Predictions of European refrigerants place on the market following F-gas Regulation restrictions[1]

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Abstract

The European Union (EU) Regulation on fluorinated greenhouse gases (F-gases) has encouraged to reduce gradually the number of hydrofluorocarbons (HFC) that can be placed on the market (POM) to 21% of the baseline level in 2030. However, to this day, the EU refrigeration, air conditioning and heat pump (RACHP) market is still dominated by these substances. This study describes a methodology to estimate the refrigerant demand by refrigeration, air conditioning, and heat pumps available to the EU customers until 2030. The work is based on the most relevant current statistical data, refrigerant distribution (R134a, R404A, R407C and R410A), and future technology acceptance and trends. The study presents a refrigerant demand grow scenario and provides a basis for a closer market follow-up to facilitate refrigeration industry stakeholders' decision-making. The results indicate that by 2021 will be challenging to accomplish the fluorinated gas quota considering the current HFC phase-down process. However, by 2030, the transition is possible in the EU, assuming the additional measures to mitigate the leakage from already installed equipment will be taken. By that time, natural refrigerants, including CO_2, ammonia, and hydrocarbons, can dominate the market. However, the share of HFC or HFC/HFO mixtures in operation is still significant (R32 or mixtures with similar behaviour, and R404A low flammability alternatives). Consequently, industrial and commercial refrigeration (large scale applications) will concentrate approximately half of the GWP weighted CO_2e, negligible direct emissions for domestic refrigeration or mobile air conditioning, dominated by natural refrigerants pure HFO refrigerants, respectively.

Keywords: refrigeration; air conditioning; natural refrigerants; HFC; HFO, low global warming potential (GWP).

Nomenclature

AC	Air conditioning
C	Confidential
	Typical charge (kg per unit)
CO_2e	Carbon dioxide equivalent
DX	Direct expansion
EU	European Union
GWP	Global warming potential
F-gases	Fluorinated gases
F-gas Regulation	Regulation (EU) No 517/2014 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases
HC	Hydrocarbon

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[1] This work adapts and updates Manuscript ID: 829 presented at the 25th IIR International Congress of Refrigeration, 24-30 August 2019 in Montreal, Canada (Makhnatch et al., 2019a).

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HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HP	Heat pumps
	Share of specific refrigerant use in the sector (% of installed units per sector)
	Annual leakage rate per sector (%)
LT	Low temperature
	Demand for a specific refrigerant (kg)
MT	Medium temperature
Mt CO_2e	Million-ton CO_2 equivalent
	RACHP equipment per sector (units)
NA	Not applicable
Nat	Natural refrigerants
POM	Placing on the market
RACHP	Refrigeration, air conditioning and heat pump
top	Top-up
VRF	Variable refrigerant flow system

Highlights

- Refrigerant place on the market (POM) in Europe will suffer a significant cut in 2021.
- Up to 2020, European refrigerants POM has been respected, despite the sustained demand.
- Meeting the 2021 quota will be challenging due to inertia in the adoption of POM mitigation measures.
- Industrial, stationary and commercial refrigeration will concentrate more than half of the total refrigerant demand, measured in CO_2e.

1. Introduction

Global society is facing a severe environmental challenge to reduce its impact on climate. Refrigeration, air conditioning and heat pump (RACHP) systems are a well-known contributor to global warming and account for 7.8% of global CO_2e (carbon dioxide equivalent) emissions (Coulomb et al., 2017) with the projections of the growing impact (Peters, 2018).

The Kigali Amendment to the Montreal Protocol is a global agreement that has been enforced from 1 January 2019 and will significantly reduce the RACHP carbon footprint. The agreement's threshold to enter into force was met as it is ratified by a significant number of countries (United Nations Environment Programme (UNEP), 2016). This agreement sets different phase-down schedules to reduce the global production and consumption of hydrofluorocarbons (HFC). Before the Kigali Amendment, legislation that included similar actions has been implemented in the European Union (EU), i.e., the Regulation No 517/2014 of the European Parliament and of the Council on fluorinated greenhouse gases (commonly known as F-gas Regulation) (European Commission and The European Parliament and the Council of the European Union, 2014).

Most importantly and among other measures, the F-gas Regulation sets a target HFC consumption levels that are gradually reduced till 2030 and prescribes control mechanisms to prevent using a more significant amount of HFC. Additionally, many prohibitions based on global warming potential (GWP) values guide the industry over the process. Thus, clear incentives have been established for the RACHP industry to reduce the supply of high GWP refrigerants by, for instance, replacing them with alternatives with lower GWP. Remarkably, environmental legislation and its practical implementation and sound business decisions have significantly reduced CO_2e emissions across commercial refrigeration (Hart et al., 2020). Moreover, the recent modification of the International Electrotechnical Commission standard 60335-2-89:2019 (IEC, 2019) will allow the extension of flammable refrigerants to new applications or larger systems with the increase in refrigerant charge.

The widespread adoption of low GWP refrigerants started more than ten years ago (Calm, 2008), with the introduction of R1234yf to replace R134a in air conditioners (Pabon et al., 2020), which was later extended to other applications and refrigerants. While the list of available low GWP refrigerants has been identified (McLinden et al., 2017), their use is currently limited due to their varying properties, e.g. flammability (Wu et al., 2019) or toxicity characteristics. In such circumstances, several refrigerant mixtures are being proposed to satisfy different requirements (trade-off) (Heredia-Aricapa et al., 2020). Depending on the RACHP particular application, the characteristics required for a refrigerant vary, and hence also the availability of lower GWP alternatives and their GWP values (Botticella et al., 2017). Simultaneously, the maximum quota approved by the F-gas Regulation for each year is the same for the whole EU market and not linked or separated to a specific application. Therefore, it reduces incentives to proactively replace HFC in RACHP applications that are not directly affected by placing prohibitions set by the F-gas Regulation. The International Institute of Refrigeration considered successful the F-gas Regulation but recommended deciding on quotas for 2030-2036 to respect the Kigali amendment to the Montreal Protocol (IIFIIR, 2020).

This work completes a long term project that started with analysing possibilities when the F-gas Regulation was approved in 2014 (Mota-Babiloni et al., 2015a). Then, a follow up of the evolution of studies in synthetic refrigerants was published in 2017 (Mota-Babiloni et al., 2017a) and an overview of the energetic performance of the future synthetic and hydrocarbon alternatives in 2020 (Heredia-Aricapa et al., 2020). This work aims to present and analyse a prediction for the future refrigerant mix plausible to comply with the F-gas Regulation quotas and GWP limitations and avoid illegal refrigerants acquisition. This prediction methodology can also be practical if extended outside the EU to follow the Kigali Amendment's reductions to the Montreal Protocol.

2. Methodology

The results of this study are based on the refrigerant allocation model that forecast replacing pattern for commonly used HFC refrigerants (R134a, R404A, R407C and R410A). The model is based on current and historical data and assumptions of future refrigerant use and regulations development.

2.1 Approach

The methodology followed in this study is based on the historical, current, and future prediction levels of high GWP refrigerants use as input data. The model is based on the initial reference unit distribution and considers supply levels observed in each of the EU 36 RACHP sectors. The initial levels of selected HFC refrigerants that have been consumed in Europe for the reference period taken by the F-gas Regulation have been defined as accounting for the most accurate data, as exposed in Annex A.

