Excellence In Design
For Greater Efficiencies

EDGE Guidance Document for

Refrigerant Selection to Reduce Climate Impact

based on the Montreal Protocol

VERSION 1

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Refrigerants and Materials Selection to Reduce Climate Impact
EDGE Guidance Document for the Building Sector
based on the Montreal Protocol
Version 1

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ABOUT

This document is published on the EDGE website as a white paper to help raise awareness about the climate impact of substances controlled by the Montreal Protocol. The white paper has been prepared by Smita Chandra Thomas and M. Esteban Muñoz H. for the EDGE program of the International Finance Corporation of the World Bank Group. The report has been reviewed by Samira Elkhamlichi, Senior Energy Specialist at the World Bank, and Laurent Granier, Senior Environmental Specialist at the World Bank, with a final review by Ommid Saberi, Senior Industry Specialist at the International Finance Corporation.

Disclaimer

This information is provided for information purposes only. The information is current at the time of writing this white paper. The recommendations contained here may change as new materials become available or the scientific understanding of the impact of materials evolves.

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List of Abbreviations

This is a ready reference of the abbreviations used in the document, presented in alphabetical order. The abbreviations are also explained in the document where they first appear.

ASHRAE	American Society of Heating, Refrigerating, and Air-conditioning Engineers
ATM	automated teller machines
BAU	business-as-usual
BREEAM	Building Research Establishment Environmental Assessment Methodology
CEIT	countries with economies in transition
CFC	chlorofluorocarbon
C3H8	propane
CH4	methane
CO2	carbon dioxide
CO2e	carbon dioxide equivalent
DGNB	German Sustainable Building Council
EDGE	Excellence in Design for Greater Efficiencies
EIA	Environmental Investigation Agency
EPA	Environmental Protection Agency
EU	European Union
GHG	greenhouse gas
GWP	global warming potential
H2O	water
HC	hydrocarbon
HBFC	hydrobromofluorocarbon
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HFOs	hydrofluoroolefin
HP	heat pump
HVAC	heating, ventilating, and air- conditioning
HVAC&R	heating, ventilating, air-conditioning, and refrigeration
IPCC	Intergovernmental Panel on Climate Change
kg	kilograms
kg/m3	kilograms per cubic meter

kj/kg	kilojoules per kilogram
kW	kilowatts
LEED	Leadership in Energy and Environmental Design
MLF	Multilateral Fund
MVAC	motor vehicle air conditioning
NH3	ammonia
NIK	not-in-kind
NOO	National Ozone Office
O3	ozone
ODP	ozone-depleting potential
ODS	ozone-depleting substance
PU	polyurethane
ppb	parts per billion
ppm	parts per million
RACHP	refrigeration, air conditioning, and heat pumps
SNAP	Significant New Alternatives Policy
TFA	trifluoroacetic acid
UN	United Nations
UNEP	United Nations Environment Programme
UPC	Urban Planning Council
UV	ultraviolet
VOC	volatile organic compounds
VRF	variable refrigerant flow
WMO	World Meteorological Organization
XPS	extruded polystyrene

Executive Summary

This paper provides comprehensive information on the opportunities to maximize the eco-elegance of buildings through the use of environmentally responsible substances in cooling equipment, foams, fire protection systems, aerosols and solvents. It is based on the international discussions and provisions of the Montreal Protocol that controls Ozone Depleting Substances (ODS). The paper also intends to support and guide users of the EDGE (Excellence in Design for Greater Efficiencies) green buildings platform on possible ways of integrating aspects related to eco-friendly refrigerants with other sustainability aspects considered under the EDGE tool such as energy efficiency. It is recommended that all potential EDGE-certified buildings follow the requirements set in this document as best practice.

This paper is part of a series of guidance documents prepared for the EDGE program and made available online for the users of the EDGE platform and any other party interested in the subject.

