (the 'F-Gas Regulation'). The most recent report referred to in this project as the 'F-Gas Report' provides EU data up to and including 2019 and covers F-gas activity (production, reclamation, imports, exports, destruction and feedstock use), supply of F-gases (trends in supply) and progress of phasing down the use of hydrofluorocarbons (HFCs) (EU, 2020b). The relative proportions to different applications of F-gases are illustrated in the figure below:

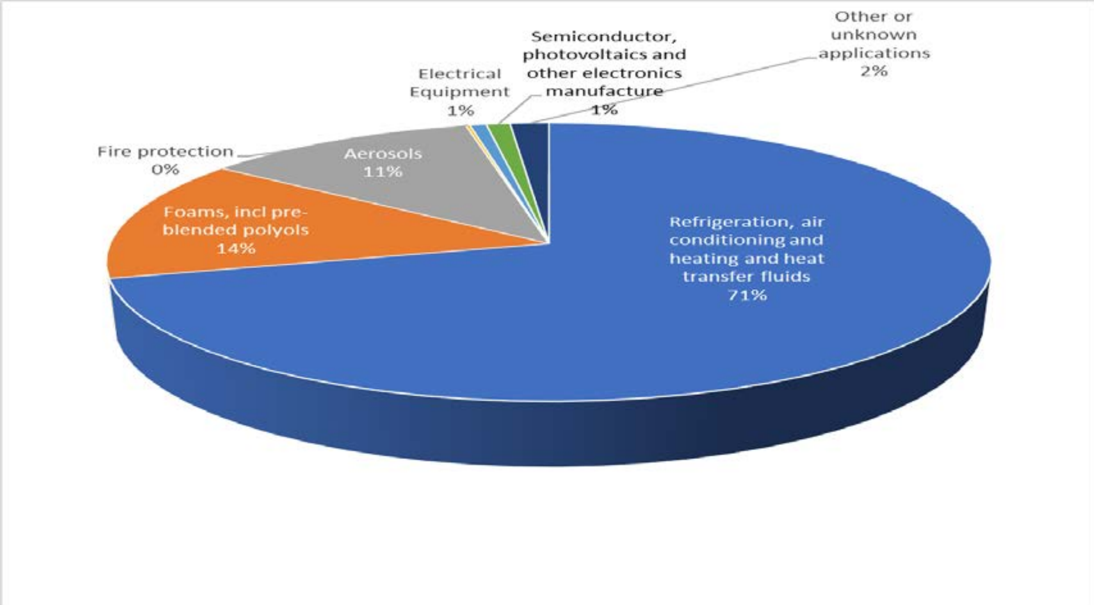

Figure 2. Supply of F-Gases to Different Applications in EU-28 (2019). Source (EU, 2020b).

4. Import & Export

Most of the F-gases in use in the EU are imported. Import accounts for about 75% of F-gases used, while 25% are manufactured in the EU.

5. Manufacturing & market price + market development

Trends in the supply in EU-28 of data 2007 – 2019 have been reported in the table in **Appendix II** and illustrated in the figure 2.

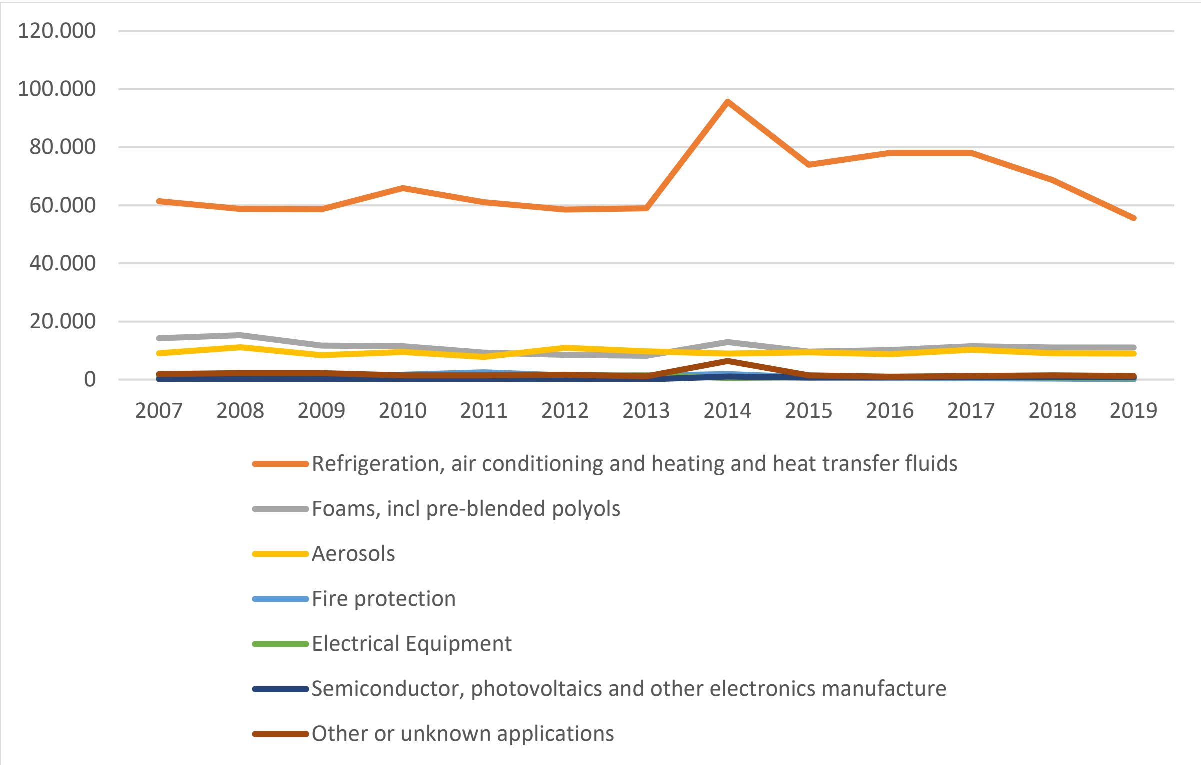

Figure 3. Trends of F-gases Supplied for Use in Products and Equipment in EU-28 (2007 – 2019). Source (EU, 2020b).