Further, the projection of the number of units in operation and the percentage of refrigerant used is presented in Annex B. The future refrigerant options have been identified considering the current technology and refrigerant development levels, their future development projections, e.g., such as discussed in detail in (Danfoss, 2020), and the future restrictions for each application. The refrigerant allocation has been modelled on an annual basis over the 2010–2030-year time frame. Two key periods have been highlighted in the discussion, namely 2021 and 2030 years, which are the F-gas Regulation target years for two quota reductions (European Parliament, 2014). Still, the presented approach is valid for any year, including those not included in the current F-gas Regulation scope but of interest in the Kigali Amendments to Montreal Protocol's scope.

2.2 Data and assumptions

Companies' historical data on the production, import, export, and destruction of F-gases in the European Union is obtained from the European Environment Agency (2020). The document provides various statistics on F-gases use in the EU for 2007-2019 years. The current study has focused on a set of HFC refrigerants representing nearly the total share of refrigerant supplied during the referencing period. The refrigerant used during the 2010-2030 period is quantified based on the methodology described in annexes. Thus, it is insensitive to the fluctuations due to refrigerant stockpiling observed in the EU market due to the discussions and adoption of the F-gas Regulation. The projections of supply are instead based on the reasonable refrigerant market development under the F-gas Regulation requirements that the authors assumed. These assumptions are further introduced in the respective parts of the paper.

3. Refrigerant inventory estimation

3.1 Implications of the F-gas Regulation

The F-gas Regulation established a legal requirement for a 79% gradual reduction in the HFC that can be placed on the market (POM) in the EU based on the average amount of POM during the period 2009-2012 baseline reference. The reduction started in 2015, but the first significant reduction took place in 2018, passing from 93% to 63% of HFC substances allowed. It is considered that this year the RACHP industry faced the first challenge. Similarly, its next great challenge to face is the year 2021, when the reduction will be 55% HFC substances allowed from the baseline.

The phase-down schedule established by the F-gas Regulation can be translated into the amount of CO_2e allowed to be POM in the EU, given the available historical data. Thus, the 100% quota is 183.1 Mt CO_2e. It is based on the allowed quota value, set by the Regulation, total CO_2e value of the baseline HFC gases use (as listed in the F-gas Regulation). The resulted values are compiled in Figure 1.

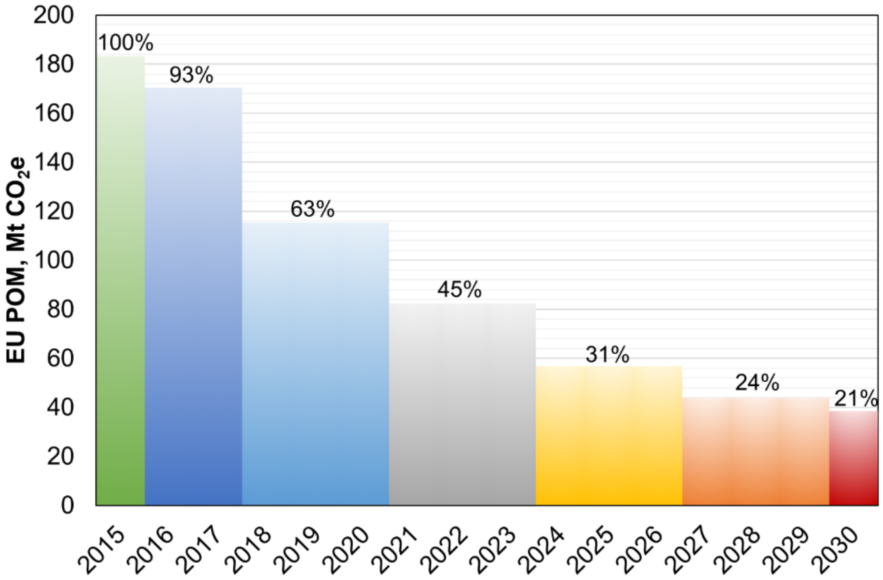

Figure 1. HFC reduction quota translated into CO_2e emissions.

The allocated quotas are carefully monitored, and the statistics are regularly published, presenting past use of the F-gases. According to the most recent European Environment Agency (2020) statistics (EEA, 2020), the quotas have been met successfully during the 2015-2019 years (Figure 2).

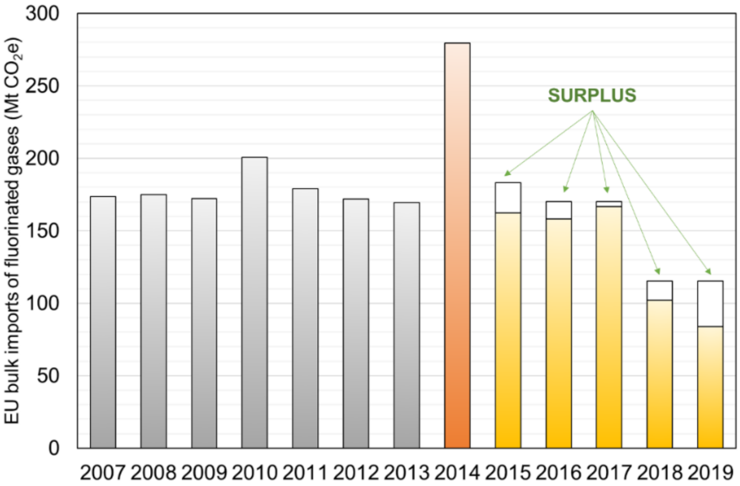

Figure 2. EU bulk imports of fluorinated gases in the period 2007-2019.

Most of the F-gases have been used in the "Refrigeration, air conditioning and heating and other heat transfer fluids" category, followed by the "Foams, including pre-blended polyols" and "aerosols" sectors. The statistics present the supply data for different F-gases. In the refrigeration sector, these gases have been consumed in pure form (e.g., R134a and R32 refrigerants) and combined in mixtures with other F-gases (e.g., R134a as a component of R404A, R32 for R410A). However, the past refrigerant supply's quantitative data is not presented in the report either available to the authors in any other form. Such data is, therefore, evaluated.

3.2 Identifying baseline refrigerant inventory

Depending on the specific refrigerating application requirements, various F-gases are used in pure form and components of a refrigerant mixture. The most widely used synthetic HFC refrigerants before the HFC phase-down are R134a, R404A, R407C and R410A. The composition of the HFC mixtures in mass percentage is presented in Figure 3.

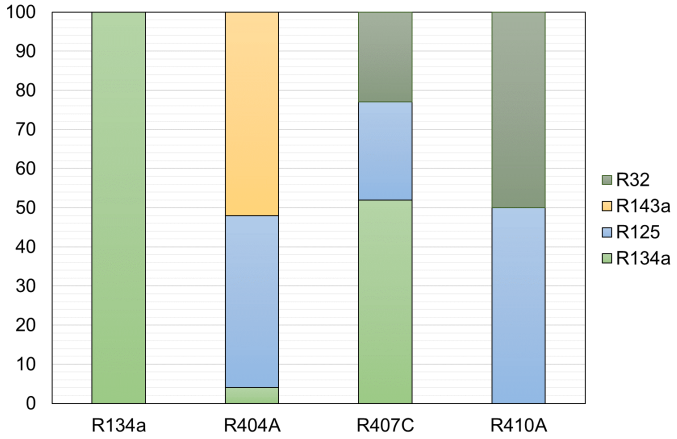

Figure 3. Composition in mass percentage of commonly used HFC refrigerants.