Buildings systems and materials may contain substances with significant negative impact on the environment

Substances contained in cooling equipment, foams, fire protection systems, aerosols, and solvents used in building systems may have negative impact on the environment, specifically by (1) destroying atmospheric ozone gas, which is critical to human and other forms of life, and (2) contributing to global warming. This is why **all countries have agreed to regulate** the production and use of these substances in an agreement referred to as the Montreal Protocol (described in Section I.0). As the use of cooling systems and modern materials increases in buildings in developing economies, it is imperative that care be taken in choosing which systems and materials to use, and how to minimize negative impacts on environment. Due to the long lifetime of buildings and related equipment and materials, it is critical to integrate these aspects with other sustainability aspects in interventions under EDGE program.

Substances with high global Warming Potential (GWP) are a key concern

A key concern is the use of hydrofluorocarbon (HFC) gases as refrigerants. As per the Montreal Protocol commitments, countries have banned the use of chlorofluorocarbons (CFCs), and consequently replaced them by Hydrochlorofluorocarbons (HCFCs). Both are known to deplete ozone. Currently, developing countries are in the process of phasing out HCFCs, which prompted the rapid increase in the use of HFCs as a replacement in a number of applications; in refrigeration, air conditioning, and heat pumps (RACHP); the manufacturing of foam insulation; fire protection; and aerosols and solvents. Of these, refrigerants accounted for 86% of global emissions from HFCs in 2012, when weighted for carbon dioxide (CO_2) emissions.

Alternative solutions are available

Alternative solutions include (1) the replacement of HCFCs and HFCs based systems and materials with the ones using substances with low global warming potential (GWP) depending on the type of applications. For example, in the refrigeration and air conditioning systems, refrigerant alternatives may include: HFOs, blended HFCs, ammonia, and CO_2 (it might be noted that changing a refrigerant may require changing the refrigeration system itself); and (2) not-in-kind (NIK) solutions, such as an improved system design that reduces refrigerant use, evaporative coolers (swamp coolers) that do not use refrigerants (because the water acts as a coolant), and so on. Section V provides a quick reference list of low GWP and natural refrigerants that may be used for air conditioning, heating-only heat pumps, and

mechanical refrigeration. Additional strategies include effective maintenance procedures to minimize leakage.

Low GWP refrigerants can contribute greatly to greenhouse gas mitigation

Estimates revealed that if all Excellence in Design for Greater Efficiencies (EDGE) users were to follow this guidance, a projected 40 million tonnes of carbon dioxide equivalent (CO_2e) emissions could be avoided by 2023. To put this in perspective, global GHG emissions (in equivalent tonnes of CO_2 emissions) are about 35 billion tonnes per year (1).

Use of Climate friendly refrigerants is recommended by EDGE

Please note that the EDGE certification process does not include emissions from refrigerants in its calculation of the CO_2e emissions from buildings. It is, however, recommended that design teams consider the guidance contained in this document to maximize climate benefits of their buildings and ultimately contribute to the global goals of minimizing the impact of buildings on the climate.

Introduction

Who Should Read this Document?

Persons responsible for decision-making in the selection of air-conditioning or refrigeration equipment, or for selecting materials such as foam, fire protection systems, adhesives, and solvents used in buildings, are the intended audience for this document. Such people may include mechanical engineers, architects, specification writers, owners, Excellence in Design for Greater Efficiencies (EDGE) auditors, and other decision makers such as green building consultants. It is also recommended that all potential EDGE-certified buildings follow the requirements set in this document as best practice.

The final selection of the right refrigerant requires good expertise in refrigeration engineering, so it must be undertaken with care by a suitable expert. Experts in the topic may wish to go directly to Section V. The early sections provide information for readers less familiar with the topic.

Why Careful Selection of Refrigerants is Important

Substances contained in the equipment and materials mentioned above and used in building systems have a significant impact on the environment, specifically by (1) destroying atmospheric ozone gas, which is critical to human and other forms of life, and (2) contributing to global warming. This impact is above and beyond the negative environmental impact inherent in the consumption of the fossil-fuel-based energy used to power the building equipment and also to the manufacture and transport of building materials.