Change in demand for refrigeration specifically (leaving aside air conditioning and the use of heat pumps) is likely to follow a mix of population and economic growth over time. However, continued growth of 2.77% has been forecast for refrigeration in Europe over the period 2021-2025 (Statista, 2021). Forecasts beyond 2025 have not been identified relative to units sold, and information on changes in demand for refrigeration as a consequence of climate change is available but does not relate directly to the number of units sold, which is a better proxy for demand for F-gases. The baseline for the use of F-gases in this sector, covering refrigeration, air conditioning and heat pumps, is anticipated to grow strongly up to 2025 and beyond.

As for insulation, it has been forecast that growth of 8%/year globally will occur in the insulation market over the period 2020 to 2024 (Global Insulation, 2020). However, a lower estimate of growth in the sector has been quantified for Europe of 3.48% annually over the period 2015-2027 (Pavel, 2018), with wool minerals, and plastic foams (EPS, XPR and PUR) being the dominant materials for insulation. Increased use of PFAS-bearing foams for building insulation where the service life of materials is long will take decades to feed through to the waste sector.

As for propellants (technical aerosols, non-technical aerosols), industry data indicate that 5.5 billion units were produced by the European aerosol industry in 2019, a modest increase from the figure of 5.4 billion for 2009 (FEA, 2020b). Available data (EU, 2020b) show a decline in the use of F-gases in both medical and non-medical aerosol products from 10,950 tonnes in 2012 down to 8,744 tonnes in 2018, despite the evidence cited above regarding growth in the European market for aerosols (Ricardo, 2019). The market is dominated by personal care products.

As for the use of F-gases as solvent as precision and electronics cleaning, the electronics market is growing at a rate of 4.8% per year globally from 2020 to 2025 (Investopedia, 2020) and there is potential for F-gas solvent use to grow with this market. However, there is nothing to indicate that it will become a significantly greater user of F-gases than it is now, and it currently represents only a small part of the market (1%).

Demand for cover gas in magnesium casting has been forecasted to grow at a compound annual growth rate (CAGR) of 9.6% in the period 2020 to 2025, driven by strong demand from the automotive and aviation sectors. There is no primary production of magnesium in the EU, with the last primary producer closing in 2000. Most of the primary production, over 80%, occurs in China (USGS, 2020). Russia is the next largest producer, with 7% of global production. There is, however, significant recycling of magnesium by EU business.

Market data (Research and Markets, 2019) suggests that the market for fire detection and suppression will show strong growth over the period 2018 to 2025 at a compound annual growth rate of 5.9%, with the fire detection and suppression market valued at USD 3.27 billion in 2018.

6. Market price & No. of production sites:

Detailed information on the market price or number of production sites is not given for the F-gases used in different applications.

7. Emissions

Estimated total emissions of F-gases from the different sub-applications may be found in **Appendix III.** All emissions are to air. Emissions are disaggregated at the subapplication level and not on the substance level. **Appendix IV** compares the activity data and emission estimates for F-gases in 2018. Emissions from manufacturing, as well as emissions from the use phase, are included.

From the GHG Inventory data (2018) and UN Methodology, it is apparent that the implied emissions during the manufacturing of products and equipment is generally between 0 – 3 % of the F-gases used and mainly from foam blowing agents (closed-cell). By contrast emissions from stocks are significantly higher as would generally be expected and are in the range 0 – 13%. Commercial and industrial refrigeration, mobile and stationary air conditioning accounting for 83% of the total emissions from stocks.

In total, the emissions of F-gases in 2018 from the different uses were as follows:

Manufacturing of products and equipment:	1,696 tonnes /a
Stocks (i.e. service-life):	38,806 tonnes /a

Industry stakeholders have underlined the importance of Hydrofluoroolefins (HFOs) and fluoroketone (FK) alternatives during the development of this dossier. Primarily this is because in a number of applications they can substitute the function provided by other F-gases alone or in blends, whilst at the same time having significantly lower global warming potential (GWP). The relative proportion of HFOs compared to other F-gases has been increasing from 2016 – 2019 from 6 to 24%. The majority of HFOs currently being used commercially as a single substance (rather than a blend) are in mobile air conditioning (MAC) systems for passenger cars and in light goods vehicles and commercial refrigeration, commercial air conditioning, heat pumps and process cooling. In contrast to HFCs, HFOs and FKs generally have atmospheric lifetimes measured in days.

Estimated range of HFO emissions from passenger car and light goods vehicle MACs in 2018:

Manufacturing: 9 – 1,170 tonnes/a

Stocks: 1,281 – 17,472 tonnes/a

The tonnage and emission information of HFOs are presenterd in **Appendix V and VI** respectively.

