Potential Impacts of the Montreal Protocol Kigali Amendment to the Choice of Refrigerant Alternatives

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Abstract

The paper first gives a description of the " Kigali Amendment" established HFC phase-down as decided by the Montreal Protocol parties in Kigali, Rwanda, October 2016. Baselines, freeze dates, schedules for the reductions of HFC consumption for both developing and developed country groups, as well as the 17 HFCs that are now included in the Montreal Protocol are summarized. The list of alternatives for HCFC-22 including high-GWP HFC replacements is given, and considerations regarding the choice of refrigerant, both low-GWP synthetic and "natural" refrigerant alternatives are presented. The low-GWP refrigerant flammability issue and the performance of equipment at high ambient regions are described. It is discussed whether the potential impacts of the Kigali Amendment will be reinforcing the momentum of applications using low-GWP refrigerants and the innovation for sustainable RACHP technologies

Keywords: *Montreal Protocol, HFCs, Kigali Amendment, HFC regulations, low-GWP refrigerants, natural refrigerants, refrigerant alternatives*

1. INTRODUCTION

Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs) and other ozone depleting substances (ODS) are potent greenhouse gases (GHG). The phase-out of these chemicals as mandated by the Montreal Protocol, and consequent resulting reductions of emissions and atmospheric concentrations have had an enormous contribution to climate protection, next to the original intent of the Montreal Protocol to protect the ozone layer. It has been estimated that the total avoided net annual ODS emissions would be equivalent to about 10 Gt $CO_{2\text{-eq}}$ in 2010, which is about five times the annual reduction target of the Kyoto Protocol for the period 2008–2012 (*Velders et al., 2007*).

According to studies and assessments (Velders et al, 2012, 2014) the climate benefit of the Montreal Protocol could be reduced or totally lost in the future if emissions of ODS substitutes with high global warming potentials (GWP), such as some HFCs, continue to increase. Based on these research results, Parties to the Montreal Protocol started discussions (based on proposals) on an amendment to add HFCs and control schedules to the Montreal Protocol in 2009.

Hydrofluorocarbons (HFCs) were largely developed and promoted as alternatives to ODS and have been used in the last 30 years in several sectors, mainly as refrigerant in refrigeration, air conditioning and heat pumps (RACHP) applications.

HFCs are greenhouse gases that can have high or very high-GWP, up to 14,800. (UNEP, 2016)

The main issues that were thought to favor the inclusion of HFCs as controlled substances under the Montreal Protocol presented by the countries proposing amendments were: HFCs were developed and promoted as a result of Montreal Protocol CFC and HCFC control measures; the framework built by the Montreal Protocol for the phase out of CFCs and HCFCs in the sectors where HFCs are being used, would be the most appropriate and effective method for the control of HFC production and consumption. On the other hand, the countries that initially were not in favor of such an amendment used arguments such as HFCs are not ODS and that would be the reason why they could not be included in an international agreement established for controlling ODS use. In the discussions that took place over the years, other issues were presented as barriers for including HFCs under the Montreal Protocol, such as financial support for the developing countries, the commercial availability of HFC alternatives, technology transfer and many others.

After 9 years of intense discussions, the parties to the Montreal Protocol overcame the main obstacles for reaching a consensus decision[1], and in the 28th Meeting of the Parties on 15 October 2016 in Kigali, Rwanda, the parties decided on the addition of 17 HFCs to the Protocol (in a Group I). They are given with Global Warming Potentials using the IPCC AR4 report values (IPCC, 2007), in a new Annex F. The annex also presents the GWP of CFCs and HCFCs. It also includes HFC-23 (in a Group II), a chemical which mainly originates as a by-product in HCFC-22 production facilities. Table 1 presents the information contained in the Annex F.