In the refrigeration, air-conditioning, and heat pumps (RACHP) market (2), refrigerants commonly used are not "green"; instead, they contribute to ozone destruction and/or global warming. A few other substances used in the building industry—including foam-blowing agents, adhesives and solvents, and fire protection systems—also have this negative impact. This is why **all countries have agreed to regulate** these substances in an agreement referred to as the Montreal Protocol (described in Section I.0), under which CFCs are already totally banned and HCFCs are in the phase-down schedule. The Montreal protocol was amended in October 2016 to include the phase-down of HFCs which, like the ODS they replaced, are potent greenhouse gases that can be hundreds to thousands of times more potent than CO_2 in contributing to climate change. As the use of cooling systems and modern materials increases in buildings in developing economies, it is imperative that care be taken to choose which equipment and materials to use, and how to minimize their negative impacts on climate.

The Intent of the Document

The intent of this document is to enable the reader to make informed choices when selecting air-conditioning or refrigeration equipment, or selecting materials such as foam, fire protection systems, adhesives, and solvents used in buildings, with a better understanding of the impact of refrigerants and other materials they contain on the climate.

Given the predominance of the impact of refrigerants, they are the primary focus of this document. It is worth noting that the selection of a "green" refrigerant would impact the choice of the cooling system itself, as refrigerants have different properties and they cannot usually be substituted for one another in a given cooling system. Similarly, an insulating foam board may be manufactured using harmful gases. The selection of the foam board will impact the amount of harmful gases being released into the environment. This document includes a brief summary of relevant materials. Due to the rapid rate of technical and market development, the information on alternatives gets out of date quickly! Up to date information of the latest refrigerants should always be used.

The EDGE[1] User Guides include guidance on selecting refrigerants and other materials for use in buildings. This document provides the background for the guidance issued in the EDGE User Guides by explaining the environmental impact of various types of substances, and less harmful alternatives.

Building Materials Covered in this Document

The following building systems are covered in this document; all of them use substances that are controlled internationally because of their high environmental impact:

1. **Refrigeration, air conditioning, and heat pumps (RACHP):** Refrigerants are used in applications that include space cooling, food refrigeration, and industrial refrigeration. Related equipment includes refrigerators, freezers, dehumidifiers, water coolers, ice machines, and air-conditioning and heat pump units. Space cooling systems include centralized and unitary/stand-alone heating, ventilating, and air-conditioning (HVAC) systems, as well as district cooling systems.
2. **Foam insulation**: Foam-blowing agents are used in spray foam insulation for roofing and walls in buildings. They are also used to insulate refrigerators. Major foam types include extruded polystyrene (XPS) foam, and polyurethane (PU)-type foams such as PU, polyisocyanurate, and phenolic foams.
3. **Fire protection systems**. Halons, CFCs and HFCs are used in fire suppression systems including stand-alone fire extinguishers and built-in systems.
4. **Aerosols and solvents**. Building-related aerosols include cleaning products and sprays used for commercial and industrial maintenance. Solvents are used as cleaning products.

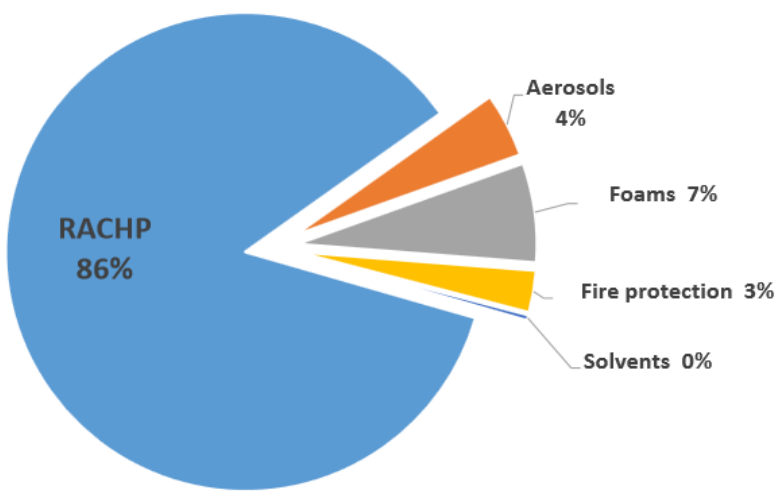

Figure 1. Markets using HFCs, expressed as a percentage of tonnes of CO_2 (2012 data), UNEP 2015 (3).