8. Worker exposures

Worker exposures to F-gases in plant manufacturing equipment or putting the gases into product should be small, given the need to use closed systems (mentioned by many respondents to the call for evidence). Outside of the manufacturing plant, however, there may be greater exposure of workers, for example at sites reclaiming refrigeration equipment at the end of its service life.

9. Summary of existing legal requirements

- The Montreal protocol
- Directive 2006/40/EC on emissions from air conditioning systems in motor vehicles
- Regulation (EU) No 517/2014 (F-gas Regulation): Annex I Fluorinated greenhouse gases (HFC, PFC) primarily targeted by the regulation, Annex II Other F-Gases subject to reporting in accordance with Article 19 of the regulation:
- Regulation (EC) No 1005/2009 of the European Parliament and of the Council of 16 September 2009 on substances that deplete the ozone layer (ODS Regulation). Annex I are controlled substances; Annex II are new substances.
- UNFCCC/Paris Agreement (HFC/PFC)

10. Alternatives

In general **51 alternative**s (Non-PFAS substances and technical methods/Not-in-kind alternatives) were identified for different applications. Some parts of the market have already switched away from the use of F-gases to alternatives such as hydrocarbons and CO2. Particularly the domestic refrigeration sector which has moved from near total reliance on F-gases at the time that the Montreal Protocol came into effect to almost total reliance on alternatives now. There are signs that a similar approach is also being taken in the clothes dryer heat pump market, with many manufacturers opting for hydrocarbon refrigerants in preference to F-gases. However, there is also strong resistance in other areas: the mobile air conditioning market seems particularly averse to a switch to alternatives, citing concerns on the grounds of safety (for hydrocarbons) and cost (for CO2).

Alternatives have been assessed for each application of F-gases at the subapplication level. An overview found in **Appendix VII.**

Review of the properties of these options (alternatives) indicates a variety of issues. The major constraints relate to safety, technical factors and legislation. However, in many cases the technical issues may be solved in the design of equipment.

11. Economic impacts in case of a full PFAS ban

The trend development and economic impact for each of the different subapplications is presented in the Table 1. Overall, restriction would have a larger effect on domestic AC systems and in heat pumps for space and water heating than for refrigeration and heat pump clothes dryers because they are both currently dependent on the use of F-gases.

Equipment would likely need to come to the end of its service life before non-F-gas systems were adopted. For small appliances and vehicles this may be a period of 10-15 years whilst for some industrial and commercial applications it may take much longer, up to 40 years. In this case, effects on manufacturers would be small and impacts on downstream users would also be low, and possibly negligible. Otherwise with a rapid transition, there is potential for significant disruption to the market.

F-gas blowing agents are more expensive than the alternatives. A cost differential of a factor 10 has been provided between for HFOs relative to CO_2 mixes. The cost of HFO in XPS can be as much as 55% of the total raw material cost, providing a strong rationale for switching to alternatives. For F-gas blowing agents, estimated costs of adaption to production lines based on responses received to the consultation is of €3 million (based on earlier costs of converting back to F-gases from having used hydrocarbons) to €100 million.

Switching to the use of **hydrocarbon propellants** would generate health and environmental risks associated with the formation of tropospheric ozone. Estimates of the costs per unit emission of non-methane volatile organic compounds (NMVOCs) are in the range of €2.3 to €6.1 per kg emission (emission-weighted average across EU Member States) in 2020 prices (EEA, 2014).

In general, Industry estimates indicate that the past transitions to new molecules have cost individual companies developing new fluorocarbons in the region of $1 billion. An estimate has also been provided based on past experience that the development of new substances has taken in the order of 7 to 10 years.

Table 1. The trend development and economic impact for each of the different subapplications

Application	Comments on Trends and impact
Domestic Refrigeration	Baseline F-gas use in absence of a restriction: No further F-gas use in this sector. Restriction will have limited economic impact as market has switched almost entirely to hydrocarbons. Similarly, there are unlikely to be significant environmental, health or social consequences of a restriction, given that it would have little impact on the market.
Commercial Refrigeration	Baseline F-gas use in absence of a restriction: Potential for growth in market in response to warmer climate though increased penetration of alternatives. Switching to HFOs. Restriction for small-scale refrigeration would be unlikely to have a significant effect as such systems already use similar designs to domestic refrigeration. There is growing acceptance of the use of alternatives using CO_2 and hydrocarbons in mid to large scale facilities in the sector. However, the sector is still dominated by the use of F-gases, and the assumption that alternatives are ready to replace them may be premature. Further research is being conducted in a number of areas. The lifetime of medium and large equipment is in the order of 15 to 25 years, and that it would take 10 to 12 years to develop new products and take them to market. On this basis, there is a significant lifetime remaining, in the order of decades, for equipment that is already in place.
Industrial Refrigeration	Baseline F-gas use in absence of a restriction: Declining usage, with ammonia systems dominant. Potentially some niches that are reliant on F-gas use. Efficient systems based on ammonia have been in place for many years in the industrial sector, though there remains some F-gas use. Other alternatives to F-gases are also practicable for some industrial applications. However, there may be situations or processes where the continued use of F-gases is argued to be required, for example to reach and maintain specific operating temperatures. It also cannot be ruled out that F-gases still provide the most cost-efficient option for some specific applications, given the breadth of the industrial sector.
Transport Refrigeration	Baseline F-gas use in absence of a restriction: Continued high demand for refrigerated transport. Probable switching to HFOs. Some alternatives are already in use in trucks, in trawlers and in reefer containers. However, they are not currently widespread. Specific barriers affect the sector, for example, size limitations are problematic for the use of active CO_2 systems given the layout of existing trucks. Use of hydrocarbons in enclosed areas may generate risks of flammability. Further design work would be needed to provide viable alternatives that are widely applicable across the market. Whilst there are feasible alternatives for some applications, there are significant gaps in the market, meaning that a reliance on F-gases in road transport refrigeration is likely to continue for some time.
Mobile Air Conditioning	Baseline F-gas use in absence of a restriction: Growth in market in response to warmer climate, increased wealth and need to control battery temperature in electric vehicles. Switching to HFOs. Major barriers for the use of alternatives to F-gases in the mobile air conditioning market: Safety and toxicity of hydrocarbon and ammonia systems and cost of the use of CO_2 . CO_2 is the leading contender as a replacement. Potential for switch to CO2-based systems in the medium term for cars, and probably vans and trucks. These currently have very limited penetration on the market so manufacturers would need time (15 years) to transition from the current R-1234yf based systems to CO2 based systems. Do-it-yourself kits for topping up MAC systems may result in significant releases to the environment. Such activities should be undertaken by professionals, with a requirement to fix leaks.

