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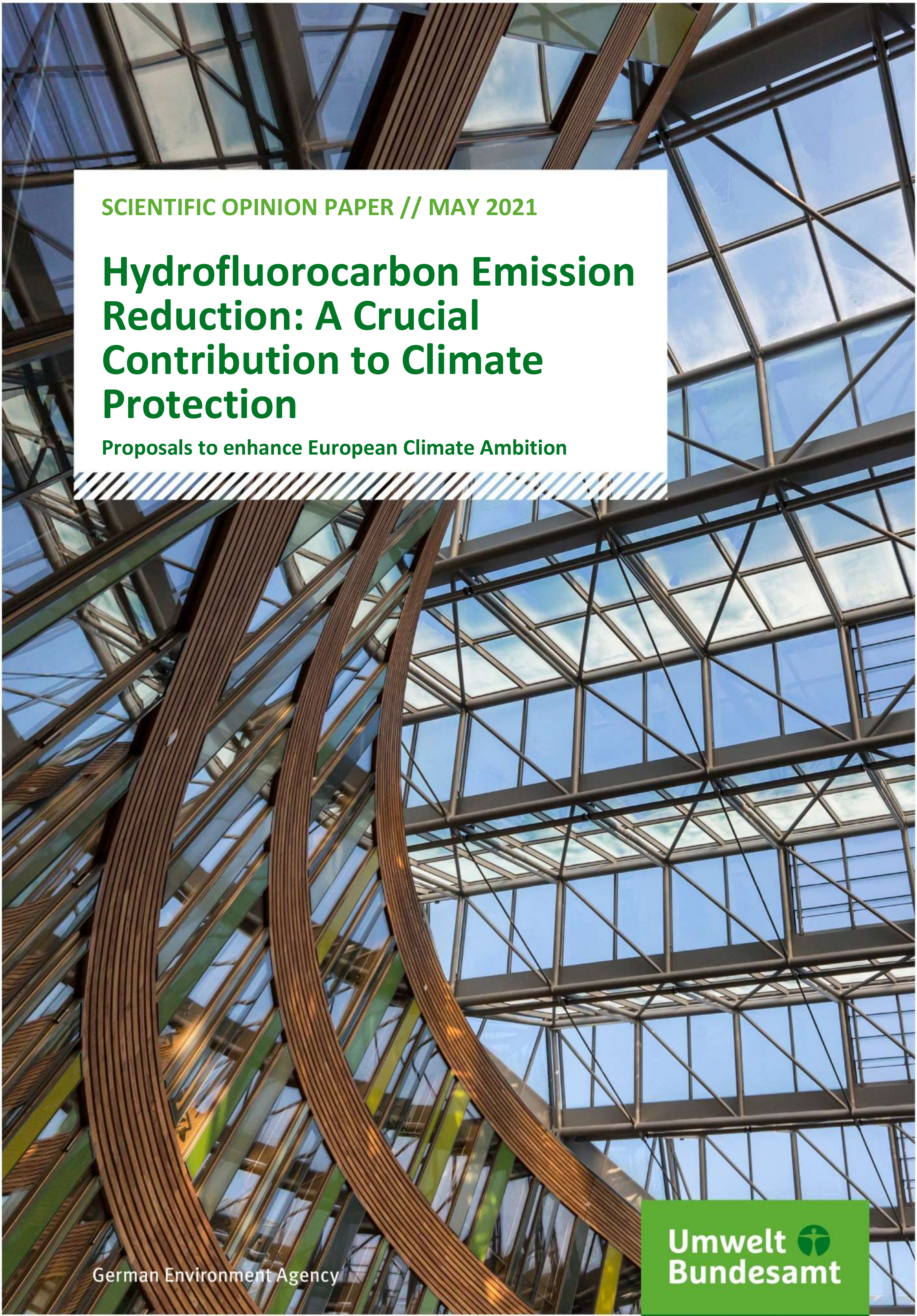
Proposals to enhance European Climate Ambition



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Hydrofluorocarbon Emission Reduction: A Crucial Contribution to Climate Protection

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by

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Executive summary

Hydrofluorocarbons (HFCs) are the dominant fraction of fluorinated greenhouse gases, also known as F-gases. HFC emissions in the European Union (EU) amounted to 112 million tonnes CO_2 equivalent (Mt CO_2eq.) in 2018. This amounts to 2,2% of the EU's total greenhouse gas emissions. Main sources of HFC emissions are refrigeration and air conditioning plants and appliances.

Following a proposal by the EU Commission, EU member states and the EU parliament just recently agreed to increase the 2030 target from 40% to 55% reduction of greenhouse gas emissions compared to the 1990 level. **This considerable step-up of climate ambition by more than a third needs to be reflected also in the revision process of the F-gas Regulation, regardless of the achievements already made to curb F-gas emissions**.

Since 2006, the EU F-gas Regulation has been seeking to reduce emissions of HFCs and other F-gases. In 2014, the revised regulation was supplemented with an element termed HFC phase-down. The phase-down restricts the amount of HFCs placed on the European market by stepwise reduction down to 21% of the baseline in 2030. The current revision process of the F-gas Regulation started in August 2020. Target date for a new proposal of the Regulation is end of 2021.

Accelerating the phase-down of HFCs in the EU

On the occasion of the F-gas Regulation revision, the German Environment Agency proposes the **acceleration of the phase-down scenario, resulting in larger reduction steps from 2024 on and a final level of 10% of the baseline by 2030 compared to 21% according to the current schedule**. In addition, to support the aforementioned tightening of HFC phase-down, we appeal to the EU Commission to impose further bans on the placing on the market of new HFC equipment such as:

- **Prohibition of single-split air conditioners using refrigerants with GWP ≥ 150 from 1. January 2025 onwards,**
- **Prohibition of stationary refrigeration equipment using refrigerants with GWP ≥ 150 and**
- **Prohibition of heat pumps using refrigerants with GWP ≥ 150.**

Furthermore, we propose to **delete the exemption of metered dose inhalers from the phase-down** according to Article 15 (2).

Taken together, these measures would **avoid more than 100 Mt CO_2eq. of HFC consumption in Europe by 2030**, keeping in mind that the majority of the gases becoming emissions during and after their use in refrigeration and air conditioning plants and appliances as well as other equipment containing HFCs. Therefore, with the suggested modifications implemented today, **significant amounts of HFC emissions will be saved in the mid- and long-term, which in turn will have a positive impact on the EU climate goals**.

Montreal Protocol: Going beyond the Kigali Amendment

On a global level, HFC emissions amounted to roughly 1.6 giga tonnes CO_2 equivalent (Gt CO_2eq.) emissions in 2020 according to latest assessments (Purohit et al., 2020) and are expected to increase to 4.3 Gt CO_2eq. in 2050. This means that, without interventions to reduce HFC use, cumulative HFC emissions would reach 92 Gt CO_2eq. for the period 2018-2050. Due to the HFC phase-down stipulated in the Kigali Amendment to the Montreal Protocol, cumulative emissions will be reduced to 30.7 Gt CO_2eq., provided that parties fully adhere to their commitments specified in the Amendment. This translates into 61.3 Gt CO_2eq. of emission reduction - an important contribution to climate neutrality.

However, there is still a large potential for HFC emission mitigation which could be exploited by **measures that go beyond the stipulations of the Kigali Amendment**. Such additional measures, to be taken by countries on a **voluntary basis**, would comprise **earlier onset of the phase-down and a lower HFC consumption target** (e.g. 10% instead of 15% of the baseline). Tapping the full technically feasible potential of HFC mitigation would result in the **avoidance of additional 17.7 Gt CO_2eq. of HFC emissions by 2050**.