[1] EDGE, or Excellence in Design for Greater Efficiencies, is an online platform developed by the International Finance Corporation Climate Business Department of the World Bank Group. Designed for new buildings in emerging markets, the EDGE application allows design teams to estimate the efficiency of a building and includes practical solutions and alternative materials. The EDGE platform website is https://www.edgebuildings.com/.

The bulk of the guidance in this document relates to refrigerants in RACHP. RACHP and foam insulation are two applications that significantly rely on the environmentally harmful substances discussed here. It might be noted that the consumption of refrigerants in RACHP applications dwarfs the consumption of foam-blowing agents. *RACHP systems account for 79% of refrigerant use, in metric tonnes, and 86% of all CO_2e emissions in 2012 from hydrofluorocarbons (HFCs), the currently prevalent refrigerants* (3).

Please note that the EDGE Application does not include emissions from refrigerants in its calculation of the carbon dioxide equivalent (CO_2e) emissions from the building. It is, however, recommended that design teams consider the guidance contained in this document to contribute to the global goals of minimizing the impact of buildings on the climate.

I. Environmental Impact of Refrigerants

This section introduces the key environmental hazards of refrigerants, and the international agreement to control these substances, known as the Montreal Protocol.

Cooling systems in buildings have not been around long. The first stand-alone systems to air-condition buildings appeared a little more than a hundred years ago, in the early 1900s. Central air-conditioning and the use of the man-made chemical refrigerant Freon-12[2] made an appearance in the 1970s, fewer than 50 years ago (4). Although refrigeration involves a closed-loop system, refrigerants may be released into the atmosphere through spills due to improper handling during manufacturing, transportation, installation, and operation, and through leakage from the condenser or compressor, during venting, or during disposal.

The substances approved for use as refrigerants in the first generation of cooling systems for buildings were selected because they were effective, non-flammable, non-toxic, and stable. However, in the early 1980s, within a decade of the advent of central cooling systems, scientists discovered that although these refrigerants were stable in the lower layer of the atmosphere (called the troposphere), they were eventually drifting into the upper layer of the atmosphere (called the stratosphere) and decomposing, causing an imbalance in critical gases and, notably, **destroying the ozone gas** in the stratosphere. Stratospheric **ozone performs the important task** of protecting the environment by absorbing a part of the ultraviolet radiation (known as UVB) from the sun. Increases in UVB radiation are linked to increased skin cancer and cataracts, and harm to crops and marine life (5).

Global warming—and climate change overall—was not well understood and not a top policy priority at the time that the impact of refrigerants on the ozone layer was first realized. However, within the next decade (starting in the early 1990s), it was realized that **refrigerant compounds and similar substances contributed to global warming**. The degree of the impact varies depending on the type of the substance and can be compared using the metrics described below.

A. Ozone-Depleting Substances (ODSs)

Most first- and second-generation refrigerants are ozone-depleting substances (ODSs). ODSs are compounds that deplete ozone gas in the stratosphere when they are exposed to intense ultraviolet (UV) light in the upper layer of the earth's atmosphere (that is, the stratosphere) by releasing chlorine or bromine, which react with the ozone. Ozone depletion is a reduction in the amount of ozone in the stratosphere beyond natural fluctuation cycles. (Ozone concentrations in the atmosphere vary naturally with sunspots, seasons, and latitude.) Although ODSs are emitted at the Earth's surface, they are eventually carried into the stratosphere, in a process that can take two to five years, according to the Environmental Protection Agency (EPA) (5). ODSs are generally very stable in the troposphere and degrade only under intense UV light in the stratosphere.

ODSs include the refrigerant families known as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), halons (nonreactive gaseous compounds of carbon with halogens such as bromine), methyl

[2] A trademark of the company Chemours, formerly DuPont.

bromide, carbon tetrachloride, and hydrobromofluorocarbons (HBFCs). The extent of damage caused by an ODS is expressed by its ozone depletion potential (ODP), which is described next.