Application	Comments on Trends and impact
Stationary Air Conditioning and heat pumps	Baseline F-gas use in absence of a restriction: Growth in air conditioning market in response to warmer climate and increased wealth. Growth in heat pump market as a result of climate actions. Switching to HFOs.
Domestic AC and domestic heat pumps for space heating	Building codes may need revision in some countries to accomodate a switch to fluorine-free alternatives. Precautions need to be recognised (e.g. installation of single split systems by qualified professionals). Use in larger domestic systems, e.g. in multi-occupancy households requiring multiple connections and large charge sizes, not recommended. Some stakeholders expressed the view that there is no alternative to HFOs (specifically R-1234yf) for the heat pump market because of concerns over the safety of using hydrocarbons.
Commercial AC and heat pumps	Most systems are F-gas based. Propane is currently mostly restricted to small applications because building codes and other regulations limit charge size. There is growing acceptance of the use of alternatives using CO_2 and hydrocarbons in mid to large scale facilities in the sector. However, the sector is still dominated by the use of F-gases, and the assumption that alternatives are ready to replace them may be premature. Further research is being conducted in a number of areas.
Domestic heat pumps (clothes dryers)	Potentially cost neutral for consumers though investment needed by some manufacturers. Review of market data on the cost of heat pump clothes dryers indicated no systematic difference in price between propane and F-gas models. Overall, Manufacturers of European heat pump clothes dryers are unlikely to be affected given their current models.
Foam Blowing Agent (Closed cell)	Baseline F-gas use in absence of a restriction: Expected growth in the next decade through increased demand for insulation, with switching to HFOs and HCFOs. Safety constraints from using hydrocarbons need to be recognized, as well as the improved quality of insulation required in line with climate objectives. Higher price of F-gas foam blowing agents provides incentive to use alternatives where possible. Mechanisms for collection and proper disposal of insulation materials at end of life would be advisable.
Electronics Cooling (e.g. at Data Centres), heat exchanger part with F-gases or other refrigerants	The feasibility of alternatives is questioned due to concerns over safety of hydrocarbon and the toxicity of ammonia. It is indicated that the existing stock would need to rely on HFOs and HFCs for the next 20 years at least.
Foam Blowing Agent (Open cell)	Baseline F-gas use in absence of a restriction: Assumed similar to situation for closed cell foams. There are unclear resons for continued use in the higher price of F-gases given that open cell foams cannot exploit the improved insulation characteristics of F-gases. High percentage emission from use of product at time of use.
Firefighting foams	Addressed under separate ECHA-led restriction process.
Fire suppression agents	Baseline F-gas use appears to be holding steady. Not switching to HFOs given flammability. Price already provides a mechanism favouring alternatives to F-gases and has led to a significant shift away from F-gases. Remaining users consider the benefits of non-toxic clean suppressants sufficient to justify price.
Propellants (non-MDI)	Baseline F-gas use declining, and some switching to HFOs. Restriction likely to be proportionate for non-technical aerosols. However, some safety constraints for some technical applications should be recognized.
Solvents	Baseline F-gas use in absence of a restriction: No clear trend beyond a switch to HFOs but source will remain small contributor to F-gas use. Minor use (<1% of emission), but wide range of applications. Higher price of F-gas solvents suggests that they provide a significantly higher level of service or safety than alternatives.

Application	Comments on Trends and impact
Cover Gas for magnesium casting	Baseline F-gas use in absence of a restriction: Expansion in magnesium casting, but source will remain small contributor to F-gas use.
Die casting	Restriction appears proportionate against indicative benchmarks.
Sand casting	Very limited data identified, but there is no indication that a restriction would not be proportionate.
Other	Not addressed. Some further uses identified (e.g. tracer gases) but effects of a restriction not characterised.

12. Other impacts in case of a full PFAS ban

12.1 Environmental

Emissions from the HVACR (heating, ventilation, air conditioning and refrigeration) sector are estimated to account for 85% of the total emissions of F-gases from stocks (EU, 2020a). A full restriction on their use in this sector would therefore in principle result in substantial reduction of additional future emissions of F-gases. However, increased use of hydrocarbons would increase atmospheric loading with volatile organic compounds (VOCs).The extent of this problem is dependent on the quantity of propane that may leak from systems. On the other hand, ammonia contributes to the formation of secondary inorganic aerosols as a component of fine particulate matter in the atmosphere. Current emissions of ammonia from refrigeration are negligible compared to those from the dominant source, agriculture.