Table 1. Annex F to the Montreal Protocol (UNEP, 2017)

HFCs (Group I)		**HCFCs**	
Substance	**GWP value (100 year)**	**Substance**	**GWP value (100 year)**
HFC-134	1100	HCFC-21	151
HFC-134a	1430	HCFC-22	1810
HFC-143	353	HCFC-123	77
HFC-245fa	1030	HCFC-124	609
HFC-365mfc	794	HCFC-141b	725
HFC-227ea	3220	HCFC-142b	2310
HFC-236cb	1340	HCFC-225ca	122
HFC-236ea	1370	HCFC-225cb	595
HFC-236fa	9810		
HFC-245ca	693	**CFCs**	
HFC-43-10mee	1640	**Substance**	**GWP value**
HFC-32	675	CFC-11	4750
HFC-125	3500	CFC-12	10 900
HFC-143a	4470	CFC-113	6130
HFC-41	92	CFC-114	10 000
HFC-152	53	CFC-115	7370
HFC-152a	124		
HFCs (Group II)			
HFC-23	14 800		

[1] *The Montreal Protocol decisions, as in other international agreements, are made based on a consensual manner not having vote and decision take by the majority*

HFCs therefore became controlled substances under the Montreal Protocol, with specific HFC control schedules adopted for developing and developed countries (parties).

Developed (n-A5) countries will start to phase down HFCs by 2019. Developing countries (A5) will follow with a freeze of HFC consumption levels in 2024, with some countries freezing consumption in 2028.

The Kigali Amendment will enter into force on 1 January 2019, provided that it has been ratified by at least 20 Parties to the Montreal Protocol (or 90 days after ratification by the 20th Party, whichever is later).

2. OVERVIEW OF THE KIGALI AMENDMENT

The GWP values in the new Annex F must be used for the conversion of HFC mass quantities in in carbon dioxide equivalent ($CO_{2\text{-eq}}$) in all the reports countries need to present related to HFC phase-down implementation.

Including HFCs under the Montreal Protocol as controlled substances, will not affect the obligations the countries have under the United Nations Framework Convention on Climate Change (UNFCCC). The amendment will not have the effect to exempt Parties of their commitments to send to UNFCC HFC emissions inventory reports (as established in Articles 4 and 12 of the UNFCCC), regarding. HFC consumption and production will be controlled under the Montreal Protocol while HFC emissions will continue to be reported under the UNFCCC.

The Kigali amendment has different years for HFC consumption used in the baseline and various phase-down schedules, i.e., two for two groups of Article 5 Parties (developing countries) and two for two groups of non-Article 5 Parties (developed countries). The tables and figures presented below show the baseline (freeze) and phase-down schedules.

The reason for including both HFCs and a percentage of HCFCs in the baseline calculation is due to the fact that HFCs are thought to be utilized as alternatives for a certain portion of HCFCs still to be phased out. The HCFC component in the calculation is assumed to take this portion into account in the baseline.

In the reporting under the Montreal Protocol, the information about production, consumption, imports, exports and emissions of HFCs shall be expressed in $CO_{2\text{-eq}}$ and not in HFC mass quantities.

	N-A5 Parties: Group 1		N-A5 Parties: Group 2	
Baseline Years	2011, 2012 & 2013		2011, 2012 & 2013	
Baseline Calculation	Average consumption of HFCs in 2011, 2012, and 2013 Plus 15% of 1989 HCFC baseline consumption		Average consumption of HFCs in 2011, 2012, and 2013 Plus 25% of 1989 HCFC baseline consumption	
Reduction steps				
Step 1	2019	10%	2019	5%
Step 2	2024	40%	2024	35%
Step 3	2029	70%	2029	70%
Step 4	2034	80%	2034	80%
Step 5	2036	85%	2036	85%

(a)

	Article 5 Parties Group 1		Article 5 Parties Group 2	
Baseline Years	2020, 2021 & 2022		2024, 2025 & 2026	
Baseline Calculation	Average production/consumption of HFCs in 2020, 2021, and 2022 plus 65% of HCFC baseline production/consumption		Average production/consumption of HFCs in 2024, 2025, and 2026 plus 65% of HCFC baseline production/consumption	
Freeze	2024		2028	
Reduction steps				
Step 1	2029	10%	2032	10%
Step 2	2035	30%	2037	20%
Step 3	2040	50%	2042	30%
Step 4	2045	80%	2047	85%