These refrigerants are used in various applications, for some of which the F-gas Regulation establishes additional regulatory measures: products and equipment POM prohibitions. Thus, considering the statistical data presented by (SKM Enviros, 2012), the refrigerant inventory has been identified for each of 36 RACHP sectors representative for the European Union (see methodology explained in Annex A, including baseline and projection details, inputs and equations). The resulting refrigerant inventory for all EU RACHP sectors in 2010 is summarised in Figure 4 on a mass and CO_2 equivalent basis, for which the GWP has an influence.

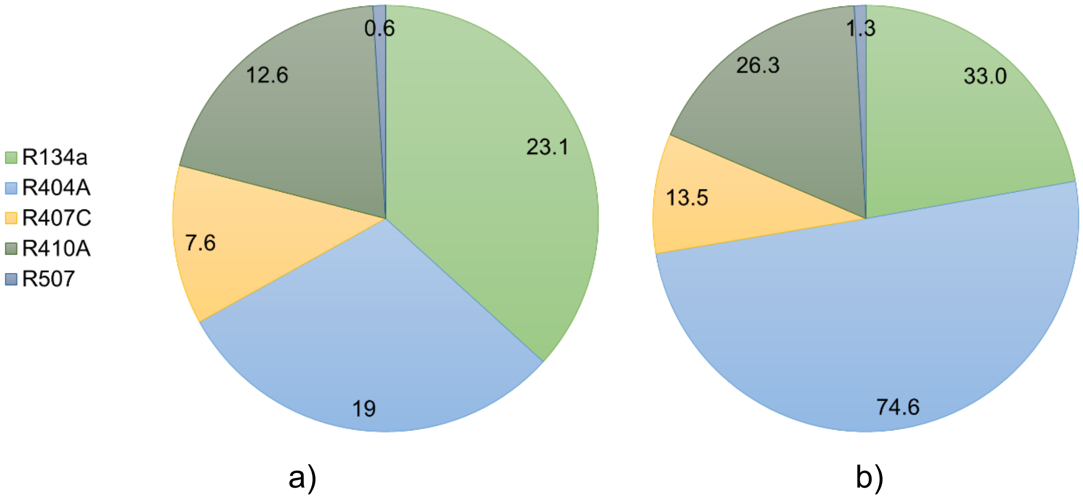

Figure 4. Common HFC refrigerants 2010 inventory on a: a) mass (million kg) basis and b) CO_2 equivalent (Mt CO_2e).

3.3 Identifying distribution of refrigerants

The refrigerant choice that replaces a conventional one follows incentives that originate from technology development and legislative incentives, thus depending on the intended application (Mota-Babiloni et al., 2017a). For instance, R404A is used in commercial refrigeration. It can be replaced, depending on the application, by lower and low GWP refrigerant mixtures (Makhnatch et al., 2017), as well as naturally occurring substances (for instance, CO_2 (Zolcer Skačanová and Battesti, 2019) and propane (Harby, 2017)). Several replacements have been developed for R134a and are suitable to substitute it in several applications (de Paula et al., 2020; Makhnatch et al., 2019b). Similarly, a wide range of alternatives exists for other HFC refrigerants considered in the current analysis of Mota-Babiloni et al. (2017a). The choice of the alternative is dependent on a few factors given the projected timeframe, including the type of equipment, viability to retrofit, and availability of alternatives.

The refrigerants' distribution over the equipment type has been taken from that reported for the European Union by SKM Enviros (2012). The reported data suggest that R134a is a dominating refrigerant by 2010 year, followed by R404A. Other commonly used refrigerants by that time are R407C, R410A and natural refrigerants. The distribution of refrigerant across 36 EU RACHP sectors is referred to in Annex B.

4. Future refrigerant inventory

4.1 Refrigerant options

Typical refrigerants used in a baseline timeframe have GWP values over some applications' limits (Mota-Babiloni et al., 2015a). Moreover, these GWP values will limit HFC' use under a reduced quota scenario (European Commission and The European Parliament and the Council of the European Union, 2014). Therefore, they will be replaced to comply with the requirements of the current legislation. The transition to lower GWP refrigerants will happen gradually. It will rely on the availability of the lower GWP refrigerants and equipment using thereof, availability of lower GWP refrigerants that can replace HFC refrigerants already used in equipment (drop-in replacement), monetary and legislative incentives, among other factors.

In this work, a scenario of the refrigerant supply development by each consequent year from 2010 till 2030 is implemented, from which such distribution by the beginning of 2021 and 2030 is presented here. This scenario is based on the expert opinion on future developments expressed elsewhere (Danfoss, 2020; Hwang, 2016) and considering what has been observed in the HCFC phase down and the current 3rd to 4th generation transition. The future possibly used alternatives can be briefly summarised in Table 1 and disclosed in detail for selected timeframes in Annex B. By 2021, a wide variety of possibilities can be combined in several applications. However, by 2030, it is predicted that many HFC/HFO mixtures and the latest considered HFC will nearly disappear from that range of options, and natural refrigerants will dominate the refrigerant market. Selected papers are included in each category to justify the authors' proposal for the refrigerants transition.

Table 1. New refrigerants adaptation based on the category.

RACHP category	**Baseline HFC refrigerant**	**Prediction**	
		By 2021	**By 2030**
1. Domestic (Palm, 2008)	R134a	HC	HC
2. Commercial (Cecchinato et al., 2012; Heredia-Aricapa et al., 2020; Karampour and Sawalha, 2018; Mota-Babiloni et al., 2015b; Zolcer Skačanová and Battesti, 2019)	R134a	HFC/HFO, CO_2/HC	Mostly CO_2/HC; HFO/HFC
	R404A	HFC/HFO, CO_2/HC	Mostly CO_2/HC, HFO/HFC
3. Transport	R134a	HFC,	HFO

(Barta et al., 2021; Li, 2017)		HFC/HFO	
	R404A	HFC/HFO	HC/CO_2
4. Industrial (similar to commercial refrigeration)	R134a	HFC/HFO, HFO, NH_3/CO_2	HFC/HFO, HFO, NH_3/CO_2
	R404A	HFC/HFO, NH_3/CO_2	HFC/HFO, NH_3/CO_2
	R410A/R407C	NH_3/CO_2/HC	NH_3/CO_2/HC
5. Stationary AC and HP (Mota-Babiloni et al., 2017b; Ribeiro and Barbosa, 2019; Shen and Fricke, 2020; Yu et al., 2021)	R410A/R407C	Mostly HFC, HC	HFC/HFO, HFC, HC
6. Chillers and hydronic heat pumps (similar to AC and HP)	R134a	HFC, HFC/HFO, HFO	HFO
	R410A/R407C	HFC, HFC/HFO	HFC, HFO/HFC
7. Mobile air conditioning (Pabon et al., 2020)	R134a	HFO	HFO, CO_2
	R407C	HFC, HFO, HC	HC, HFC, HFO

4.2 Estimation of refrigerant demand under POM limitations of F-gas schedule

In the refrigeration industry, HFC refrigerants are utilised to fill in new or newly commissioned products and systems produced or imported to the European market, either as pure fluid or as a component in a refrigerant mixture. Additionally, substantial demand for HFC fluids is utilised for topping-up eventual accidental leakages from existing RACHP equipment. The estimated demand for HFC refrigerants in EU under a period from 2010 to 2030 is presented in Figure 5.