There is potential for additional impacts to health and the environment to arise from the use of alternatives:

- Changes in energy use
- Changes in waste streams (e.g. generation of aqueous effluents)
- Increased failure rate during manufacture leading to increased wastage (improvement in performance leading to reduced wastage currently seems unlikely given the current preference for F-gas solutions and that suitable alternatives have not been identified for all applications).

The major health concern of a switch away from F-gases is the risk of fire. This will limit the application of hydrocarbons as alternatives to F-gases through non-compliance with building codes. It also limits the use of hydrocarbons in spray foam applications in environments where there is a significant risk of fire.

12.2 Social impacts

- Increased employment through the development of innovative product lines
- Reduced employment through loss of market share for EU companies
- Downstream effects on society through changes in the quality of goods and the price for attaining an equivalent level of service
- Willingness to pay (WTP): Social preference for avoiding the release of persistent substances
- Legacy burdens: materials that will need to be managed over long (inter-generational) periods particularly construction materials where lifetimes are commonly in the order of decades.

The ubiquitous demands for heating and cooling mean that the number of organisations and facilities that could potentially be affected is very large. For some there could be a loss of business (e.g. F-gas manufacturers), for others there would be a need for retraining and retooling (e.g. installers and service agents). For some downstream users (e.g. many private households) there might be no direct impact. Key to the effects on these groups are the questions of when a restriction would be introduced and how it would be applied to existing facilities, in particular for how long they would be permitted to continue using F-gases.

Table 2. Summary of availability of alternatives to the Use of F-gases in New HVACR Systems

Sub-use	New Products
Domestic refrigeration	Cost effective alternatives already widely used.
Domestic AC and heat pumps	Hydrocarbon based alternatives already on the market for smaller systems. Calls for relaxation of the limits on charge size. Specific situations may continue to be problematic, e.g. use in high rise buildings, where the risks of accidents may be considered to exceed the risks from emissions of F-gases.
Domestic clothes dryers	Cost effective alternatives already widely used.
Commercial HVACR[1]	There is growing acceptance of the use of alternatives using particularly CO_2 or hydrocarbons in the commercial sector. However, the sector is still dominated by the use of F-gases, and the assumption that alternatives are ready to replace them may be premature. Further research is being conducted in a number of areas.
Industrial heating and cooling [1]	Efficient systems based on ammonia have been in place for many years. Other alternatives to F-gases are also practicable for some industrial applications. There may be situations or processes, however, where the continued use of F-gases is required.
Electronics cooling, heat exchanger part with F-gases or other refrigerants	Large, isolated data centres may be able to use alternative refrigerants such as ammonia without problems. Very small systems may be cooled using basic ventilation or small scale AC systems for which hydrocarbon charge size would not be problematic.
Transport refrigeration	Some alternatives are already in use in trucks, in trawlers and in reefer containers. However, they are not currently widespread. Specific barriers affect the sector, for example, size limitations are problematic for the use of active CO_2 systems given the layout of existing trucks. Further design work would be needed to provide viable alternatives that are widely applicable across the market.
Mobile air conditioning	An estimate has been provided of an additional cost of €300/vehicle for adoption of CO_2 MAC systems. The motor industry regards this as too expensive for adoption other than as an option. Assuming leakage of the full quantity of F-gas used in a system over its lifetime, a restriction would cost less than €1 000/kg F-gas which is the lower indicative benchmark derived by (Oosterhuis, 2017).

1. The distinction between industrial and commercial HVACR is not clear cut. A regulation on either sector would need to define very clearly what was covered.

Restriction scenario envisaged: mainly total phase-out of PFAS-based F-gases. However, it may be needed to take into account that alternatives are not currently readily available for all applications. For existing systems, there is specifically a lack of drop-in alternatives.

13. Methods used & uncertainties

The approach used to calculate emission estimates is in line with United Nations (UN) methodology using implied emission factors (IEFs)

à IEF application A = Tonnes of F-gas emitted from stocksapplication A /Tonnes of F-gas in stocksapplication A x 100.

Emissions = activity data * emissions factors

Emission factors can be either default or specific to a country, application or even sub-application. The methodology for Member States to collect and compile this data has been published in the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).

Uncertainties

GHG Inventory data:

- Only data that are attributed to specific F-gases have been included in the data set. This results in an underestimate of the resulting emissions because emissions associated with 'unspecified' F-gases have not been taken into account in the data set. Unspecified F-gases are estimated to be <1% of the total emissions in CO_2 equivalents.
- Emission estimates of blowing agents from open and closed cell foams presented in the GHG Inventory are inconsistent with the reports from stakeholders received during consultation for this project. Specifically emissions during manufacturing reported in the GHG Inventory seem to be very high and emissions from closed cell foams from stocks also appear to be elevated.
- It is unclear if the application stationary air conditioning includes F-gases used in heat pumps
- Further differentiation of reported emissions would be useful in some cases, to better understand how emissions for AC systems split between domestic and commercial use.
- Diversity of applications of F-gases as propellants
- Data for the manufacturing of F-gases or emissions reported from disposal or recovery which are not included.