(b)

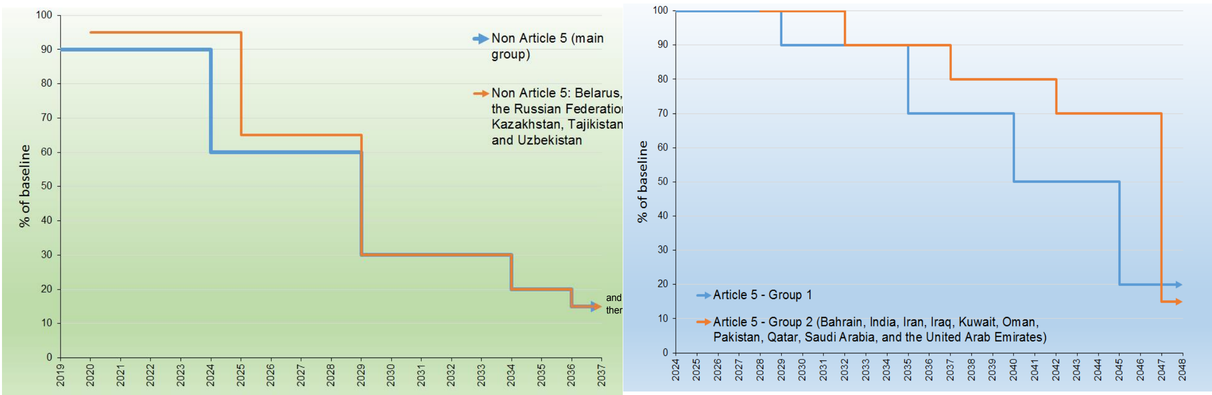

Figure 1. Kigali Amendment baseline calculation and phase-down schedules for N-A5 Parties (a) and A5 Parties (b) (UNEP, 2016)

2.1 Exemption for high ambient temperature countries

During the preparatory amendment discussions that took place during the last years, one of the issues that Parties had to deal with was the one presented by the countries experiencing high ambient temperatures (HAT). In these regions, due to high ambient temperature, the refrigerant condensing temperature in RACHP equipment is relatively high during part of the year and approaches the refrigerant critical temperature. For an air cooled system, the closer the critical temperature of the refrigerant is to the ambient temperature, the less efficient is the cycle with lower capacity, thus increasing energy consumption, as showed in figure 2 (Peixoto et al, 2016).

Operation of a RACHP system at high ambient temperatures intrinsically results in a lower coefficient of performance. This is the case for all refrigerants but the COP reduction is different among the various refrigerants (Motta and Domanski, 2000). Over the years, countries experiencing HAT conditions expressed their concerns and worries of meeting an HFC freeze (date and level of consumption) as well as reduction targets. This is where low-GWP alternatives to HCFC-22 in small/medium size air-conditioning applications are not yet introduced and verified by local markets. Some of these countries have already started to apply new minimum energy performance requirements.

In the discussion of the HFC amendment proposals, these issues were addressed. The solution agreed on was found in a different phase-down schedule for the countries experiencing high ambient temperatures, specifically India, Iran, Pakistan and the Gulf States. This exemption allows for a delay in the HFC freeze date and following phase-down obligations by a period of four years. It applies for the following equipment:

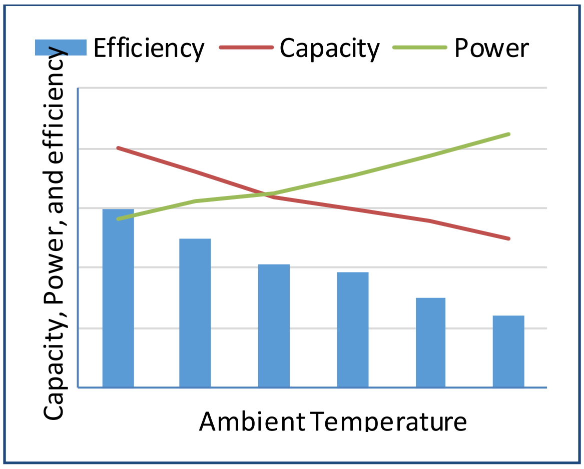

Figure 2 Impact of ambient temperature in the performance of RAC equipment

- Multi-split air conditioners (commercial and residential);
- Split ducted air conditioners (residential and commercial);
- Ducted commercial packaged (self- contained) air conditioners.