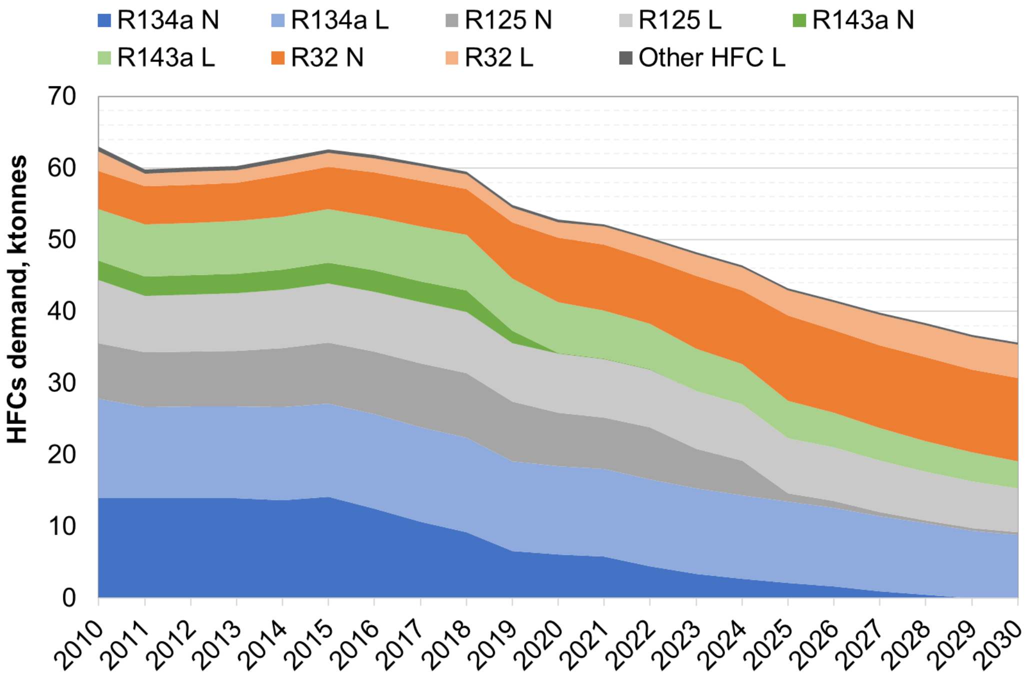

Figure 5. Estimated demand for HFC refrigerants in EU, mass basis (solid colour - demand for newly (N) introduced systems; patterned colour - demand for top-up (L) of the installed systems)

Even considering a 3% annual unit growth projected in the current study, the demand for refrigerants is projected to gradually decrease following the inception of the new F-gas Regulation and consequent interest in alternative refrigerants that use less or no HFC substances in the composition.

The estimated demand for HFC refrigerant in EU expressed in their CO_2e emissions is presented in Figure 6. This data highlights that a significant portion of the demand is considered for maintaining the already installed equipment. The refrigerants are added to replace continuous leakages common for many types of RACHP systems. With proper refrigerant management, refrigerant from decommissioned equipment can be recycled or reclaimed and placed into use again, thus reducing the amount of refrigerant that is accounted under the POM limitation of the F-gas Regulation.

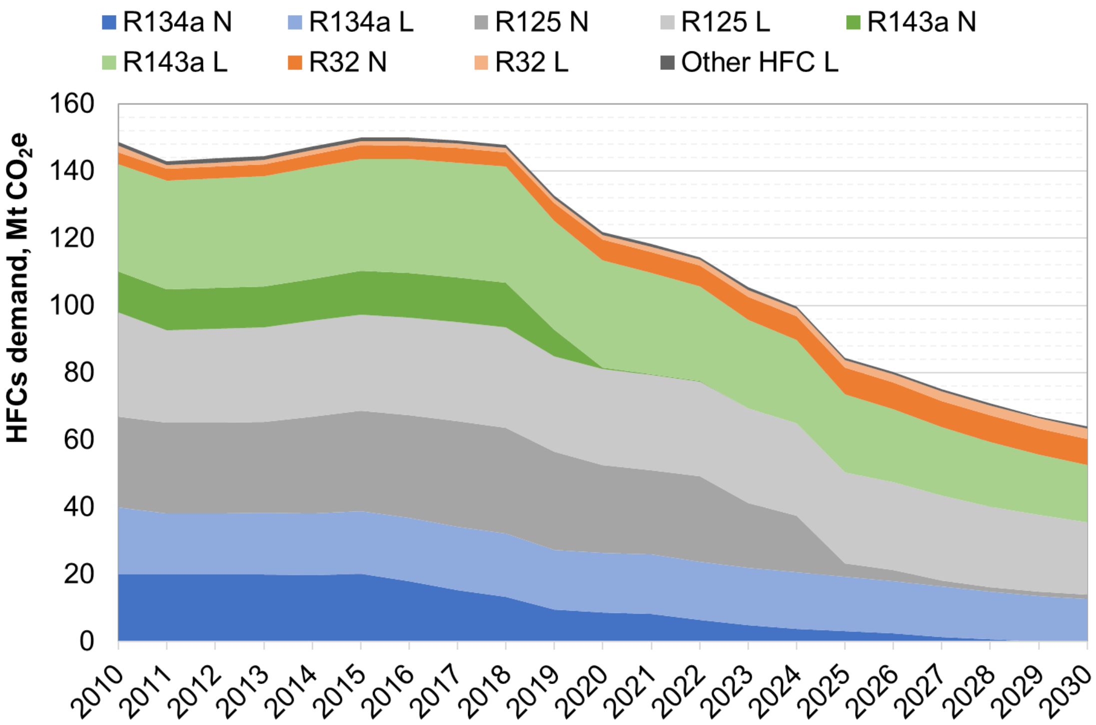

Figure 6. Estimated demand for HFC refrigerants in EU, CO_2e basis (solid colour - demand for newly introduced systems; patterned colour - demand for a top-up of the installed systems)

Gradual increase of recycled and reused refrigerant is modelled considering 20% annual increase of recycled/reused refrigerant from 2018 until reaching a constant 90% rate from and including 2022. Demand for HFC refrigerant, excluding the amount covered by the use of recycled/reused refrigerant, Figure 7, is representative of the POM metric that is relevant to compliance with the EU HFC phase-down, as defined by the F-gas Regulation and also described in detail by the European Environment Agency (2020).