Appendix I

A list of the specific F-gas substances identified in commercial use in this assessment.

Entry	F-gas substance	F-gas code	F-gas structure
1	Difluoromethane	HFC-32	CH2F2
2	1,1,1,2,2,3,4,5,5,5- Decafluoropentane	HFC-43-10mee	CF3-CF2-CHF-CHF-CF3
3	Pentafluoroethane	HFC-125	CF3-CHF2
4	1,1,1,2-Tetrafluoroethane	HFC-134a	CF3-CH2F
5	1,1,1-Trifluoroethane	HFC-143a	CF3-CH3
6	1,1-Difluoroethane	HFC-152a	CHF2-CH3
7	1,1,1,2,3,3,3-Heptafluoropropane	HFC-227ea	CF3-CHF-CF3
8	1,1,1,3,3,3-Hexafluoropropane	HFC-236fa	CF3-CH2-CF3
9	1,1,1,3,3-Pentafluoropropane	HFC-245fa	CF3-CH2-CHF2
10	1,1,1,3,3-Pentafluorobutane	HFC-365mfc	CF3-CH2-CF2-CH3
11	1-Chloro-1,2,2,2-tetrafluoroethane	HCFC-124	CHClF-CF3
12	1,1-Dichloro-1-fluoroethane	HCFC-141b	CCl2F-CH3
13	3,3-Dichloro-1,1,1,2,2-pentafluoropropane	HCFC-225ca/cb	CF3-CF2-CHCl2
14	1-Chloro-2,3,3,3-tetrafluoropropene	HFO-1224yd(Z) *	CHCl=CF-CF3
15	1-Chloro-3,3,3-trifluoro-1-propene	HFO-1233zd(E) **	CHCl=CH-CF3
16	2,3,3,3-Tetrafluoropropene	HFO-1234yf	CH2=CF-CF3
17	Trans-1,3,3,3-tetrafluoroprop-1-ene	HFO-1234ze(E) ***	CHF=CH-CF3
18	1,3,3,3-Tetrafluoropropene	HFO-1234ze(E) ***	CHF=CH-CF3
19	Trans-1,1,1,4,4,4-hexafluorobut-2-ene	HFO-1336mzz(E)	CF3-CH=CH-CF3
20	Cis-1,1,1,4,4,4-Hexafluoro-2-butene	HFO–1336mzz(Z)	CF3-CH=CH-CF3
21	(Z)-1-Chloro-2,3,3,3-tetrafluoropropene	HCFO-1224yd *	CHCl=CF-CF3
22	Trans-1-chloro-3,3,3-trifluoropropene	HCFO-1233zd(E) **	CHCl=CH-CF3
23	2-Bromo-3,3,3-trifluoroprop-1-ene	BTP, 2-BTP, Halotron BrX	CH2=CBr-CF3

Entry	F-gas substance	F-gas code	F-gas structure
24	Methoxytridecafluoro-heptene isomers	MPHE, SionTM (fluoroketone)	CF3-CF2-CF2-CF=C(OCH3)-CF2-CF3
25	Dodecafluoro-2-methyl-3-pentanone	NOVEC (TM) 612 (fluoroketone)	CF3-CF(CF3)-C(=O)-CF2-CF3
26	1,1,2,2-Tetrafluoro-1-(2,2,2-trifluoroethoxy) ethane	HFE-347pc-f2	CF3-CH2-O-CF2-CHF2
27	Methyl nonafluorobutyl ether + Methyl nonafluoroisobutyl ether	HFE-449s1 (7100)	CH3-O-CF2-CF2-CF2-CF3
28	1-Ethoxy-nonafluorobutane	HFE-569sf2 (7200)	CH3-CH2-O-CF2-CF2-CF2-CF3
29	3-Ethoxyperfluoro(2-methylhexane)	HFE-7500	CF3-CF(CF3)-CF(OCH2-CH3)-CF2-CF2-CF3

Appendix II

Intended Applications of EU-28 Total Supply of F-gases. Source Data Reported in the F-Gas Report (EU, 2020b)

Intended Applications of Bulk Supply	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
Refrigeration, air conditioning and heating and heat transfer fluids	61,377	58,720	58,678	65,964	61,045	58,574	58,999	95,688	74,023	78,016	78,012	68,676	55,600
Foams, incl pre-blended polyols	14,286	15,284	11,709	11,503	9,234	8,526	8,202	12,967	9,572	10,157	11,521	11,083	11,041
Aerosols	9,090	11,131	8,425	9,547	7,808	10,950	9,690	8,954	9,421	8,728	10,300	9,109	8,964
Fire protection	649	491	531	1,677	2,508	1,451	1,385	1,858	818	585	502	324	130
Electrical Equipment	1,197	1,422	969	1,290	1,344	1,362	1,419	622	745	813	951	640	534
Semiconductor, photovoltaics and other electronics manufacture	127	301	184	265	243	169	71	1,057	715	755	924	897	769
Other or unknown applications	1,861	2,219	2,185	1,501	1,437	1,684	1,132	6,402	1,485	997	1,266	1,450	1,255
Totals (including SF_6)*	**88,586**	**89,569**	**82,681**	**91,749**	**83,620**	**82,715**	**80,898**	**127,547**	**96,779**	**100,050**	**103,475**	**92,179**	**78,293**
SF_6 quantities	1,810	1,860	1,435	1,522	1,502	1,490	1,535	716	909	1,004	1,225	843	727
Totals (excluding SF_6)	**86,776**	**87,709**	**81,246**	**90,227**	**82,118**	**81,225**	**79,363**	**126,831**	**95,870**	**99,046**	**102,250**	**91,336**	**77,566**

Notes: *SF_6 included in these figures but not separated out per application. SF6 is primarily used in electrical equipment because of its excellent electrical insulation properties and in the manufacture of semiconductors; it also has other medical uses and as a cover gas in magnesium casting for installations using less than 850kg SF_6/year until 2018 (sand casting may still be permitted). It is outside of the scope of this project however and therefore it has been deducted.