B. Ozone Depletion Potential (ODP)

The degree of the destructive impact of a substance on the ozone in the stratosphere is expressed as its ozone depletion potential (ODP). By definition, the ODP of a chemical is the ratio of the amount of stratospheric ozone destroyed by the release of a unit mass of that chemical at the Earth's surface to the amount destroyed by the release of a unit mass of chlorofluorocarbon 11, CFC-11 (CFCl3). In other words, the ODP of CFC-11 (also known as R-11, where "R" stands for refrigerant) is fixed at one (1.0), and the ODP of other chemicals is expressed relative to this. For other CFCs, the ODP ranges from 0.01 to 1.0. For instance, the ODP of CFC-115 (C2F5Cl) is 0.6. ODPs of other substances such as bromine compounds can be outside this range. For instance, the ODP of halon-1301 (CF3Br) is 10.0. Carbon tetrachloride—a compound consisting of one carbon atom and four chlorine atoms, widely used as a raw material in many industrial uses, including in the production of chlorofluorocarbons (CFCs), and as a solvent—has an ODP of 1.1 (6).

C. Global Warming Potential (GWP)

Besides the destruction of ozone, refrigerants also contribute to global warming. Global warming refers to an increase in the average temperature of the lower atmosphere. Global warming can have many different causes, but it is most commonly associated with human interference, specifically the release of excessive amounts of greenhouse gases (GHGs). GHGs, such as carbon dioxide (CO_2), methane (CH_4), water vapor, and fluorinated gases, act like a greenhouse around the earth. This means that they let the heat from the sun into the atmosphere, but do not allow the heat to escape back into space (7). Many of the conventional refrigerants are GHGs. An increase in GHGs is estimated to be the largest contributor to global warming, especially during the past few decades (8).

Global warming potential (GWP) is a quantified measure of the globally averaged, relative radiative forcing impact of a particular greenhouse gas. It is defined as the cumulative radiative forcing of both direct and indirect effects integrated over a period of time (*typically 100 years* and indicated by the tag *100-year value*) from the emission of a unit mass of gas relative to some reference gas (9). CO_2 was chosen by the Intergovernmental Panel on Climate Change (IPCC) as this reference gas, and its GWP is set equal to one (1.0). GWP values allow the comparison of the impacts of emissions and reductions of various gases. The higher the GWP value, the more infrared radiation the gas will tend to absorb over its lifetime in the atmosphere, leading to more warming (10).

Figure 2 shows the ODP and GWP values of a few common refrigerants. Note the contrast in the values between the first set of refrigerants, which are first-generation man-made refrigerant chemicals, and the last set of refrigerants, which are natural compounds.

Refrigerant Type and Name	ODP	GWP	Use
Chlorofluorcarbons			
CFC-11	1.0	4,680	Centrifugal chillers
CFC-12	1.0	10,720	Refrigerators, chillers
CFC-114	0.94	9,800	Centrifugal chillers
CFC-500	0.605	7,900	Centrifugal chillers, humidifiers
CFC-502	0.221	4,600	Low-temperature refrigeration
Hydrochlorofluorocarbons			
HCFC-22	0.04	1,780	Air conditioning, chillers
Hcfc-123	0.02	76	CFC-11 replacement
Hydrofluorocarbons			
HFC-23	< 4 x 10-4	12,240	Ultra-low-temperature refrigeration
HFC-134A	< 1.5 x 10-5	1,320	CFC-12 or HCFC-22 replacement
HFC-245FA	~10-5	1,030	Insulation agent, centrifugal chillers
HFC-404A	~10-5	3,900	Low-temperature refrigeration
HFC-407C	~10-5	1,700	HCFC-22 replacement
HFC-410A	< 2 x 10-5	1,890	Air conditioning
HFC-507A	~10-5	3,900	Low-temperature refrigeration
Natural refrigerants			
Carbon dioxide (CO_2)	0	1	
Ammonia (NH_3)	0	0	
Propane (C_3H_8)	0	3	

Figure 2. Examples of ozone depletion and global warming potentials of refrigerants (100-yr values) (11).