The key element for phasing down HFC consumption are refrigeration and air conditioning technologies with natural refrigerants such as ammonia, water, CO_2 and hydrocarbons. They are available in nearly all refrigeration and air conditioning fields of application and exhibit similar or better energy efficiency performances compared to their HFC counterparts. In countries where HFCs have not been fully introduced to replace ozone depleting substances (ODS), **HFC may be leapfrogged by directly switching from ODS to natural refrigerants**. This strategy already proved to be successful in the European Union and beyond more than 25 years ago for fridge-freezer appliances.

1 Introduction

Since their use started in the early 1990s, hydrofluorocarbons (HFCs) evolved quickly into the most dominant fraction of fluorinated greenhouse gases (F-gases) regarding both, use and emissions. Acknowledging their impact on the climate, HFCs have already been addressed by including them in the basket of greenhouse gases (GHGs) which has been subject to the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) to mitigate greenhouse gas emissions.

With the adoption of the Paris Agreement in 2015 at the 21st Conference of the Parties to the UNFCCC, which aims at keeping the man-made global warming well below 2 °C and pursuing efforts to limit it to 1.5 °C, there is international consensus to reduce GHG by 70-80% at least by 2050 in order to prevent uncontrollable consequences for the climate and the biosphere. This, of course, also applies for HFCs. With the Kigali Amendment to the Montreal Protocol in 2016, the international community agreed on a scheme to decrease the use of HFCs, termed HFC phase-down, and thereby established a detailed roadmap for effective emission mitigation of this group of GHGs. In order to implement this ambitious roadmap, countries have to act now to prevent the built-up of large banks of HFCs in plants and appliances which will be operated for 20 years and more, constantly generating emissions.

The solution for a successful and thorough phase-down of HFCs with energy efficiency benefits is the replacement of these substances with natural refrigerants in developed countries and leapfrogging HFC use in developing countries. For the latter, this means transitioning from hydrochlorofluorocarbons (HCFC) directly to natural refrigerants without taking the uneconomical and environmentally hazardous detour via HFCs.

This opinion paper provides scientifically based views and recommendations on what needs to be done in Europe and worldwide to not only implement the Kigali Amendment, but to exploit the full potential of HFC mitigation. As HFC emission reductions are cost-effective compared to mitigation options for other GHGs and thus considered ‘low hanging fruits’, they may balance other sectors which fall short of their climate targets.

2 Hydrofluorocarbons: characteristics, use and alternatives

2.1 Hydrofluorocarbon properties and applications

Hydrofluorocarbons (HFCs) are a fraction of fluorinated greenhouse gases (F-gases). They are used predominantly as refrigerants in refrigeration and air conditioning plants and appliances, as foam blowing or fire extinguishing agents and as propellants (Becken et al., 2011). As the name indicates, these gases are derived from aliphatic, non-circular hydrocarbons with some hydrogen atoms substituted by fluorine. Due to their similar thermodynamic properties, HFCs have been introduced in the 1990s as alternatives to chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). CFCs and HCFCs exhibit an Ozone Depletion Potential (ODP), i.e. they harm the stratospheric ozone layer which protects the surface of the earth against ultraviolet radiation. That is why they have been phased out under the Montreal Protocol on Substances that deplete the Ozone Layer.

HFCs, unlike CFCs and HCFCs, do not exhibit an ODP. Comparable to CFCs and HCFCs, however, they are potent greenhouse gases with Global Warming Potentials (GWPs) of commonly used representatives ranging from 124 in the case of HFC-152a (1,1-difluoroethane) up to 14,800 in the case of HFC-23 (trifluoromethane) for a 100 years timeframe (GWP_{100}; see Table 1). For comparison: carbon dioxide (CO_2), responsible for approximately 75% of anthropogenic greenhouse gas emissions, has a GWP of 1.

Table 1: Selection of commonly used HFCs and HFC blends

HFC / HFC blend	Chemical Name	GWP_{100}*
HFC-23 (R-23)	Trifluoromethane	14,800
HFC-32 (R-32)	Difluoromethane	675
HFC-125 (R-125)	Pentafluoroethane	3,500
HFC-134a (R-134a)	1,1,1,2-tetrafluoroethane	1,430
HFC-143a (R-143a)	1,1,1-trifluoroethane	4,470
HFC-152a (R-152a)	1,1-difluoroethane	124
u-HFC-1234yf (R-1234yf)	2,3,3,3-tetrafluoropropene	4**
R-404A (blend)	44% HFC-125, 4% HFC-134a, 52% HFC-143a	3,922
R-407C (blend)	23% HFC-32, 25% HFC-125, 52% HFC-134a	1,774
R-410A (blend)	50% HFC-32, 50% HFC-125	2,088
R-449A (blend)	24.3% HFC-32, 24.7% HFC-125, 25.7% HFC-134a, 25.3% R-1234yf	1,397

u-HFC: unsaturated hydrofluorocarbon, i.e. the molecule contains double or triple covalent bonds (in this case: double bond) between adjacent carbon atoms.

*Source: IPCC (2007)

**Source: Regulation (EU) No 517/2014 on fluorinated greenhouse gases

HFC-134a (1,1,1,2-tetrafluoroethane) is the most widely used HFC (44% of all HFC mass) in the European Union (EU), followed by HFC-32 (25%) (EEA, 2020). In refrigeration and air conditioning, HFCs are used as single substance refrigerants (e.g. HFC-134a) or as blends such as R-410A (mixture of 50% HFC-32 and 50% HFC-125). They are released into the atmosphere during filling, operation, maintenance, repair and disposal of plants and appliances. Average annual leakage rates during operation reach up to 35% or more, depending on the kind of application[1]. HFCs leak out from vapour compression refrigeration and air conditioning plants and appliances not only when in operation, but also during downtimes. This feature illustrates that containment measures of HFCs are difficult to implement, especially in the case of applications with open-drive compressors, long refrigerant piping as well as numerous joints and connections to plant components such as evaporators. Since most of these characteristics apply for direct expansion plants installed in e.g. supermarkets, leakage rates are high in such applications during the use phase.

2.2 HFC alternatives

2.2.1 Natural refrigerants

Non-halogenated refrigerants do not contain halogens like fluorine, chlorine, or iodine. Since they occur naturally in our environment in significant quantities, they are often called natural refrigerants. Their excellent thermodynamic properties qualify them as substitutes for halogenated substances in refrigeration and air conditioning, as propellants and foam blowing agents. Table 2 gives an overview of commonly used natural refrigerants.

Substances such as ammonia (R-717) and CO_2 (R-744) were broadly used in refrigeration until the 1930ies, when they were forced back by the deployment of the easier to handle inflammable CFCs. Nonetheless, in some applications natural refrigerants remained to be viable options, such as ammonia in industrial refrigeration and cold warehouses.

In the search for alternatives that do not harm the ozone layer, natural refrigerants have been rediscovered and are in use today in nearly all fields of former CFC or HCFC application, especially in refrigeration and air conditioning. In many parts of the world, including Europe, hydrocarbons replaced CFCs in home appliances such as fridges and freezers, thereby leapfrogging the use of HFCs in this field. In supermarket refrigeration, CO_2 has been established as a new standard, replacing the HFC blend R-404A which has a high GWP. In mobile air conditioning systems, CO_2 has been introduced in some conventional and electric buses and cars in Germany. Energetic advantages are expected especially in colder climates with heat pump function mode in winter.