Appendix III

Estimated total emissions of F-gases from the different sub-applications.

Application	New use	Amount in stocks	Total emission	% of total emission
	t/y	t	t/y	
Domestic Refrigeration	122	4,496	17	0.04%
Commercial Refrigeration	7,915	90,992	9,547	24%
Industrial Refrigeration	2,360	34,358	3,680	9%
Transport Refrigeration	1,010	9,915	1,341	3%
Mobile Air Conditioning	5,221	115,763	11,726	29%
Stationary Air Conditioning and heat pumps	7,465	148,791	7,458	18%
Domestic AC and domestic heat pumps for space heating	No data identified to enable split to subsectors here.			
Commercial AC and heat pumps				
Domestic heat pumps (clothes dryers)				
Foam Blowing Agent (Closed cell)	4,940	57,635	4,186	10%
Foam Blowing Agent (Open cell)	271	9,848	1,074	3%
Fire protection	863	20,201	703	2%
Firefighting foams	No data identified to enable split to subsectors here.			

Application	New use	Amount in stocks	Total emission	% of total emission
	t/y	**t**	**t/y**	
Fire suppression agents				
Propellants (non-MDI)	504	907	701	2%
Solvents	No data	0	>11	0.03%
Cover Gas for magnesium casting	No data	No data	>23	0.06%
Die casting	No data identified to enable split to subsectors here.			
Sand casting				
Other	No data	267	35	0.09%

Appendix IV

Activity Data and Emission Estimates for F-gases in 2018.

Sub-	Annual Activity Data (2018) (tonnes of F-gas)*			Annual Emissions (2018)					
				Manufacturing			Stocks		
	Filling into New Manufactured Products	In Operating Systems (Stocks)	Remaining at Decomm-issioning	From Manufacturing (tonnes)	Emissions as % of F-gases used in an application	Emissions as % of Total F-gas Emissions from Manufacturing	From stocks (tonnes)	Emissions as % of F-gases used in an application	Emissions as % of Total F-gas Emissions from Stocks
Commercial Refrigeration	7,915	90,992	5,717	121	2	7	9,426	10	24
Domestic Refrigeration	122	4,496	671	1	1	0	16	0	0
Industrial Refrigeration	2,360	34,358	1,219	77	3	5	3,603	10	9
Transport Refrigeration	1,010	9,915	226	29	3	2	1,312	13	3
Mobile Air Conditioning	5,221	115,763	4,647	78	1	5	11,648	10	30
Stationary Air Conditioning	7,465	148,791	6,865	47	1	3	7,411	5	19

Foam Blowing Agent (Closed cell)	4,940	57,635	170	1,272	26	75	2,914	5	8
Foam Blowing Agent (Open cell)	271	9,848	No data	45	17	3	1,029	10	3
Fire protection	863	20,201	208	1	0	0	702	3	2
Aerosols (non-MDI)***	504	907	No data	2	0††	0	699	77	2
Solvents	No data	0††	No data	No data	No data	No data	11	No data	0
Cover Gas**	No data	No data	No data	23	No data	1	No data	No data	No data
Other	No data	267	No data	0†	No data	0	35	13	0
Totals or Range	**30,671**	**493,173**	**19,724**	**1,696**	**0 – 26**	**100**	**38,806**	**0 – 77**	**100**

Appendix V

Estimation of Quantities of Hydrofluoroolefins Used, as a Proportion of F-gases in Products and Equipment for EU-28 (2018). Source (EU, 2020c).

Intended Applications of Bulk Supply Usage data for F-gases	**2016**	**2017**	**2018**	**2019**
Refrigeration, air conditioning and heating and heat transfer fluids	78,016	78,012	68,676	55,600
Foams, incl pre-blended polyols	10,157	11,521	11,083	11,041
Aerosols	8,728	10,300	9,109	8,964
Fire protection	585	502	324	130
Electrical Equipment	813	951	640	534
Semiconductor, photovoltaics and other electronics manufacture	755	924	897	769
Other or unknown applications	997	1,266	1,450	1,255
Totals (including SF6)*	100,050	103,475	92,179	78,293
SF6 quantities	1,004	1,225	843	727
Totals (excluding SF6)	**99,046**	**102,250**	**91,336**	**77,566**
Usage data for unsaturated HFOs and HCFOs	6,305	13,400	17,767	18,350
HFO & HCFO Proportion of total (%)*	**6**	**13**	**19**	**24**

Notes: *HFOs are mainly used in mobile air conditioning and commercial refrigeration (stakeholder discussions).