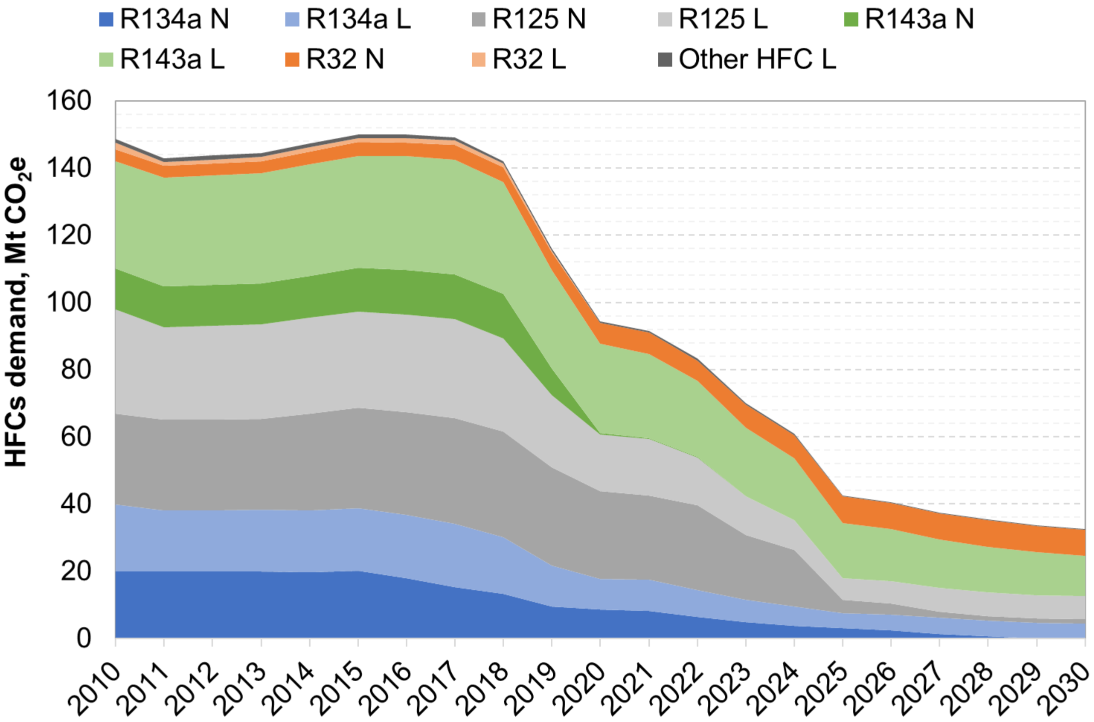

Figure 7. Estimated demand for HFC refrigerants in EU excluding that covered by reused/recycled HFC, CO_2e basis (solid colour - demand for newly introduced systems; patterned colour - demand for a top-up of the installed systems)

A sharp decline in the POM of HFC refrigerant can be achieved when adopting new RACHP systems and using reused/recycled refrigerant. However, this should be done at a high rate of 90% already from 2022 to achieve presented results. The results presented in Figure 7 indicate that, at a given rate of new refrigerants adoption, the amount of HFC refrigerants expected to be POM during the current year is 81.42 Mt CO_2e. This case is considering that nearly all retrofitted refrigerants will be reclaimed or recycled for their consequent use.

Such results are likely due to the European refrigeration and air conditioning stakeholders' delayed response to the F-gas Regulation requirements. The delay in implementing available low and lower GWP refrigerants caused that installed equipment that uses high GWP refrigerants represents a bank of high GWP refrigerants needed to be maintained (top-up to compensate for accidental leakages (Francis et al., 2017)). Additionally, such equipment retrofit is often limited to the non-flammable HFO/HFC mixtures, which GWP is still relatively high (Bell et al., 2019). However, the use of refrigerants with different safety classification (higher flammability) requires a replacement of equipment by another designed for that purpose (for example, R32, mildly flammable, cannot be used in R410A air-conditioning systems, A1). Moreover, the utilisation of new design equipment can benefit from optimised components to improve energy efficiency (Longo et al., 2019).

Regarding the modelled future CO_2e emissions from refrigerants to be POM in 2030, the model's result is quite encouraging since significant reductions in CO_2e emissions will be possible following the projected rate of new equipment adoption and refrigerant recycling and reclamation. This is caused by the availability of low GWP alternatives and assumes that all stakeholders will move to equipment using the lowest GWP possible in each of the analysed sectors. Meanwhile, the projected demand for virgin refrigerants is still higher than that allowed for all F-gases (including, e.g., foams and fire protection application) controlled by the F-gas

Regulation by that year. Additional efforts in reducing refrigerant leakage, especially in industrial and commercial applications, will be necessary to meet the 2030 requirement.

According to the results shown in Figure 8, the sectors with the highest contribution to refrigerants POM by 2030 will be commercial, stationary and industrial refrigeration, produced by lower GWP HFC/HFO mixtures alternatives to R404A and R507 (e.g., R448A, R449A, R455A or R454C) (Llopis et al., 2019; Mota-Babiloni et al., 2018). Then, in air conditioning, heat pumps and industries, lower GWP HFC/HFO mixtures (e.g., R454B, R466A (Devecioğlu and Oruç, 2020)) and pure HFC alternatives (R32) to R410A and R407C (Mota-Babiloni et al., 2017b) will have more presence.

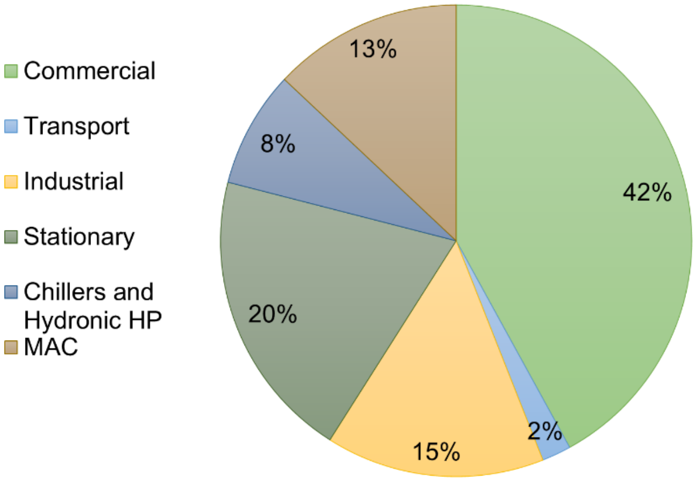

Figure 8. Estimated demand (in % of total) for HFC refrigerants at the European market in 2030

A great effort from the RACHP industry will be required to train technicians and engineers to handle new refrigerants with different characteristics than those typically managed (Mota-Babiloni et al., 2018), e.g. more dangerous refrigerants and to recover refrigerants from existing installations efficiently. Paurine et al. (2021) warned that there are inconsistent levels of knowledge and awareness of how alternative refrigerants can be utilised and discussed the availability of skills and existing training materials and template in specific European countries.

Note that ultralow-temperature applications (below –50 °C) have not been mentioned before, given the reduced number of units in operation before the pandemic situation in 2020. The low number of units and difficulties in finding suitable replacements for R23 has caused this application not to be included in regulations like the European F-gas Regulation. However, a recent work analysed this technology's situation and the alternatives to reduce its environmental impact (Mota-Babiloni et al., 2020). It is expected that the number of ultralow-temperature freezers (cabinet and storage rooms) will increase for storing a specific type of vaccines and depending on the refrigerant selected (HFC or HC). The direct carbon footprint of the application will vary enormously because the HFC used in these applications possess GWP values above 10000.