It is important to mention that considerations for equipment that will be operated at high ambient temperature conditions must not only be based on the choice of refrigerant but also on overall system design applied to obtain optimum and reliable performance under HAT conditions.

3. POTENTIAL IMPACT TO REFRIGERANT CHOICE

The Kigali amendment has reinforced the momentum towards applications using low-GWP refrigerants and accelerates innovation for sustainable RACHP technologies. One of the key issues for the Kigali amendment implementation is the replacement of HCFC-22 and high-GWP HFCs with low-GWP refrigerants

Considering the R-410A and HCFC-22 replacement, the list of alternatives includes single-component or pure refrigerants, such as HFC-32, HC-290, HC-1270, R-717, R-744, and new blended refrigerants. These blends include the so-called hydrofluoroolefins (HFOs), unsaturated HFCs, such as HFO-1234yf and HFO-1234ze(E), along with traditional (saturated) HFC refrigerants to achieve the desired attributes of the blend, e.g., low-GWP, lower flammability, or lubricant compatibility. (UNEP, XXVII-4). Table 2 presents an overview of past, current and possible future refrigerant for the different RACHP applications.

In the last 3 years about 80 fluids, most of them blends containing HFOs, have been proposed for testing or are being tested in industry programmes, are pending publication, or have been published in ISO 817 and ASHRAE 34 refrigerant standards since the 2014 RTOC Assessment Report. The majority of these fluids are new mixtures (UNEP, 2016).

Table 2 Overview of refrigerant use and alternatives to HCFCs and high-GWP HFCs

Sector	CFCs	HCFCs	HFCs Pure & Blends	HCs	CO2 Ammonia	Unsaturated HFCs (HFOs) Pure	Blends with Unsaturated HFCs (HFOs)
Domestic Refrigeration	CFC-12		HFC-134a	HC-600a	Ammonia	HFC-1234yf	R-450A, R-513A,…
Commercial Refrigeration (SA, CU, CS)	CFC-12 R-502	HCFC-22	HFC-134a R-404A R-407A R-407F	HC-600a HC-290	CO2 Ammonia	HFC-1234yf HFC-1234ze(E)	R-450A, R-448A, R-444B, R-442A, R-455A, R-450A, R-513A, R-448A, R-449B,…
Transport Refrigeration		HCFC-22	HFC-134a R-410A R-407C	HC-290 HC-1270	CO2	HFC-1234yf	R-450A, R-448A, R-444B, R-455A, R-446A, R-447A, R-447B, R-448A, R-449A R-450A, R-513A,…
Industrial refrigeration		HCFC-22	HCFC-22 HCFC-123	HC-1270 HC-290	Ammonia CO2	HFC-1234yf	R-450A, "L-40", R-444B, R-455A, R-446A, R-447A, R-447B,R-450A, "XP-10", R-448A, R-449A,…
Water heating heat pumps		HCFC-22	HCFO-1233zd(E)	HC-290 HC-600a	CO2 Ammonia	HFC-1234yf HFC-1234ze(E)	R-450A, "L-40", R-444B, R-455A, R-446A, R-447A, R-447B, R-450A, R-513A, R-448A, R-449A,…
Air Conditioners	CFC-12	HCFC-22	HFC-134a HFC-32 R-410A R-407C	HC-290	CO2	HFC-1234yf	R-450A, "L-40", R-444B, R-455A, R-446A, R-447A, R-447B, R-450A, R-513A, R-448A, R-449A,…
Chillers	CFC-12 CFC-11	HCFC-22 HCFC-123 HCFO-1233zd(E)	HFC-134a R-404A R-410A R-407C	HC-290 HC-1270	Ammonia CO2	HFC-1234yf HFC-1234ze(E) HFO-1336mzz(Z)	R-450A, "L-40", R-444B, R-455A, R-446A, R-447A, R-447B, R-450A, R-513A, R-448A, R-449A,…
Mobile Air Conditioner	CFC-12		HFC-134a R-410A R-407C		CO2	HFC-1234yf	R-450A, R-513A