Appendix VI

Estimated Emissions of HFOs in 2018 from Passenger Cars and Light Goods Vehicle Mobile Air Conditioning (EU-28 & IS & NO)

Use	Range	Emissions (tonnes/a)	
		Manufacturing	Stocks
Total emissions of F-gases from MACs (GHG Inventory)	Lower end	78	11,648
Proportion of HFO emissions (GHG Inventory)	Lower end	(78 x 0.11) = 9	(11,648 x 0.11) = 1,281
Proportion of HFO emissions (expert judgement)	Upper end	(78/1) x 15 = 1,170	(11,648/10) x 15 = 17, 472

Appendix VII

Alternatives

Assessment of the availability of fluorine free alternatives for each use disaggregated into subapplication level.

Summary of the Identified Alternatives to F-gases in the HVACR Market.

	Domestic refrigeration	Commercial refrigeration	Industrial refrigeration	Electronics cooling	Transport refrigeration	Stationary air conditioning	Mobile air conditioning	Heat pumps
CO_2 refrigerant		✓	✓	✓	✓	✓	✓	✓
NH_3 refrigerant			✓	✓	✓	✓		
CO_2, N_2 as direct coolant					✓			
Iso-butane	✓	✓						
n-butane			✓					
Propane	✓	✓		✓	✓	✓	✓	✓
Not in-kind refrigeration cycles (Absorption refrigeration, thermoelectric refrigeration Stirling cycle and magnetic refrigeration)	✓							
Not in-kind refrigeration: Advanced cool box storage					✓			

Summary of the Identified Alternatives to F-gases in Foam-blowing Applications.

	Rigid PU foam for Refrigeration and domestic appliances	Rigid PU boardstock and panels	PU spray foam	Rigid PU pipe-in-pie and block foam	PU integral skin	Extruded polystyrene foam (XPS)	Phenolic foam
Cyclopentane	✓	✓		✓		✓	
Iso-pentane	✓	✓		✓		✓	✓
n-pentane		✓		✓	✓	✓	✓
Isobutane						✓	
n-butane						✓	
2-chloropropane							✓
Dimethyl ether (DME)						✓	
Methyl formate	✓	✓	✓	✓	✓		
Methylal				✓	✓	✓	
CO_2 / methyl formate						✓	
CO_2 (water)	✓	✓	✓	✓	✓	✓	
CO_2 (liquid)			✓				
CO_2 / ethanol						✓	
Water blown foams							
Not-in-kind options	1	2	3		4	2	

F-gases as solvent

Alternatives to F-gases used as solvents depend very much on the specific properties needed to fulfil the desired function. The alternatives may vary a lot between the different applications. However, the following have been identified as potential alternatives for different cases:

- Isopropyl alcohol (IPA)
- n-Propyl bromide (nPB)
- Dichloromethane (DCM, Methylene chloride)
- Trans-1,2-dichloroethylene
- Trichloroethylene (TCE)
- Perchloroethylene (PER)
- Volatile methyl siloxanes
- Hydrocarbons (Hexane, Heptane, Benzene, Acetone)
- Semi-aqueous / aqueous cleaning
- Manual cleaning methods – aerosols, brush, trigger spray, liquid immersion, spot cleaning, wipes
- Ultrasonic
- Plasma cleaning
- Supercritical fluids – CO2
- No clean fluxes

F-gases as propellants

The following alternatives have been assessed for the propellants market:

- Compressed gases:
  - Air
  - Nitrogen
  - Nitrous oxide
  - Carbon dioxide

- Liquefied gases:
  - Butane
  - Propane
  - Isobutane
  - Dimethyl ether

- Not-in-kind alternatives
  - Trigger sprays, finger pumps, squeeze bottles
  - Non-sprayed products, including roll-ons
  - Bag-on-valve products

Review of the properties of these options indicates a variety of issues. Nitrous oxide is used in some food applications (spray cream) but its use as a propellant is limited because of potential for misuse as a recreational drug with serious side effects including death. The compressed gases generally have lower capacity per can than other options. The liquefied gases that have been identified are all hydrocarbons with flammability risks. Despite these risks they are used widely and safely in the domestic market. Not-in-kind alternatives such as trigger sprays are also widely used but typically have an inferior quality of spray (inconsistent particle size and spray rate) which is limiting for some applications. Bag-on-valve alternatives overcome a number of these issues (the propellant has the properties of the compressed gases but remains inside the can). However, they are not appropriate for applications where the propellant also acts as a solvent for the payload (for example, products where the can needs to be shaken before use), or the propellant is the payload (e.g. air dusters).

F-gases as cover gas in magnesium casting

Three non-F-gas alternatives were identified:

- SO2
- Argon
- Salt fluxes and powdered sulfur

The most likely option is SO2 for which there is a long history of successful use in the magnesium casting industry. The other alternatives have drawbacks (risk of explosion or of contamination) that have limited their application.

F-gases as fire suppressants

A number of PFAS-free alternatives are available on the market, including the use of:

- Inert gases (nitrogen and argon)
- CO2
- Water mist technologies
- Inert gas generators
- Fine solid particle technology
- Dry chemical agents
- Water and aqueous salt solutions

Use of PFAS for fire suppressants is not universal, and there has been a switch away from their use. The added price of PFAS systems is an effective driver for change in the sector. However, for some parts of the market there is a lack of alternatives to the use of F-gases that are clean (not leaving residues), of limited toxicity and fast acting. There is also no indication that a non-PFAS solution will be available in the near future.

The costs and benefits of continued use of PFAS for fire suppression have not been quantified, though it is noted that there is potential for fire damage to be substantial, involving threats to (e.g.) life, data centres, cultural heritage, stocks of merchandise, etc. in the event that less-effective alternatives are used.

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