Table 2: Commonly used natural refrigerants

Refrigerant	Chemical name/mixing ratio	Sector	GWP_{100}*
R-290	Propane	Room air conditioning, chillers, heat pumps	3
R-1270	Propene	Industrial refrigeration	3
R-600a	Isobutane	Domestic refrigeration	3
R-717	Ammonia	Industrial refrigeration, chillers	0

[1] In Germany, average annual leakage rates range from 0.3% for hermetically sealed household appliances such as refrigerators and freezers, ice cream machines, dishwashers with heat pump function and heat pump tumble dryers to 35% for refrigeration technology on seagoing cargo vessels. Typical direct expansion refrigeration systems in supermarkets emit an average of 8.4% annually (NIR, 2020).

Refrigerant	Chemical name/mixing ratio	Sector	GWP_{100}*
R-718	Water	Chillers	0
R-723	60% ammonia, 40% dimethyl ether	Industrial refrigeration, air conditioning	0.4
R-744	Carbon dioxide	Commercial refrigeration, mobile air conditioning	1

*Source: Regulation (EU) No 517/2014 on fluorinated greenhouse gases

Compared to HFCs, natural refrigerants have a negligible GWP and their general impact on the environment is low. Except for CO_2 and water, natural refrigerants are flammable, and ammonia is also toxic and thus require safety measures and appropriately trained personnel for installation and maintenance of the equipment in which they are used. A large number of examples worldwide show that such equipment can be operated safely, energy-efficiently and thus economically if appropriate installation and operation instructions are adhered to.

2.2.2 HFCs with lower GWP

Unsaturated halogenated refrigerants (u-HFC, also termed hydrofluoroolefins, HFO) with low GWP are also discussed and used as HFC alternatives. However, due to their high production expense, safety issues due to their flammability and toxic combustion products such as hydrofluoric acid (HF), and the persistent atmospheric degradation product trifluoroacetic acid (TFA)[2], u-HFC cannot be regarded as overall sustainable alternatives.

Furthermore, blends of u-HFCs and HFCs still exhibit high GWP values, the majority of them have GWP values above 500. For example, R-449A used as refrigerant for retrofits (R-404A replacement) and new equipment in commercial refrigeration (e.g. central refrigeration plants in supermarkets) has a GWP of 1,397. This is lower than the GWP of R-404A (GWP=3,922) which has been used so far as a standard refrigerant in supermarket refrigeration, but cannot be recommended as an alternative in new equipment compared to natural refrigerants with negligible GWP.

A similar problem arises with the use of R-32 (GWP=675) to replace R-410A (GWP=2,088) in split air conditioners and chillers. Whereas this means a GWP reduction of about two thirds, it is not sufficient to comply with the phase-down schemes in Europe (F-gas Regulation) and globally (Kigali Amendment to the Montreal Protocol) in the near term and mid-term/long run, respectively. Moreover, GWP reduction is likely to be fully compensated by a growing use of air conditioning equipment (see below). Therefore, natural refrigerants such as hydrocarbons with GWPs close to zero are the better choice.

[2] TFA is an atmospheric degradation product of several HCFCs and HFCs, hence the use of u-HFCs is expected to increase the input of the persistent TFA in the environment considerably (Behringer et al. 2021). Due to their potential to form persistent fluorinated substances, several fluorinated refrigerants are currently assessed in the ongoing work for a restriction proposal under REACH for per- and polyfluoroalkylsubstances (PFAS).

3 HFC regulation in the EU and its impact on HFC consumption and emissions

3.1 EU consumption and emissions of HFCs

HFCs are responsible for the largest share of CO_2 equivalent consumption and emissions of fluorinated greenhouse gases. In the years 2015 to 2017, HFC supply[3] in the EU ranged between 167.2 to 180.4 million tonnes CO_2 equivalent (Mt CO_2eq.), which translates into an 80 to 85% share of the overall F-gas supply to the EU (EEA, 2020). HFC supply dropped significantly to 120.6 and 93.6 Mt CO_2eq. in 2018 and 2019, respectively, due to legal interventions such as the HFC phase-down scheme according to the EU F-gas Regulation (see below), whereas the HFC share on total F-gas supply decreased only slightly (78.9 and 77%, respectively). F-gas emissions totalled 122 Mt CO_2eq. in 2015 and 112 Mt in 2018, of which 91% and 88% are attributed to HFCs, respectively (European Union, 2020). Comparison between the HFC emission level in the year 2000 (55 Mt CO_2eq.) and the peak level determined so far in 2014 (114 million tons) reveals doubling due to the phase-out of CFCs and HCFCs and growing demand for air conditioning and refrigeration. Since HFC emissions follow the supply trend with a timely shift, and provided that HFC regulation in the EU is complied with by the vast majority of stakeholders, it is expected that emissions will keep declining significantly in the future. Today, the share of HFCs on total EU GHG emissions is 2.2% (European Union, 2020).

3.2 HFC regulation[4]

In order to mitigate F-gas emissions in general, and to curb the dynamically growing emissions from HFC containing equipment in particular, the European Union passed two legal acts in 2006, Directive 40/2006/EG and Regulation (EC) No 842/2006. Whereas the first solely addresses mobile air conditioning in passenger cars and light duty vehicles, being the largest source of F-gas (HFC) emissions, the latter encompasses all other F-gas equipment, such as stationary air conditioning and refrigeration. At the time, these measures were already considered as significant contributions to the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol to limit the effects of climate change to manageable levels.

3.2.1 European F-gas Regulation

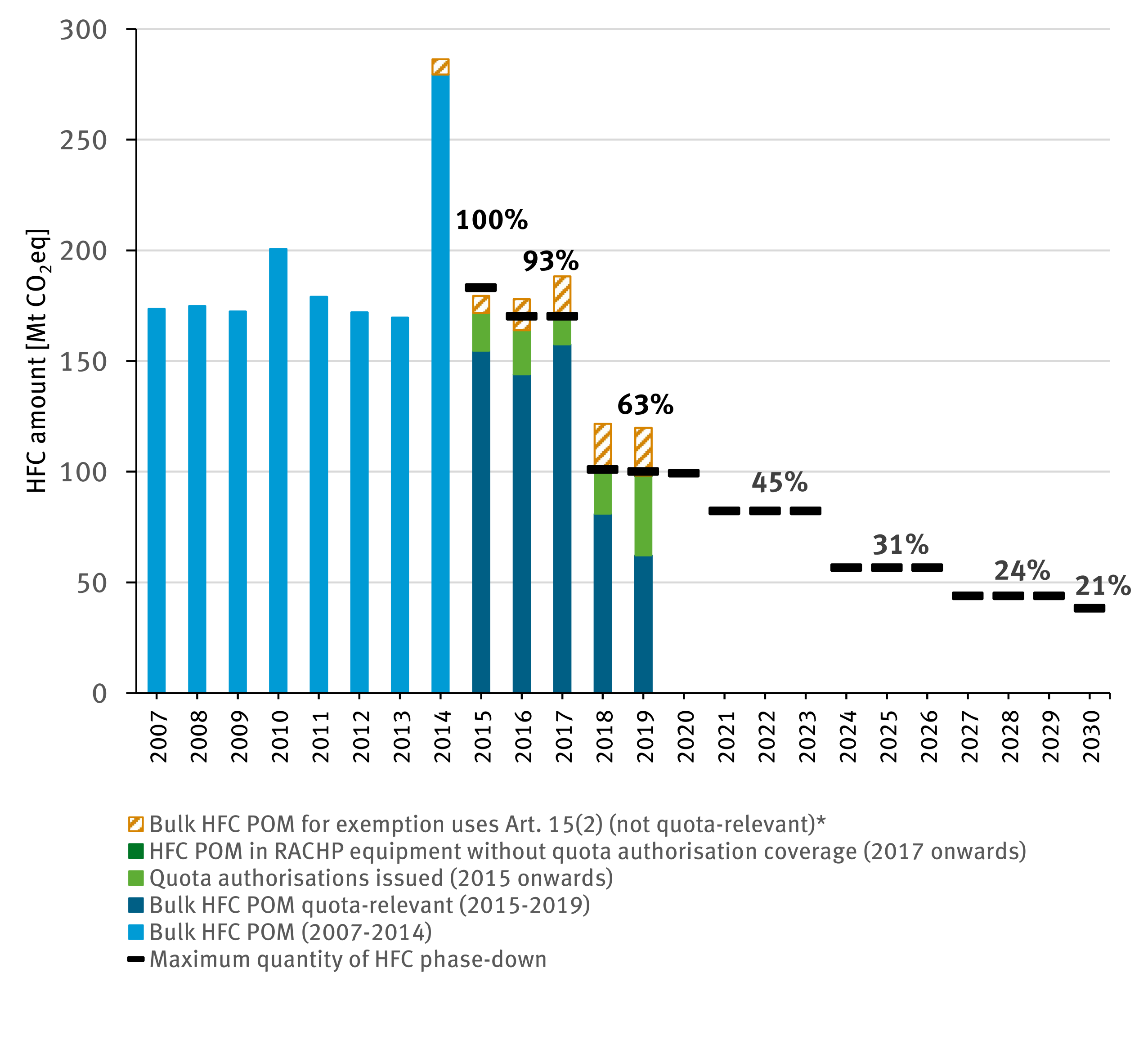
Until 2006, the use of F-gases was not subject to any European legal act. The F-gas Regulation (at that time termed Regulation (EC) No 842/2006) which came into effect in July 2007 set forth for the first time provisions addressing the handling of F-gas equipment such as containment (Article 3) and recovery (Article 4) of F-gases as well as training and certification of personnel which installs and maintains such equipment (Article 5). In addition, the regulation imposed reporting obligations on F-gas producers, importers and exporters (Article 6). Certain products containing F-gases such as footwear and tyres were prohibited to be placed on the European market.