Historical use (pink)
Current use on a commercial-scale (cyan)
Potentially feasible or limited use, and for demonstration, trials, niche applications, etc (yellow)

(source: UNEP, 2015a,b)

Considering the probability of the development of new molecules (pure refrigerants), it is important to mention that significant efforts have been done in the past to find new fluids. A recent study (McLinden, et al. 2015) started with a database of over 150 million chemicals, screening more than 56,000 small molecules and finding none of them ideal. It can be concluded from the study that the prospects of discovering new chemicals that would offer better performance than the fluids currently known are minimal (UNEP, 2017).

Considering specific RACHP applications, the following aspects can be mentioned. HFC-32 is an alternative for use in a certain range of middle size air conditioners, and there is an opportunity for a much wider application of hydrocarbons as well as in larger capacity commercial refrigeration equipment. The issue of hydrocarbon flammability (A3 refrigerant) is very important and it will need to be addressed via a revision of standards. This now is an ongoing discussion inside the international standards technical committees. Once this flammability issue will have been adequately addressed in standards, it may lead to the acceptance of larger quantities in equipment than possible at present. There is a recent European Commission report (EC, 2016) on barriers posed by codes, standards and legislation to using climate-friendly technologies in the refrigeration, air conditioning, heat pumps and foam sectors.

In case of mobile air conditioning systems (MACs), a certain percentage portion may use R-744 (carbon dioxide), however, the majority is expected to use HFO-1234yf. For chillers, two pure HFOs, HFO-1234ze and HFO-1233zd, already commercialized, are now applied in larger chiller equipment.

Natural refrigerants such as R-744 are increasingly being used in supermarket systems worldwide – both in cascaded systems (R-744 for low temperature cascaded with a second refrigerant such as HFC-134a or similar and R-717 in limited cases) and in transcritical systems. Transcritical systems are being researched extensively to reduce their energy penalty at high ambient conditions through the use of component and system technologies such as ejector, adiabatic condensing, sub-cooling and parallel compression (UNEP, 2014). In lower ambient temperatures transcritical systems offer advantages associated with heat recovery and reuse in an adjacent heating/ hot water scheme. There are already some supermarket refrigeration systems installed in the field using these technologies.

The refrigerant selections that can be expected in the near future will be very much related to the perceived longer term "certainty" of low-GWP refrigerants, where the commercial availability, costs, energy efficiency, safety and servicing aspects will all be important. At present the choice is likely to be between the natural fluids (ammonia, CO_2, hydrocarbons) in equipment developed for their use and more expensive synthetic fluids (HFO, HCFO, HFC/HFO blends) in the types of equipment as used for HCFCs and HFCs. Considering the HFC/HFO blends the question is whether they will be restricted to equipment where no major redesign is being planned, or will also be applied in newly re-engineered designs. It is likely that there can and will only be a very limited amount of HFC-HFO blends in future (Kuijpers, 2017).

It is important to emphasize that the refrigeration, air conditioning and heat pump industry and refrigerant servicing sector cannot be assumed to cope with the large number of HFC/HFO blends. Tables 3 and 4 present an overview of the present status of refrigerant alternatives being applied and proposed to HCFC and high-GWP replacements.