5. Conclusions and future considerations

The currently used high GWP HFC refrigerants are about to be phased down or entirely phased out from the EU market. The reduction in their use is facilitated by the European F-gas Regulation and the Kigali Amendment to the Montreal Protocol. For the coming years, low GWP refrigerants are considered to dominate the market. However, there is still a wide variety of them and a great uncertainty on how they will be distributed in the market. This paper estimates the demand for HFC refrigerants in the European Union within the period until 2030, i.e. for a period when significant F-gas quota reductions will occur.

Results show that under current assumptions, the POM by 2021 could not be satisfied by the HFC allowed within F-gas Regulation quota since the RACHP sector was not prepared for this fast transition and the dramatic decrease in quota. However, by 2030, the RACHP sector can adapt to the new situation, but additional measures will be required to remain below the POM limit. This year, the use of natural refrigerants such as CO_2, HC, and NH_3 is likely to increase, but synthetic low and lower GWP refrigerants may share the market in applications R404A/R507 and R410A/R407C are being used.

Two concerns arise in the use of these refrigerants if the current refrigerant distribution is considered. Firstly, safety issues must be taken seriously since today; flammable refrigerants were avoided when possible or only introduced in small refrigerant charges. Secondly, although several studies have been carried out, synthetic refrigerants and their decomposition products may have unexpected effects on the environment and health and should, therefore, be avoided when possible.

The discrepancy of the projected demand for HFC refrigerants and reported historical POM of such refrigerant suggests that a portion of currently consumed HFC refrigerants were not POM under the F-gas mechanisms for this particular period. Partly it can be due to the use of a previously purchased refrigerant that has been stored in anticipation of the increased demand.

Finally, it is worth highlighting that the conclusions depicted from this model can be extended to benefit the worldwide transition to low and lower GWP refrigerants. The quota HFC phase-down step of the Kigali Amendment is similar to the F-gas Regulation (there is a slight delay, but quota reduction magnitude and steps are comparable). Lessons and experiences learned from the European transition can also be valuable. Thus, relevant data should be collected from the early stages of Kigali Amendment implementation to provide the industry with more transparency and knowledge and reduce uncertainty in decision making when choosing refrigerant and refrigeration equipment use. Today, it is expected that a significant number of countries will not meet the HFC freeze in 2024 without additional HFC restrictions. It is also vital to act early since the significant share of current HFC demand is used to maintain previously installed equipment.

Acknowledgements

Adrián Mota-Babiloni acknowledges the financial support of the Valencian Government under the postdoctoral contract APOSTD/2020/032.

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Appendix A. Baseline refrigerant inventory

The phase-down mechanism implied by the F-gas Regulation focuses on reducing HFC quantities that can be placed on the EU market until 2030. The list of controlled HFC is limited to substances explicitly listed in Annex I of the F-gas Regulation, Table A.1 (European Commission and The European Parliament and the Council of the European Union, 2014).

Table A.1. Fluorinated greenhouse gases referred to Article 2 of the F-gas Regulation (European Commission and The European Parliament and the Council of the European Union, 2014)

Industrial designation	**Chemical name (Common name)**	**Chemical formula**	**GWP**
HFC-23	Trifluoromethane (fluoroform)	CHF_3	14800
HFC-32	difluoromethane	CH_2F_2	675
HFC-41	Fluoromethane (methyl fluoride)	CH_3F	92
HFC-125	pentafluoroethane	CHF_2CF_3	3500
HFC-134	1,1,2,2-tetrafluoroethane	CHF_2CHF_2	1100
HFC-134a	1,1,1,2-tetrafluoroethane	CH_2FCF_3	1430
HFC-143	1,1,2-trifluoroethane	CH_2FCHF_2	353
HFC-143a	1,1,1-trifluoroethane	CH_3CF_3	4470
HFC-152	1,2-difluoroethane	CH_2FCH_2F	53
HFC-152a	1,1-difluoroethane	CH_3CHF_2	124
HFC-161	Fluoroethane (ethyl fluoride)	CH_3CH_2F	12
HFC-227ea	1,1,1,2,3,3,3-heptafluoropropane	CF_3CHFCF_3	3220
HFC-236cb	1,1,1,2,2,3-hexafluoropropane	$CH_2FCF_2CF_3$	1340
HFC-236ea	1,1,1,2,3,3-hexafluoropropane	CHF_2CHFCF_3	1370
HFC-236fa	1,1,1,3,3,3-hexafluoropropane	$CF_3CH_2CF_3$	9810
HFC-245ca	1,1,2,2,3-pentafluoropropane	$CH_2FCF_2CHF_2$	693
HFC-245fa	1,1,1,3,3-pentafluoropropane	$CHF_2CH_2CF_3$	1030
HFC-365mfc	1,1,1,3,3-pentafluorobutane	$CF_3CH_2CF_2CH_3$	794
HFC-43-10mee	1,1,1,2,2,3,4,5,5,5-decafluoropentane	$CF_3CHFCHFCF_2CF_3$	1640

The baseline F-gas POM is calculated following the approach stipulated in Articles 15-16 of the F-gas Regulation. The European Environment Agency has reported the bulk supply quantities of the F-gases to be phased down. Table A.2. summarises the calculation of baseline HFC bulk supply based on the data reported in (European Environment Agency, 2014). The most considerable HFC quantities supplied during the baseline period were intended for refrigeration and air-conditioning applications (approx. 61.1 ktonnes). Additionally, 9% of the total amount of F-gases intended for these applications were supplied in undisclosed proportions. The rest of the baseline supply (approx. 23 ktonnes) was supplied for use in other applications, most notably foams, fire protection and aerosols.

Table A.2. Bulk supply during the reference period, in tons of F-gas (EEA, 2015)

Industrial designation	**2009**	**2010**	**2011**	**2012**	**Baseline average**	**Baseline, refrigeration**[a]
Values reported for all applications						
HFC-23	190	239	181	106	179	179
HFC-32	4394	5361	4921	5007	4921	4889
HFC-41	C [b]	C	C	C	C	C
HFC-125	13906	18150	15283	15316	15664	14668
HFC-134	- [b]	C	-	C	C	C
HFC-134a	4233	43564	40082	39939	41205	26324
HFC-143	-	-	-	-	-	-
HFC-143a	9575	10484	8840	8969	9467	9467

HFC-152	-	-	-	-	-	-
HFC-152a	5182	5744	6130	5567	5656	C
HFC-161	-	-	-	-	-	-
HFC-227ea	1776	2083	2038	1469	1841.5	C
HFC-236cb	-	-	-	-	-	-
HFC-236ea	-	-	-	-	-	-
HFC-236fa	C	C	43	30	36.5	8
HFC-245ca	-	-	-	-	-	-
HFC-245fa	C	C	C	C	C	C
HFC-365mfc	C	C	C	C	C	-
HFC-43-10mee	C	C	C	C	C	-
Total (disclosed)	76256	85625	77518	76403	78969	55529
For refrigeration and air-conditioning (including heat pump)						
Total	58678	65964	61045	58574	61065	61065
For HFC supplied						
Total (reported)	80632	90604	82932	81842	84003	84003

[a] baseline bulk supply, adjusted to the share of respective F-gas intended for refrigeration and air conditioning, as reported in Table 2.5.