[3] The calculations of supply and placing on the market (POM) by the EEA as well as consumption of HFCs according to the Montreal Protocol are not the same and, hence, lead to slightly different amounts.
[4] The ongoing work for a restriction proposal for PFAS under REACH (https://www.reach-clp-biozid-helpdesk.de/SharedDocs/Meldungen/DE/REACH/2020-05-08-RMOA-PFAS.htm, 29.04.2021) concerns also some HFCs due to their potential to form persistent fluorinated substances.

3.2.1.1 HFC phase-down scheme

The regulation underwent a revision process which was concluded with a new F-gas Regulation (Regulation (EU) No. 517/2014). It applies since 1 January 2015. In addition to further detailed provisions on F-gas containment, recovery as well as training and certification of personnel, the revised regulation also contains some new articles which stipulate the placing on the market of HFCs as bulk ware or in products, also known as HFC phase-down scenario. This scenario limits the amount of HFCs to be placed on the European market, starting in 2015 from a baseline of 183.1 Mt CO_2eq. (100%) which equals the average supply to the European market in 2009 to 2012. This amount is reduced in several steps to reach 21% of the baseline in 2030 through the allocation of a quota, i.e. a certain amount of HFCs in CO_2eq., to HFC producers and importers. Placing on the EU market of HFCs and phase-down steps are shown in Figure 1. The data presented are based on the reporting of undertakings in line with Article 19 of Regulation (EU) No 517/2014 published yearly by the European Environment Agency (EEA). Undertakings have to report on their annual production, import, export, feedstock use and destruction of HFCs and other F-gases listed in Annexes I or II of the Regulation.

Figure 1: HFC phase-down and placing on the market (POM) in the EU-27 and the United Kingdom in Mt CO_2eq.



Exceptional high HFC POM amounts in 2014 have been observed after publication of the revised F-gas Regulation in the Official Journal of the EU in May 2014. It reveals stockpiling activity of stakeholders anticipating future HFC shortages due to the above given phase-down set forth in the regulation. Issued authorisations to use quota are needed for POM of HFCs contained in refrigeration, air conditioning and heat pump equipment since 2017. RACHP: refrigeration, air conditioning and heat pumps.

*Note: For reasons of confidentiality, the values for 2014 to 2016 of not quota-relevant bulk HFC POM for exemption uses according to Art. 15(2) do not contain data for metered dose inhalers (MDI).

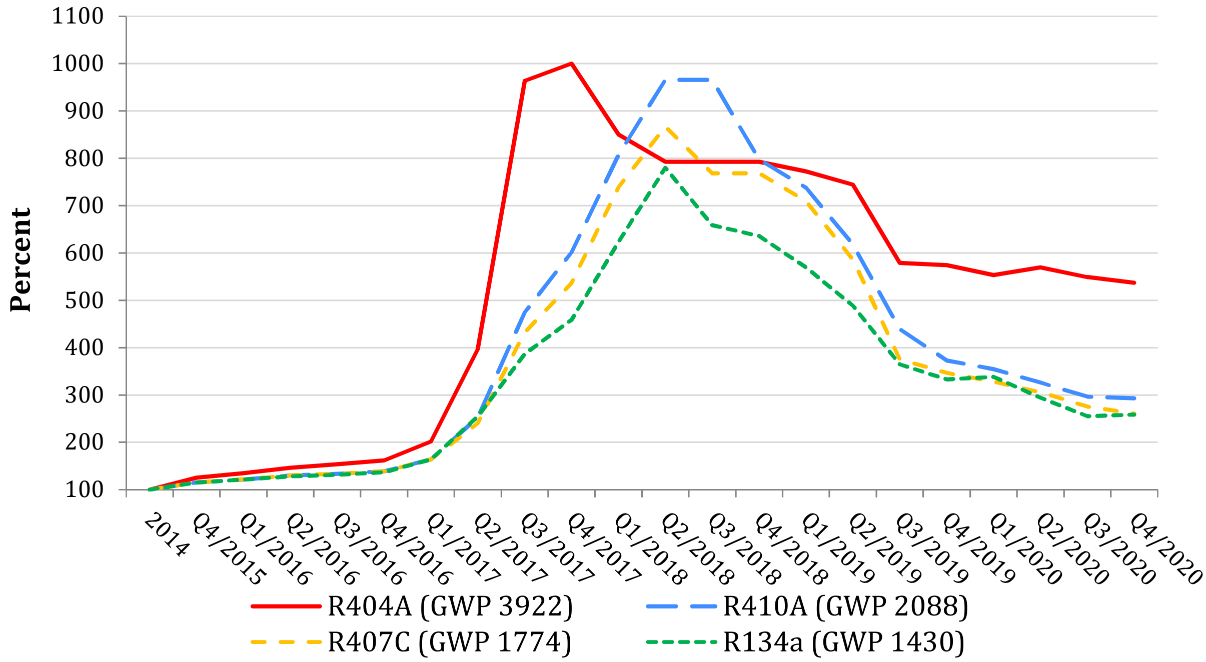
Data taken from EEA, 2020

The HFC phase-down scenario implies certain consequences: Firstly, in order to maintain the amount of HFC refrigerant mass available in the EU, the average GWP of all refrigerants placed on the market needs to decrease to the same extent as the placing on the market limit drops. This means that by 2030, the average HFC refrigerant GWP needs to take a value of 420 from todays 2000, i.e. the average GWP needs to decrease by 79%. With increasing HFC use (metric tonnes) due to the expected growth of refrigeration and air conditioning demand, this limit presumably has to decrease even further or HFC have to be replaced by non-HFC refrigerants.

Secondly, with proceeding HFC phase-down, it will become more and more difficult to obtain the amounts of refrigerant needed for maintenance and refill purposes for existing equipment containing HFCs on the market.