Table 3 Pure substances proposed to HCFCs and high-GWP HFCs replacement

Refrigerant Designation	Proposed to replace	Safety Class	Chemical Formula	Molecular Weight	Boiling Point (°C)	ATEL/ ODL (kg/m³)	LFL (kg/m³)	GWP
HFC-32	R-404A, R-410A*	A2L	CH_2F_2	52,0	−52	0,30	0,307	675
HC-290	HCFC-22, R-404A, R-407C	A3	$CH_3CH_2CH_3$	44,1	−42	0,09	0,038	
HC-600a	HFC-134a	A3	$CH(CH_3)_2$-CH_3	58,1	−12	0,059	0,043	
R-717	HCFC-22, R-407C	B2L	NH_3	17,0	−33	0,000 22	0,116	
R-744	R-404A, R-410A	A1	CO_2	44,0	−78◊	0,072	NF	1
HCFO-1233zd(E)	HCFC-123	A1	CF_3CH=CHCl	130,5	18,1	0	NF	1
HFO-1234yf	HFC-134a	A2L	$CF_3CF=CH_2$	114,0	−29,4	0,47	0,289	<1
HFO-1234ze(E)	HFC-134a	A2L	CF_3CH=CHF	114,0	−19,0	0,28	0,303	<1
HC-1270	HCFC-22, R-407C	A3	$CH_3CH=CH_2$	42,1	−48	0,001 7	0,046	
HFO-1336mzz (Z)	HCFC-123	A1	$CF_3CH=CH$-CF_3	164,1	33,4	0	NF	2
HCC-1130(E)	HCFC-123	B2	CHCl=CHCl	96,9	47,7			<1

(source: UNEP, 2017)

Table 4 Blend refrigerants proposed to HCFCs and high-GWP HFCs replacement

Refrigerant Designation	Refrigerant development name	Proposed to replace	Safety Class	Composition (%)	Bubble point/ dew or Normal boiling point (°C)	GWP
	XP30	HCFC-123	B1	R-1336mzz(Z)/1130(E) (74,7/25,3)		1,7
—	ARM-41a	HFC-134a	A1	R-134a/1234yf/32 (63/31/6)		860
R-513A	XP10	HFC-134a	A1	R-1234yf/134a (56/44)	−29,2	570
—	N-13a	HFC-134a	A1	R134a/1234ze(E)/1234yf (42/40/18)		550
R-450A	N-13b	HFC-134a	A1	R-1234ze(E)/134a (58/42)	−23,4/−22,8	550
R-515A	HDR-115	HFC-134a	A1	R-1234ze(E)/227ea (88/12)	-19,2	400
R-513B		HFC-134a	A1	R-1234yf/134a (58,5/41,5)	−29,9	540
—	D-4Y	HFC-134a	A1	R-1234yf/134a (60/40)		520
—	AC5X	HFC-134a	A1	R-1234ze(E)/134a/32 (53/40/7)		570
—	ARM-42a	HFC-134a	A2L	R-1234yf/152a/134a (82/11/7)		110
R-444A	AC5	HFC-134a	A2L	R-1234ze(E)/32/152a (83/12/5)	−34,3/−24,3	89
R-445A	AC6	HFC-134a	A2L	R-744/134a/1234ze(E) (6/9/85)	−50,3/−23,5	120
—	R290/R600a	HFC-134a	A3	R-600a/290 (60/40)		
R-456A		HFC-134a	A1	R-32/134a/1234ze(E) (6/45/49)	-31,1/ -25,7	630
R-407G		HFC-134a	A1	R-32/125/134a (2,5/2,5/95,0)	-29,1/ -27,2	1300
—	LTR4X	HCFC-22, R-407C	A1	R-1234ze(E)/32/125/134a (31/28/25/16)		1200
R-514A	XP30	HCFC-123	B1	R-1336mzz(Z)/1130(E) (74,7/25,3)	29,0/29,0	2
—	N-20	HCFC-22, R-407C	A1	R134a/1234ze(E)/1234yf/ 32/125 (31,5/30/13,5/12,5/12,5)		890
—	D52Y	HCFC-22, R-407C	A2L	R-1234yf/125/32 (60/25/15)		890
—	L-20	HCFC-22, R-407C	A2L	R-32/1234ze(E)/152a (45/35/20)		330
—	LTR6A	HCFC-22, R-407C	A2L	R-1234ze(E)/32/744 (63/30/7)		200
R-444B	L-20a	HCFC-22, R-407C	A2L	R-32/1234ze(E)/152a (41,5/48,5/10)	−44,6/−34,9	300
—	ARM-32a	HCFC-22, R-404A, R-407C	A1	R-125/32/134a/1234yf (30/25/25/20)		1400
R-442A		HCFC-22, R-404A, R-407C	A1	R32/125/134a/152a/227ea (31,0/31,0/30,0/3,0/5,0)	−46,5/ −39,9	1800
R-449B		HCFC-22, R-404A, R-407C	A1	R-32/125/1234yf/134a (25,2/24,3/23,2/27,3)	−46,1/−40,2	1300
R-449C	DR-93	HCFC-22, R-407C	A1	R-32/125/1234yf/134a (20/20/31/29)	−45,5/−38,5	1100
R-453A	RS-70	HCFC-22, R-407C	A1	R-32/125/134a/227ea/600/ 601a (20,0/20,0/53,8/5,0/0,6/0,6)	-42,2/ -35,0	1600
R-407H		HCFC-22, R-407C	A1	R-32/125/134a (32,5/15,0/52,5)	-44,6/ -37,6	1400