[b] C = Declared confidential in the original report, - = negligible.

Appendix B. Refrigerant and number of units projection

Refrigerant use during 2010-2030 has been projected for 36 RACHP sectors, taking installed base (number of units and share of refrigerants used) for 2010 as reported for the EU region in the report by SKM Enviros (2012) as the reference. The RACHP subsectors, installed base, assumed lifetime, annual leakage rate and typical refrigerant charge are summarised in Table B.1.

Table B.1. Product distribution and key parameters of EU RACHP sectors, by 2010 (SKM Enviros, 2012)

Sector	**Charge, kg**	**Lifetime, yr**	**Leakage rate, % per year**	**Installed base, thousand of units**
1. Domestic refrigeration				
1.1 Refrigerators (MT)	0.05	15	0.01	250000
1.2 Freezers (LT)	0.05	15	0.01	61000
2. Commercial refrigeration				
2.1 Small hermetic MT	0.24	15	1	8200
2.2 Small hermetic LT	0.24	15	1	3900
2.3 Single condensing units MT	3.6	15	14	1320
2.4 Single condensing units LT	2.7	15	14	1550
2.5 Multipack centralised MT	200	15	21	198
2.6 Multipack centralised LT	100	15	21	186
3. Transport refrigeration				
3.1 Vans and light trucks MT+LT	1.6	9	24	143
3.2 Large trucks and ISO Containers	6	15	20	429
4. Industrial refrigeration				
4.1 Small direct expansion DX LT	30	18	14	106
4.2 Small direct expansion DX MT	45	18	14	222

4.3 Medium DX LT	120	24	14	33
4.4 Medium DX MT	150	24	14	61
4.5 Large DX LT	450	30	14	8.9
4.6 Large DX MT	600	30	14	15.3
4.7 Medium industrial chillers	100	24	9	30.6
4.8 Large industrial chillers	450	30	9	12.2
4.9 Industrial refrigeration, large flooded LT	3000	30	5	5.3
4.10 Industrial refrigeration, large flooded MT	3000	30	5	3.2
5. Stationary AC and HP				
5.1 Small portable units, cooling only (air--to-air)	0.5	12	2	16500
5.2 Small split systems, cooling only (air-to-air)	0.8	12	6	8400
5.3 Small split systems, heating and cooling (air-to-air)	1.2	12	6	40000
5.4 Medium split systems, cooling only (air-air)	2	12	6	2200
5.5 Medium split systems, heating and cooling (air-air)	2.5	12	6	14000
5.6 Large split systems, cooling only (air-to-air)	5.6	15	6	960
5.7 Large split systems, heating and cooling (air-air)	5.6	15	6	2200
5.8 Packaged systems, cooling only (air-to-air)	20	15	5	67
5.9 Packaged systems, heating and cooling (air-to-air)	20	15	5	109
5.10 VRF, cooling only (air-air)	25	15	6	44
5.11 VRF, heating and cooling (air-air)	25	15	6	320
6. Chillers and hydronic heat pumps				
6.1 Small, cooling only (scroll/screw, air-cooled)	29	18	5	513
6.2 Medium, cooling only (scroll/screw, air-cooled)	150	18	5	103
6.3 Large, cooling only (screw, air-cooled)	360	18	5	11
6.4 Small, cooling only (scroll/screw, water-cooled)	29	18	5	15
6.5 Medium, cooling only (scroll/screw, water-cooled)	150	18	5	13
6.6 Large, cooling only (centrifugal, water-cooled)	750	18	5	10
6.7 Domestic, heat only, air-source. Hydronic	4.4	18	5	2200
6.8 Small, heat only, air-source. Hydronic	29	18	5	55
6.9 Small, reversible heating/cooling, air-source. Hydronic	29	18	5	142
6.10 Medium, reversible	150	18	5	28

heating/cooling, air-source. Hydronic				
7. Mobile air-conditioning				
7.1 Cars, vans, cabs	0.6	9	5	95000
7.2 Busses, trains	14	15	18	2700

Finally, all sectors' refrigerant demand in a specific year was calculated as a sum of the refrigerant required to top up existing refrigerant, Eq. (B.1), and that used in new systems, Eq. (B.2).

Eq. B.1

Eq. B.2

and is the demand for a specific refrigerant for top-up and newly installed units (kg), and is the installed and new RACHP equipment per sector, (units), is the typical charge (kg per unit), is the share of specific refrigerant use in the sector (% of installed units per sector), and is the annual leakage rate per sector (%).

The newly installed RACHP equipment is calculated considering the equipment lifetime and the typical growth rate for a specific sector, Eq. B.3.

Eq. B.3

Finally, the share of specific refrigerant use in the sector, % of installed units per sector, has been adopted from SKM Enviros (2012) for the year 2010, and each consequent year has been modified based on the past and projected future refrigerant adoption by each of 36 analysed sectors. Table B.2 summarises such data for the years 2010, 2021, and 2030.

Table B.2. Installed base and projected new systems using different refrigerants by 2021 and 2023

Sector	Installed base, 2010	New systems, 2010	New systems, 2021	New systems, 2030
1. Domestic refrigeration				
1.1	69% R134a, 23% HC, 8% R12	10% R134a, 90% HC	100% HC	100% HC
1.2	66% R134a, 27% HC, 8% R12	10% R134a, 90% HC	100% HC	100 HC
2. Commercial refrigeration				
2.1	84% R134a, 14% R22, 2% R12, 1% HC, 1% CO_2	93% R134a, 5% HC, 2% CO_2	80% R134a, 20% Nat	50% Nat, 40% HFO, 10% R513A
2.2	84% R134a, 13% R22, 2% R502, 1% HC, 1% CO_2	93% R134a, 5% HC, 2% CO_2	80% R134a, 20% Nat	50% Nat, 40% HFO, 10% R513A
2.3	53% R404A, 34% R134a, 13% HCFC	60% R404A, 40% R134a	15% R134a, 60% R448A/R449A, 15% R513A	30% Nat, 30% HFO, 10% R513A, 30% R455A
2.4	86% R404A, 12% HCFC, 2% other HFC	100% R404A	100% R448A/R449A	45% Nat, 5% HFO, 50% R455A
2.5	77% R404A, 9% R134a, 11% HCFC, 2% other HFC, 1% NH_3	88% R404A, 10% R134a, 2% NH_3	5% R134a, 90% R448A/R449A, 5% R513A	30% Nat, 35% HFO, 35% R455A