Thirdly, according to a fundamental economic rule, goods exhibiting constant or even increasing demand in combination with a concomitantly growing scarcity undergo significant price increases. As can be seen in Figure 2, refrigerant prices have increased sharply since the onset of the HFC phase-down. An unprecedented sharp increase was observed for the refrigerant blend R-404A in 2017 (first quarter). Prices for R-404A used in commercial applications such as food retail stores peaked in the same year (fourth quarter) and thus experienced a tenfold increase compared to 2014 price levels. A similar development was monitored for other refrigerants with a later onset of dramatic increase and peak (third quarter 2017 and second quarter 2018, respectively).

Figure 2: Price development of commonly used HFC refrigerants in the EU



Data presented include prices reported by three large gas distributors. Prices are indexed to the baseline year 2014 (= 100 %). Increase in HFC price level coincides with a major reduction step from 2017 to 2018 of 30% of the baseline. Source: Öko-Recherche (2020) on behalf of the EU Commission (DG CLIMA)

Since then, prices fell for R-410A, R-407C and R-134a until 2019 (third quarter) with a comparable dynamic as the preceding rise and seem to stabilize now at roughly 250-300% compared to the 2014 baseline. These observations raise the question why prices, reflecting the availability of HFC refrigerants, did not stabilize at the much higher levels. Possible explanations for the observed price reliefs are, among others, consolidation of an exaggerated price rally, stockpiling of HFCs in preparation of the steep 2018 reduction step, rapid introduction of low-GWP alternatives and illegal import of HFCs into the EU market. There are strong indications from European customs authorities that significant amounts of bulk HFCs are illegally entering the EU market and seem to be a reasonable explanation for HFC price development since the third quarter of 2018.

3.2.1.2 Illegal import of HFC refrigerants into the European Union

The lower HFC supply accompanied by drastic refrigerant price increases in the EU made illegal actions such as theft and smuggling accidentally attractive and quite frequent in the past years (Cooling Post, 2018a, 2018b, 2020a, 2020b).

For illegal trade of HFCs, there is understandably no official data available. The Environmental Investigation Agency (EIA) published estimates based on customs and trade data (EIA, 2019). EIA reported that about 10 Mt CO_2eq. of HFCs were illegally placed on the European market in 2015 and suggested a rise to 14.8 and 16.3 Mt CO_2eq. for 2017 and 2018, respectively[5]. Considering an increased HFC trade from China to EU neighbouring countries, European FluoroCarbons Technical Committee (EFCTC) estimated an illegal trade amount for 2018 and 2019 of 33 and 31 Mt CO_2eq.[6], i.e. around one third above the respective quota (EFCTC, 2019, 2021). For 2018, a report by the EU Commission (EU COM, 2019) ruled out misreporting, and concluded that illegal trade takes place by evasion of customs.

Notwithstanding the controversial discussion about the actual volume and ways of illegal trade, illegal import of HFCs into the EU is a fact. As a consequence, HFCs are still available at a reasonable price. This delays the HFC phase-down and requires action by the European Commission and the EU member states to ensure proper enforcement of the F-gas Regulation.

To prevent illegal imports, customs authorities, for example, should be enabled to check whether the holder of F-gas quota has already exploited his quota. This would require HFC registry life updates of the amounts already used by the quota holder. Further measures which could be taken by EU member states are market surveillance and regular inspections including the online market, increased penalties in case of regulation offences, and a better traceability of HFCs.

The latter was addressed by Germany, where HFC sellers will be obliged to keep record of the origin of HFC containers (Cooling Post, 2021). This measure enables refrigerant buyers to tell whether the offered bulk ware comes from legal sources. The stipulation is implemented through a change in the German Chemicals Act and expected to come into effect in 2021.

To support the HFC phase-down in Europe, the international HFC production needs to be reduced as soon as possible. Otherwise, incentives for illegal refrigerant trade will not cease to exist and the switch to HFC-free systems will be delayed even more. The overall demand for HFCs will only decrease effectively when new equipment and systems do not require HFCs anymore. Thus, implementing HFC phase-down schemes on the European as well as the global level (according to the Kigali Amendment to the Montreal Protocol, see below) should focus on supporting a switch to HFC-free techniques.

3.2.2 Options to develop the F-gas-Regulation for enhanced climate protection

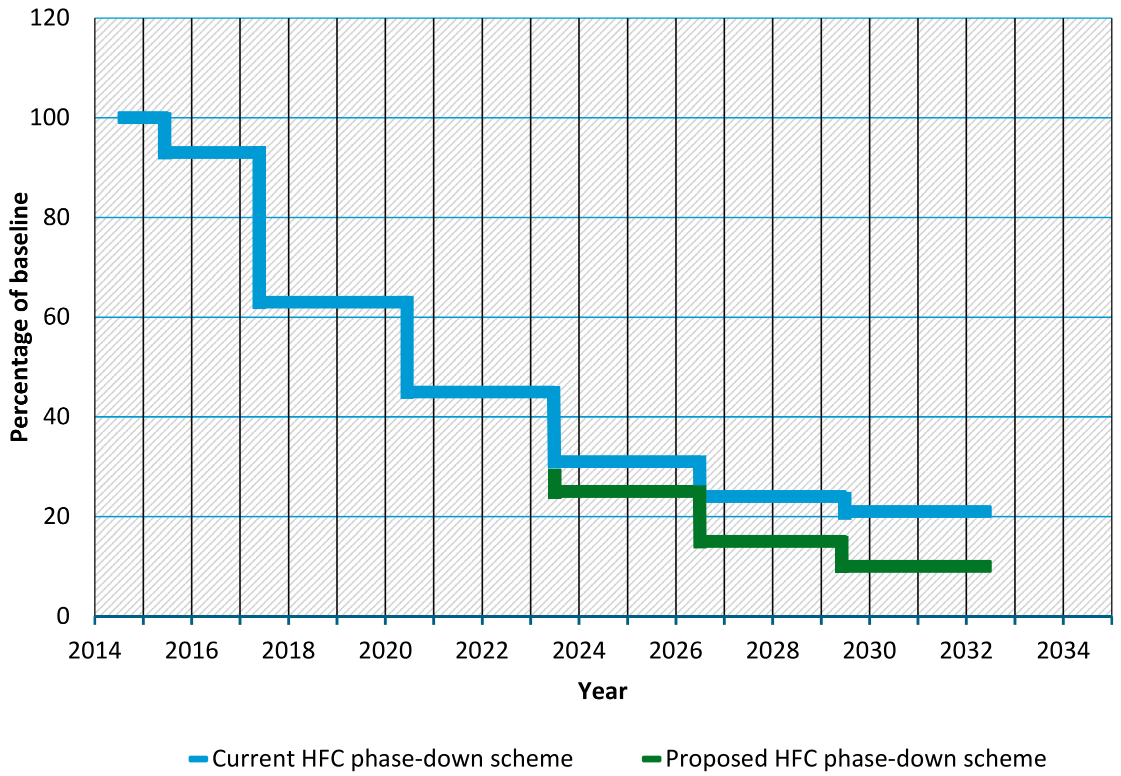
The EU has just recently strengthened its climate targets for the year 2030 significantly (European Council, 2020). Whereas climate neutrality by 2050 as the long-term goal still applies, the 2030 target was increased from 40% to 55% reduction of greenhouse gas emissions compared to the 1990 level. This means a further emissions reduction by 15 percentage points or 37.5% for all greenhouse gases, including F-gases and, thus, HFCs. The EU F-Gas Regulation provides for a 66% reduction in emissions of all F-gases, and thus also HFCs, by 2030 compared to the 2014 level. Relatively speaking, F-gases will thus already make a high contribution to

[5] Based on the official quota of 170.1 and 101.2 Mt CO_2eq. for 2017 and 2018, respectively, for HFC imports, the EIA data translate into an illegal trade of 8.7% and 16.1% above the available quota.
[6] Based on the official quota of 101.2 Mt CO_2eq. (2018) and 100.3 Mt CO_2eq. (2019), this is 32.6 % (2018) and 30.9% (2019) above the available quota.

climate protection efforts compared to other greenhouse gases, but this does not mean that the ambition level may not be advanced.