Table 4 (cont) Blend refrigerants proposed to HCFCs and high-GWP HFCs replacement

Refrigerant Designation	Refrigerant development name	Proposed to replace	Safety Class	Composition (%)	Bubble point/ dew or Normal boiling point (°C)	GWP
R-458A	TdX 20	HCFC-22, R-404A R-507A	A1	R32/125/134a/227ea/236fa (20,5/4,0/61,4/13,5/0,6)	-39,8/ -32,4	1600
R-460A		HCFC-22, R-404A	A1	R-32/125/134a/1234ze(E) (12,0/52,0/14,0/22,0)	-44,6/-37,2	2100
R-460B	LTR4X	HCFC-22, R-404A	A1	R-32/125/134a/1234ze(E) (28,0/25,0/20,0/27,0)	-45,2/-37,1	1300
R-449A	DR-33 (XP40)	R-404A	A1	R-32/125/1234yf/134a (24,3/24,7/25,3/25,7)	–46,0/–39,9	1300
—	N-40a	R-404A	A1	R-32/125/134a/1234ze(E)/ 1234yf (25/25/21/20/9)		1200
—	N-40b	R-404A	A1	R-1234yf/32/125/134a (30/25/25/20)		1200
R-452A	DR-34 (XP44)	R-404A	A1	R-1234yf/32/125 (30/11/59)	–47,0/–43,2	1900
R-452C	ARM-35	R-404A	A1	R-32/125/1234yf (12,5/61,0/26,5)	-47,8/ -44,4	2000
R-448A	N-40c	R-404A	A1	R-32/125/1234yf/134a/ 1234ze(E) (26,0/26,0/20,0/21,0/7,0)	–45,9/–39,8	1300
—	R32/R134a	R-404A	A2L	R-32/134a (50/50)		990
—	ARM-31a	R-404A	A2L	R-1234yf/32/134a (51/28/21)		460
—	L-40	R-404A	A2L	R-32/1234ze(E)/1234yf/ 152a (40/30/20/10)		290
R-454A	DR-7◊	R-404A	A2L	R-1234yf/32 (65/35)	–48,4/–41,6	240
R-454C	DR-3	R-404A	A2L	R-1234yf/32 (78,5/21,5)	–45,8/–38,0	150
R-454A	D2Y-65	R-404A	A2L	R-1234yf/32 (65/35)	–48,4/–41,6	240
R-457A	ARM-20a	R-404A	A2L	R-32/1234yf/152a (18/70/12)		140
—	ARM-30a	R-404A	A2L	R-1234yf/32 (71/29)		200
R-455A	HDR-110	R-404A	A2L	R-32/1234yf/744 (21,5/75,5/3)	-51,6/ -39,1	150
—	R32/R134a	R-410A	A2L	R-32/134a (95/5)		710
—	R32/R152a	R-410A	A2L	R-32/152a (95/5)		650
—	DR-5	R-410A	A2L	R-32/1234yf (72,5/27,5)		490
—	L-41a	R-410A	A2L	R-32/1234yf/1234ze(E) (73/15/12)		490
—	L-41b	R-410A	A2L	R-32/1234ze(E) (73/27)		490
—	ARM-70a	R-410A	A2L	R-32/1234yf/134a (50/40/10)		470
—	HPR1D	R-410A	A2L	R-32/1234ze(E)/744 (60/34/6)		410
—	D2Y-60	R-410A	A2L	R-1234yf/32 (60/40)		270
R-454B	DR-5A	R-410A	A2L	R-32/1234yf (68,9/31,1)	–50,9/–50,0	470
R-452B	DR-55 (XL55)	R-410A	A2L	R-32/1234yf/125 (67/26/7)	-50,9/-50,0	680
R-446A	L-41-1	R-410A	A2L	R-32/1234ze(E)/600 (68,0/29,0/3,0)	–49,4/–44,0	460
R-447A	L-41-2	R-410A	A2L	R-32/125/1234ze(E) (68,0/3,5/28,5)	–49,3/–44,2	570
R-447B	L-41z	R-410A	A2L	R-32/125/1234ze(E) (68,0/8,0/24,0)	–50,3/–46,2	710