2.6	85% R404A, 12% HCFC, 2% other HFC, 1% NH_3	98% R404A, 2% NH_3	90% R448A/R449A, 10% Nat	40% Nat, 10% HFO, 50% R455A
3. Transport refrigeration				
3.1	68% R404A, 32% R134a	100% R404A	60% R404A, 30% R452A, 10% Nat	60% Nat, 40% HFO
3.2	78% R404A, 14% R134a, 6% HCFC, 1% CFC	91% R404A, 9% R134a	5% R134a, 50% R404A, 30% R452A, 10% Nat	60% Nat, 40% HFO
4. Industrial refrigeration				
4.1	83% R404A, 15% HCFC, 3% other HFC	100% R404A	100% R448A/R449A	50% Nat, 50% R455A
4.2	40% R404A, 37% R134a, 20% HCFC, 5% other HFC	50% R404A, 50% R134a	25% R134a, 50% R448A/R449A, 15% R513A, 10% HFO	25% Nat, 40% HFO, 35% R455A
4.3	73% R404A, 21% HCFC, 7% other HFC	100% R404A	90% R448A/R449A, 10% Nat	40% Nat, 60% R455A
4.4	34% R404A, 31% R134a, 26% HCFC, 9% other HFC	50% R404A, 50% R134a	40% R134a, 20% R448A, 25% R449A, 5% R513A, 10% HFO	25% Nat, 55% HFO, 20% R455A
4.5	53% R404A, 24% HCFC, 15% NH_3, 8% other HFC	80% R404A, 20% NH_3	35% R448A, 30% R449A, 5% R513A, 10% HFO, 20% Nat	50% Nat, 15% HFO, 35% R455A
4.6	27% R404A, 22% R134a, 28% HCFC, 15% NH_3, 9% other HFC	45% R404A, 35% R134a, 20% NH_3	20% R134a, 40% R448A/R449A, 5% R513A, 15% HFO, 20% Nat	40% Nat, 40% HFO, 20% R455A
4.7	35% R134a, 22% HCFC, 15% NH_3, 12% R410A, 9% R407C, 8% other HFC	50% R134a, 30% R410A, 20% NH_3	30% R134a, 10% R513A, 30% R410A, 10% HFO, 20% Nat	40% Nat, 50% HFO, 10% R452B
4.8	37% R134a, 25% HCFC, 38% NH_3	60% R134a, 40% NH_3	40% R134a, 5% R513A, 15% HFO, 40% Nat	75% Nat, 25% HFO
4.9	87% NH_3, 13% R22	100% NH_3	100 NH_3	100% Nat
4.10	87% NH_3, 10% R22, 3% R134a	95% NH_3, 5% R134a	5% R134a, 95% NH_3	100% Nat
5. Stationary AC and HP				
5.1	71% R410A, 24% R407C, 4% R22	100% R410A	70% R410A, 20% R32, 10% Nat	20% Nat, 55% R32, 25% R452B
5.2	24% R410A, 37% R407C, 39% R22	70% R410A, 30% R407C	70% R410A, 25% R32, 5% R407C	20% Nat, 55% R32, 25% R452B
5.3	44% R410A, 35% R407C, 21% R22	70% R410A, 30% R407C	70% R410A, 25% R32, 5% R407C	10% Nat, 50% R32, 40% R452B
5.4	21% R410A, 39% R407C, 40% R22	60% R410A, 40% R407C	75% R410A, 20% R32, 5% R407C	5% Nat, 50% R32, 45% R452B
5.5	39% R410A, 41% R407C, 20% R22	60% R410A, 40% R407C	75% R410A, 20% R32, 5% R407C	5% Nat, 50% R32, 45% R452B
5.6	26% R410A, 42% R407C, 33% R22	60% R410A, 40% R407C	95% R410A, 5% R407C	5% Nat, 30% R32, 65% R452B
5.7	26% R410A, 37% R407C, 37% R22	60% R410A, 40% R407C	95% R410A, 5% R407C	5% Nat, 30% R32, 65% R452B
5.8	19% R410A, 33%	60% R410A,	95% R410A, 5% R407C	5% Nat, 30%

	R407C, 47% R22	40% R407C		R32, 65% R452B
5.9	19% R410A, 29% R407C, 51% R22	60% R410A, 40% R407C	95% R410A, 5% R407C	5% Nat, 30% R32, 65% R452B
5.10	43% R410A, 44% R407C, 14% R22	60% R410A, 40 R407C	95% R410A, 5% R407C	5% Nat, 30% R32, 65% R452B
5.11	42% R410A, 41% R407C, 17% R22	60% R410A, 40% R407C	95% R410A, 5% R407C	5% Nat, 30% R32, 65% R452B
6. Chillers and hydronic heat pumps				
6.1	14% R410A, 37% R407C, 25% R134a, 20% HCFC, 4% other HFC	40% R410A, 30% R407C, 30% R134a	15% R134a, 60% R410A, 5% R407C, 5% R32, 5% R513A, 10% HFO	35% HFO, 40% R32, 25% R452B
6.2	14% R410A, 14% R407C, 47% R134a, 22% HCFC, 4% other HFC	60% R134a, 40% R410A	45% R134a, 40% R410A, 5% R513A, 10% HFO	5% Nat, 60% HFO, 20% R32, 15% R452B
6.3	14% R410A, 5% R407C, 62% R134a, 17% HCFC, 3% other HFC	70% R134a, 30% R410A	55% R134a, 30% R410A, 5% R513A, 10% HFO	5% Nat, 70% HFO, 5% R32, 20% R452B
6.4	15% R410A, 39% R407C, 26% R134a, 17% HCFC, 3% other HFC	40% R410A, 30% R407C, 30% R134a	15% R134a, 60% R410A, 5% R407C, 5% R513A, 5% R32, 10% HFO	35% HFO, 40% R32, 25% R452B
6.5	15% R410A, 15% R407C, 49% R134a, 18% HCFC, 4% other HFC	60% R134a, 40% R410A	35% R134a, 40% R410A, 10% HFO, 15% R513A	5% Nat, 55% HFO, 15% R32, 25% R452B
6.6	95% R134a, 4% HCFC, 2% other HFC	100% R134a	85% R134a, 10% HFO, 5% R513A	90% HFO, 5% R32, 5% R452B
6.7	21% R410A, 45% R407C, 33% R134a, 1% HCFC	40% R410A, 30% R407C, 30% R134a	R134a, 5% R407C, 60% R410A, 10% HFO, 5% R32, 5% R513A	35% HFO, 40% R32, 25% R452B
6.8	20% R410A, 18% R407C, 60% R134a, 1% HCFC	40% R410A, 60% R134a	45% R134a, 40% R410A, 10% HFO, 5% R513A	5% Nat, 55% HFO, 15% R32, 25% R452B
6.9	17% R410A, 42% R407C, 29% R134a, 12% HCFC	40% R410A, 30% R407C, 30% R134a	15% R134a, 5% R407C, 60% R410A, 10% HFO, 5% R32, 5% R513A	35% HFO, 40% R32, 25% R452B
6.10	17% R410A, 17% R407C, 54% R134a, 12% HCFC	60% R134a, 40% R410A	45% R134a, 20% R410A, 10% HFO, 20% R513A	5% Nat, 55% HFO, 15% R32, 25% R452B
7. Mobile air-conditioning				
7.1	100% R134a	100% R134a	100% HFO	5% Nat, 95% HFO
7.2	69% R134a, 6% R410A, 3% R407C, 21% HCFC	80% R134a, 20% R410A	50% R134a, 20% R410A, 10% HFO, 20% R513A	20% Nat, 55% HFO, 25% R32

Mixtures mentioned in the table must be taken only as an example of properties and GWP value. Therefore, for instance, the transition considered for R513A is valid for R450A and other similar replacements.