The F-gas Regulation review process, which is supposed to be concluded by 2022, is the only option within the next ten years to amend the HFC phase-down by introducing larger reduction steps and a lower final reduction level compared to the current scheme. According to the IPCC 1.5 °C report (IPCC, 2018), GHG mitigation measures in the coming decade will determine whether climate change will stay within controllable parameters by avoiding climate tipping points or not. In light of what is at stake, we call on the different sectors emitting greenhouse gases to exploit the full potential of emission mitigation, especially those whose mitigation costs are considered relatively low such as the refrigeration and air conditioning sector as well as other sectors using HFCs.

Figure 3: Current vs. proposed EU HFC phase-down scheme



HFC placing on the market amounts are given as percentage of the baseline. In comparison to the current EU F-gas Regulation (blue line), a more ambitious phase-down as proposed here (green line) would result in a cumulative consumption reduction of 102.5 Mt CO_2eq. by 2030. Hereafter, 20.1 Mt CO_2eq. would be saved each year.

As shown in Figure 3, the HFC mitigation level of ambition could be stepped up by lowering the 2024 phase-down level to 25% and 2027 to 15% of the baseline, compared to the currently set levels of 31 and 24%, respectively. In 2030, the phase-down could be as low as 10% instead of 21% required by the current F-gas Regulation. Taken together, the proposed changes would result in an additional cumulative consumption reduction of 102.5 Mt CO_2eq. by 2030 compared to the current schedule. Furthermore, from 2031 on, additional 20.1 Mt CO_2eq. could be saved each year. In contrast, implementing a less ambitious amendment of the HFC phase-down starting only in 2029 with a reduction step down to 10%, only 42.1 Mt CO_2eq. could be saved by 2030, 60.4 Mt CO_2eq. less than in the above outlined scenario. Since it is crucial to exploit the full mitigation potential in order to keep climate change at manageable levels, there are substantial reasons for opting for a stricter pathway.

A more ambitious phase-down should be accompanied by stricter and additional prohibitions. Prohibitions are a clear signal to the affected industry and provide for a better planning capability. In addition, enforcement of prohibitions is carried out easier compared to the rather abstract phase-down schemes. Therefore, prohibitions are an important element which should be strengthened in order to point out clear and lasting phase-out schemes for certain application fields of HFCs.

Prohibitions are set forth in Annex III of the F-gas Regulation and address different applications, almost half of them considering refrigeration and air conditioning equipment. For example, it is no longer allowed to place movable (i.e. portable) room air conditioners on the market which deploy refrigerants with a GWP ≥ 150 (No 14, Annex III of the F-gas Regulation).

A less severe restriction applies for single-split air conditioners with a refrigerant charge size of 3 kg (No 15, Annex III of the F-gas Regulation). Such appliances need to be equipped with a refrigerant owning a GWP that is less or equal to 750 from the year 2025 on. The given limit still allows for the use of R-32 with a medium GWP of 675 in single-split air conditioning units which is roughly one third of the GWP of the current standard refrigerant R-410A. This appears to be a massive reduction of CO_2-weighted refrigerant use. Albeit, a closer look considering future sales estimates for air conditioning appliances reveals that it is not. In Germany, for example, the number of air conditioners installed in households is expected to grow (Koch et al., 2017) due to warmer summers with an increase of days with more than 30 °C and more tropical nights (i.e. nights with temperatures not falling below 20 °C). Based on surveys addressing consumer's plans to install air conditioning in households, it is expected that the sales of AC appliances will increase with a yearly rate of 10%. This means that by 2030, 13.1% of all German households will be equipped with air conditioning compared to the 2015 level of 3.14%. This would mean a fourfold increase in home AC installations. Provided that a similar development will occur throughout Europe, even complete replacement of R-410A single-split AC units by appliances with R-32, would not lower the HFC use measured in CO_2 equivalents. This is a rather likely scenario since the European air conditioning market is believed to still have significant growth potential (Pezzutto et al., 2017) and growth rates exceeding 10% have been observed in recent years (Stokel-Walker, 2019). Thus, only lowering the GWP limit for single-split room AC units to 150 would bring about considerable use and, as a result, emission mitigations. The earlier the measure is taken, the more it contributes to mitigation. From that perspective, adjusting the GWP 150 limit for single-split room AC units earlier, i.e. starting in 2025 would avoid 7.8 million single-split units[7] filled with R32 per year. With 1 kg of average refrigerant charge size this equals about 4.1 Mt CO_2eq. in Europe and an HFC use reduction of at least 80%. In comparison, to adjust the GWP limit to 150 only in 2028 would entail an additional 12.1 Mt CO_2eq. as refrigerant banks. Since roughly 80% of the refrigerant contained in single-split appliances is emitted within the unit's lifetime, this translates into emissions of at least 9.7 Mt CO_2eq.

For stationary refrigeration equipment, the regulation could be strengthened as well. Set forth in No 12 of Annex III of the F-gas Regulation, the current limit of 2,500 could also be lowered to 150 since alternative technologies with natural refrigerants are already broadly available.

So far, the placing on the market of heat pumps using fluorinated greenhouse gases is not regulated by a ban in the F-gas Regulation. However, alternatives are available on the market and bans should be introduced. In 2018, the European heat pump stock amounted to 11.8

[7] In 2018, approximately 4 million single-split air conditioners have been sold on the European market. With a 10% growth rate, about 7.8 million units will be sold in 2025.

million units which corresponds to a heat pump market share in the building stock of about 5% (EHPA, 2019). Since 2014, the stock of heat pumps in Europe has grown by approximately 12% per year, according to the European Heat Pump Association (EHPA; Nowak, 2019). Assuming that the market share of heat pumps in the EU continues to grow at the same rate, the stock of heat pumps could already be around 45 million units in 2030 and the share in the building stock about 18%. With the aim of decarbonisation of buildings, the European Commission has set the targets that "in the residential sector, the share of electricity in heating demand should grow to 40% by 2030 and to 50-70% by 2050" within its *EU Strategy for Energy System Integration* (European Commission, 2020). These targets are expected to be achieved "through the roll-out of heat pumps for space heating and cooling" (European Commission, 2020) which requires "quadrupling the current amount of residential heat pumps by 2030" according to the EHPA (EHPA, 2020). Hence, continuous growth of the heat pump stock could be sufficient to meet the targets of the European Commission to decrease the CO_2 emissions from heating. In 2020, the stock of 14.5 million heat pump units saved 40.5 Mt CO_2 (EHPA, 2021). But on the other hand, refrigerant emissions from heat pumps would more than quadruple to over 4,000 tonnes by 2030, equivalent to over 8 Mt CO_2eq. if the average GWP of the refrigerants used remains the same in the coming years.

Finally, the exemption for HFC-containing metered dose inhalers from the phase-down according to Article 15 (2) of the F-gas Regulation should not be prolonged. This would reduce the HFC use by approximately 8 Mt CO_2eq. per year (EEA, 2020), roughly 10% of the HFC amount placed on the market in 2018.