(source: UNEP, 2017)

4. CONCLUDING REMARKS

The adoption of the Kigali Amendment has reinforced the momentum towards applications using low-GWP refrigerants and is expected to accelerate innovation for sustainable RACHP technologies. Some HFC-free technologies face barriers to widespread uptake due to restrictive technical standards, in particular for flammable refrigerants. In order to enable transitions to flammable low-GWP refrigerants, a revision of the standard charge limits currently used is on the way.

The low GWP argument only cannot be expected to be the determining factor whether certain fluids will be considered. Energy efficiency, or rather, energy consumption reduction will be important. This is not only related to refrigerant thermo-physical properties, it is also determined by equipment design, system configuration, component efficiencies, operating conditions, system capacity, and system hardware.

The choice for refrigerants is very likely to be a combination of energy efficiency, costs, and environmental performance including safety aspects associated with refrigerant toxicity and flammability. Regional and national regulations (e.g. flammability and charge) will drive many developments that will take place.

The use of pure refrigerants, i.e., HFOs and non-synthetic “natural” refrigerants, including hydrocarbons, can reasonably be assumed to expand widely after 2019-2020, and this in a substantial amount of applications in various RACHP subsectors. It can already now be observed that there is a remarkably high level of activity in the RACHP equipment development sector, which is also evidence to the commitment of companies engaged in this research and development to finding useful long term solutions in a market of ever-changing goals and objectives. As a result, the emphasis on equipment with improved energy efficiency (i.e., lower energy consumption levels) and refrigerants with a low-GWP is much more significant than before.

Both types of refrigerants, natural and synthetic, can and will co-exist in a near future, and can be complementary.

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Nomenclature

A5	Countries operating under Article 5 of the Montreal Protocol (i.e. developing countries)
AR	Assessment report
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATEL	Acute Toxicity Exposure Limit
CFC	Chlorofluorocarbon
GHG	Greenhouse gas
GWP	Global Warming Potential
HAT	High ambient temperature
HC	Hydrocarbons
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbons
HFO	Hydrofluoroolefin (Unsaturated HFC)
HPMP	HCFC Phase-out Management Plan
IPCC	International Panel on Climate Change
ISO	International Organization for Standardization
LFL	Lower flammability level
MAC	Mobile air conditioning
MLF	Montreal Protocol Multilateral Fund
n- A5	Countries not operating under Article 5 of the Montreal Protocol (i.e. developed countries)
ODL	Oxygen Deprivation Limit
ODP	Ozone Depleting Potential
ODS	Ozone Depleting Substances
RACHP	Refrigeration, air Conditioning and heat pump
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Climate Change Convetion
RTOC	Refrigeration, Air Conditioning, Heat Pump Technical Options Committee