Emissions of other F-gases

HFCs are only one group of substances among the fluorinated greenhouse gases (F-gases). Besides HFCs, perfluorocarbons (PFCs), sulphur hexafluoride (SF_6), and nitrogen trifluoride (NF_3) are F-gases as well. Between 1990 and 2018, F-gas emissions have grown by 54% in EU-28 and reached a maximum of 124 Mt CO_2eq. in 2014 [EEA, 2021]. Compared to 2017, 2018 emissions of HFCs decreased by 6.6% but F-gas emissions only by 5.2% because of increasing emissions of NF_3 (+ 13.1%), PFCs (+ 5.0 %), SF_6 (+ 1.4%) and an 'unspecified mix of HFCs and PFCs' (+ 61.9%). In addition to HFCs, over the last ten years (2009-2018) these other F-gases were responsible for emissions of about 11 Mt CO_2eq. per year, whereof SF_6 accounts for 6.3 Mt CO_2eq. and PFCs for 3.7 Mt CO_2eq. Thus, these other F-gases should also be considered and measures to reduce their emissions need to be implemented to meet EU climate protection goals.

3.3 Natural refrigerant examples: sustainable HFC alternatives at work

As already mentioned, solutions are available for nearly every HFC application which have a similar or, in most cases, higher energy efficiency compared to their HFC counterparts.

In the field of single-split air conditioning for example, 600,000 units have been produced already by September 2018 by an Indian manufacturer (Yoshimoto, 2018). According to the Indian Seasonal Energy Efficiency Ratio (ISEER), the latest single-split product with a capacity of 1.5 tons (5.3 kW) shows an energy efficiency of 5.2 and is one of the best performing units on the Indian market. Production capacity is 300,000 units per year. Since R290 (propane) is flammable, safety guidelines need to be followed during installation and maintenance to prevent accidents. Installation and operation safety are ensured by the company's own qualification programme for technicians which install, service and repair the units (Becker et al, 2019).

Energy-efficient refrigeration systems using CO_2 (R-744) as a refrigerant are now available for food retail stores for all climate zones. The CO_2 transcritical booster system has been considered the standard cost-effective system solution for new supermarkets in cold climates such as Scandinavia for over 10 years. Parallel compression and ejector technology are recognized and proven solutions for operating CO_2 transcritical refrigeration systems at high average ambient temperatures (SuperSmart, 2017).

In the Middle East, for example, the first transcritical CO_2 system was commissioned in January 2018 in a converted supermarket in Amman, Jordan. The replacement of the HCFC-22 refrigeration system reduced the store's annual electricity demand by 40,000 kWh, equivalent to a CO_2 emission reduction of approximately 32 metric tons. In addition, direct HCFC refrigerant emissions of 35 tonnes CO_2eq. are saved annually and food wastage in the store can be completely avoided due to the stable operation of the CO_2 refrigeration system (Hafner, 2019).

4 Global HFC emissions, their regulation and importance for climate protection

4.1 Current and future HFC emissions on a global scale

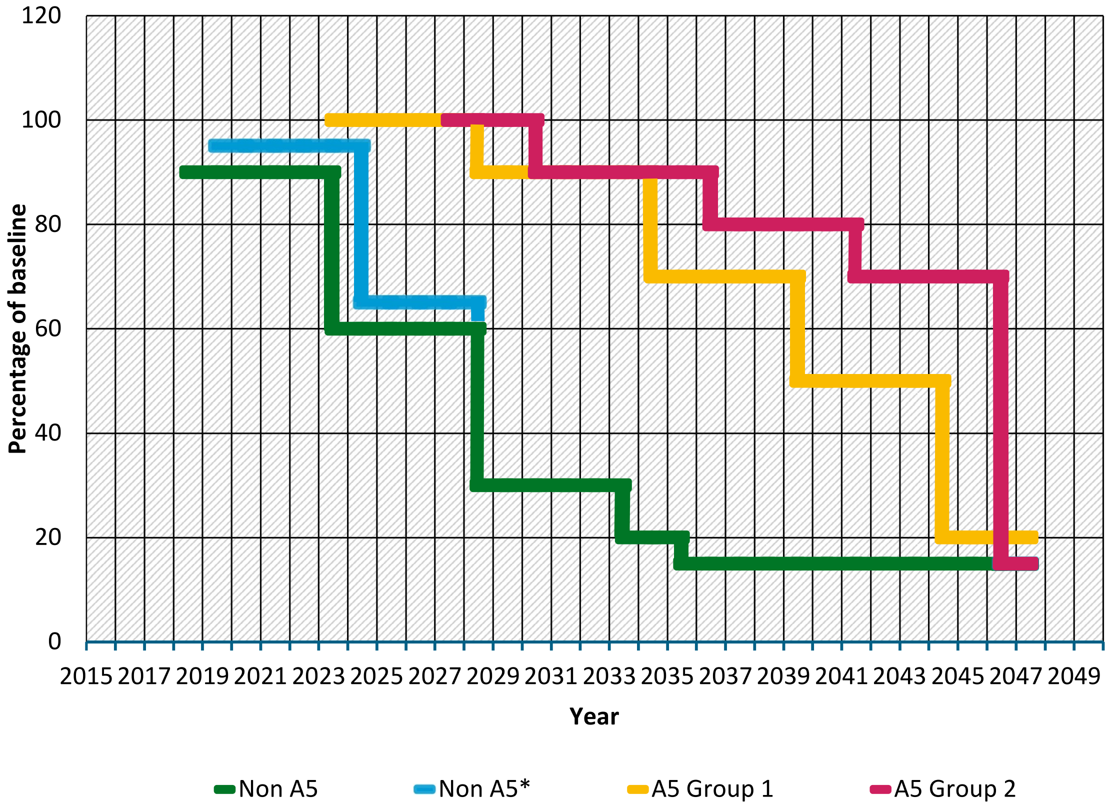
In contrast to developed countries which have installed national systems to monitor their greenhouse gas emissions including the most important F-gases annually under the United Nations Framework Convention on Climate Change (UNFCCC), the majority of developing countries does not maintain such detailed systems to the same extent. This makes it difficult to indicate sound F-gas and, in particular, HFC emissions on a global scale. Thus, research has been carried out to assess worldwide HFC emissions in the past and the future. For developing countries, HFC emission estimates build on historical HCFC use and emissions as well as on the assumption that HCFCs are replaced by HFCs in patterns that have been observed in developed countries. Baseline scenarios developed in this research do not include the reduction steps stipulated in the Kigali Amendment of the Montreal Protocol (see below).

According to Gschrey et al., projected overall F-gas emissions amounted to approximately 1.15 giga tonnes CO_2 equivalent (Gt CO_2eq.) in 2015 and will reach 4.0 Gt CO_2eq. in 2050, out of which 3.65 Gt CO_2eq. are due to HFC emissions (Gschrey et al., 2011). Velders et al. estimated HFC emissions only, excluding the HFC-23 contribution, at 4.0 to 5.3 Gt CO_2eq. in 2050, with 0.8-1.0 Gt CO_2eq. from developed and 3.2-4.4 Gt CO_2eq. from developing countries (Velders et al., 2015). In a current article, HFC emissions in 2015 reached 1.1 Gt CO_2eq. and thus the highest level so far, and are projected to reach 4.3 Gt CO_2eq. in 2050 (Purohit et al., 2020). Taken together, all estimates found in the literature concerning future HFC emissions - excluding the reduction stipulated by the Kigali Amendment - predict, firstly, increasing emissions, and secondly, levels of yearly emissions of around 4 Gt CO_2eq. in 2050. According to the latest baseline scenario estimates, 92 Gt CO_2eq. of cumulative HFC emissions will be released globally by 2050 (Purohit et al., 2020; Purohit, 2021).

4.2 Worldwide regulation of HFCs: The Kigali Amendment to the Montreal Protocol and its climate protection effect

In October 2016, the parties to the Montreal Protocol decided to impose a phase-down scheme on HFC use and production at their meeting in Kigali, Rwanda. The scheme termed Kigali Amendment comprises four groups, two with developed countries (non A5 countries) characterised by only minor differences in the phase-down pattern and two with developing countries (A5 countries) featured by more independent pathways in a timely manner. Whereas non A5 countries started to phase-down HFC consumption and production in 2019 and 2020, respectively, A5 country groups will follow in 2024 and 2028 with a freeze of HFC use. The actual phase-down will begin in 2029 and 2032, respectively (UNEP, 2016). As for the European F-gas Regulation, HFC amounts indicated in the Kigali Amendment are calculated in CO_2 equivalents. Details of the HFC phase-down according to the Kigali Amendment are given in Figure 4. It is important to note that it regulates production and consumption of HFCs and not HFC emissions, notwithstanding the fact that the final goal of the Amendment is climate protection and, hence, the reduction of HFC emissions contributing to global warming. By Mai 2021, 119 parties ratified the Kigali Amendment (UNEP, 2021).

Figure 4: HFC phase-down according to the Kigali Amendment



HFC baseline for non A5 countries is their average consumption level for 2011-2013 plus 15% of the HCFC baseline. For Belarus, Kazakhstan, Russian Federation, Tajikistan, and Uzbekistan (Non A5*), 25% of the HCFC baseline is added, and the first two reduction steps are changed to -5 and -35 percentage points in 2020 and 2025, respectively. Baselines for A5 country group 1 and 2 are the average HFC consumption levels for 2020-2022 and 2024-2026, respectively, plus 65% of the HCFC baseline. A5 country group 2 comprises Bahrain, India, the Islamic Republic of Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia, and the United Arab Emirates. A5 country group 1 includes all A5 parties not part of group 2.
Data taken from UNEP (2016)

As already mentioned, cumulative HFC emissions are estimated to reach 92 Gt CO_2eq. between 2018 and 2050 in a baseline scenario without global efforts to mitigate HFC emissions (i.e. without the Kigali Amendment; Purohit et al., 2020; Purohit, 2021). Due to the measures to be taken in order to comply with the Kigali Amendment, cumulative emissions will be reduced by 66% and amount to 30.7 Gt CO_2eq. by mid-century. Therefore, emission savings in total will be 61.3 Gt CO_2eq. for that period. For comparison: The Intergovernmental Panel on Climate Change (IPCC) estimates that the total carbon (CO_2eq.) emission budget left to mankind in order to not exceed the 1.5 °C global warming limit is 570 to 770 Gt with a probability of 66 to 50%, respectively, when global mean surface temperatures[8] are considered (IPCC, 2018). This means that the global HFC phase-down can save 10.8 to 8.0% of the 1.5°C global warming pathway carbon budget. These numbers illustrate the potential of HFC emission mitigation and the importance of the Kigali Amendment contribution to climate protection.

[8] Using global mean surface air temperatures, remaining carbon budget is only 420 to 580 Gt CO_2eq. with a probability of 66 to 50%, respectively, to keep the 1.5 °C goal. Based on these values, the share of carbon budget savings due to the HFC phase-down is even greater (14.7 to 10.6%).

4.3 HFC emission mitigation with and beyond Kigali: the way forward

An issue which has not been discussed on a broader scale yet is illegal trade of HFCs in respect to the implementation of the Kigali Amendment. It is very likely that the experiences made in the European Union regarding illegal trade will be similar to those in other developed and developing countries which implement the HFC phase-down according to the Kigali Amendment. This is due to the different onsets of the HFC phase-down. Since the main entry route of illegally traded HFCs seems to be circumvention of customs control, countries should put a focus on enabling respective authorities to counteract illegal activities. Sufficient personnel which is appropriately trained on this issue therefore is the most important measure parties may take to prevent HFCs entering their country illegally.

From a technical point of view, HFC emission mitigation could be achieved earlier and to a greater extent than it is agreed on in the Kigali Amendment. In a reduction scenario which exploits the full mitigation potential by making use of all technical feasible options of HFC replacement, cumulative HFC emissions could be reduced by 86% to 12.9 Gt CO_2eq. by 2050 (Purohit, 2021). This would mean an additional HFC emission reduction of 17.7 Gt CO_2eq. Including the period past 2050 to the end of the 21st century, the maximum technical feasible reduction (MTFR) scenario from 2018 to 2100 would result in cumulative HFC emissions of 13 Gt CO_2eq. compared to 48 Gt CO_2eq. if the Kigali Amendment is fully implemented (Purohit et al., 2020). This is a difference of remarkable 35 Gt CO_2eq. Moreover, the replacement of HFCs will open up considerable electricity saving potentials which brings about the same GHG mitigation as the HFC replacement due to the migration to more energy efficient equipment (Purohit et al., 2020).

5 Conclusions

The Kigali Amendment to the Montreal Protocol is an indispensable contribution to climate protection in general and to the achievement of the 1.5 °C ('well below 2 °C') goal set in the Paris Agreement in particular. However, as shown above, a significantly greater HFC emission mitigation of 17.7 and 35 Gt CO_2eq. by 2050 and 2100, respectively, could be reached with implementing a pathway which exploits the full technical potential of HFC replacement.

Additional GHG savings of about the same magnitude will be achieved by more energy-efficient equipment. Since these numbers are derived from estimations and provide that all actors step up their ambition to a maximum, it is not the most likely scenario to become reality.

Nevertheless, the Kigali Amendment shows that giga tonnes of HFC emissions alone will be saved if actors (i.e. parties to the Montreal Protocol) increase their ambitions and go beyond the Amendment schedule and phase-down emissions more quantity-wise by aiming a lower limit (i.e. 10% of the baseline and below in contrast to 15 or 20%) and more rapidly. The latter could be implemented by starting the HFC phase-down earlier on a voluntary basis.

Europe, which already launched the phase-down of HFCs, according to the F-gas Regulation illustrated above, four years before the Kigali Amendment phase-down started in 2019 for developed countries, is a good example in this respect and leads the way forward. Data provided by the European Environment Agency (EEA) show that EU HFC consumption amounts to only 45% of the permitted amount for 2019 according to the Kigali Amendment (EEA, 2020).

With the review process of the F-gas Regulation which has been started in 2020, it is very likely that European HFC use will be restricted further and the impact on emissions will be accordingly. Crucial and in our view necessary changes and additions are the following:

- A more ambitious HFC phase-down as described above,
- Prohibition of single-split air conditioners using refrigerants with GWP ≥ 150 from 1. January 2025 onwards (No 15, Annex III),
- Prohibition of stationary refrigeration equipment using refrigerants with GWP ≥ 150 (No 12, Annex III),
- Cancelation of the exemption of metered dose inhalers from the phase-down according to Article 15 (2) and
- Prohibition of heat pumps using refrigerants with GWP ≥ 150.

Thus, the EU may not only be a role model for other countries in setting ambitious mitigation pathways for HFCs, but also for the step-up of climate protection efforts for this class of greenhouse gases.

Preventing the use and thus emissions due to early action is crucial to stay well below 2 °C warming since irreversible climate tipping points such as the melt down of the Greenland Ice Sheet are already surpassed by a warming of less than 2 °C (Robinson, Calov and Ganopolski, 2012). In the HFC application fields such as refrigeration and air conditioning, climate- and environmentally-friendly natural refrigerant technologies are established and ready to replace HFCs and HCFCs not only in Europe but worldwide, even in warmer climates, and also in economic terms. Therefore, there is a viable pathway to completely phase-down HFCs and even surpass the mitigation aims of the 1.5 °C target (-70 to -80% compared to the 2010 emission level) for this group of greenhouse gases.

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