Figure 3 shows examples of currently used refrigerants categorized by their GWP. It also shows the complexity involved in making the right choice considering other key factors such as toxicity and flammability, which are also discussed in Section II.

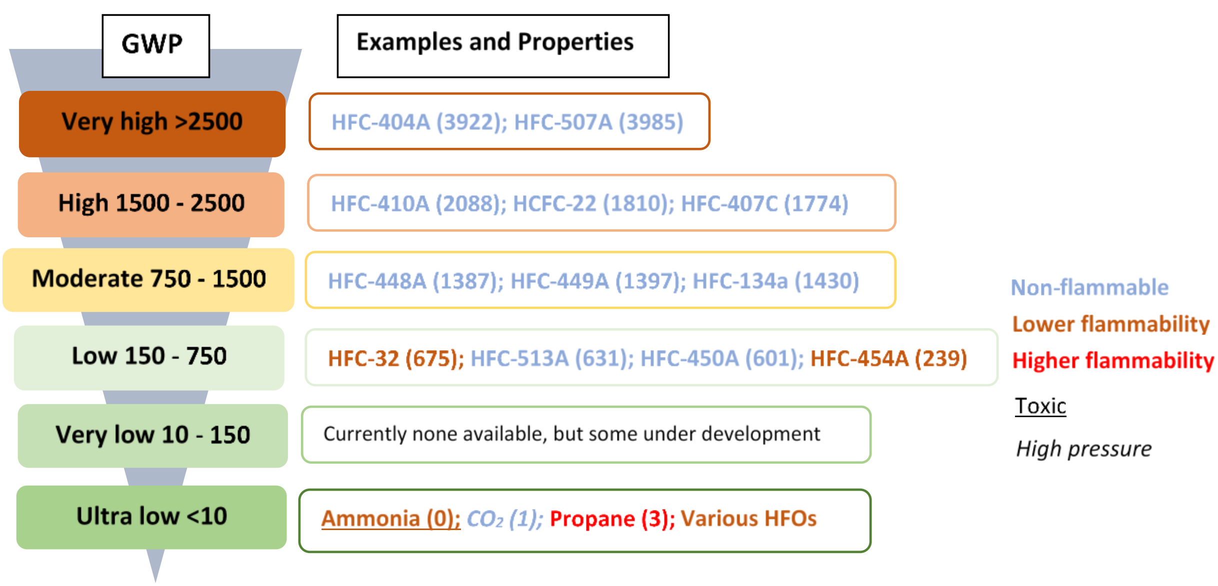

Figure 3. Currently used refrigerants categorized by their GWP

D. The Montreal Protocol

The Montreal Protocol is shorthand for the Montreal Protocol on Substances that Deplete the Ozone Layer. It is an international treaty that is designed to protect the ozone layer in the atmosphere by phasing out the production and consumption of substances that are responsible for ozone depletion, thus protecting human health and the environment, including minimizing impacts on the Earth's climate. The Montreal Protocol emerged in 1987 from the United Nations Environment Programme's (UNEP's) Vienna Convention for the Protection of the Ozone Layer. The Montreal Protocol is enforced through control of the production, import, and export of controlled substances. The official list of controlled substances is published on the UNEP website as the "Summary of Control Measures under the Montreal Protocol," which is part of the *Handbook for the Montreal Protocol on Substances that Deplete the Ozone Layer* (12).

Key terms related to the Montreal Protocol include the following.

- **Article 5 Parties** are developing countries whose annual level of consumption of ODSs and halons is less than 0.3 kilograms per capita.
- **Article 2 Parties,** or non–Article 5 parties, refers to countries in the developed world.
- The **Multilateral Fund (MLF)**, short for the Multilateral Fund for the Implementation of the Montreal Protocol, is a unique funding mechanism established in 1990 through which developed countries assist developing countries in meeting their commitment to phase out ODSs. It is managed by an executive committee with equal member representation from developed and developing countries. Since 1991, the Multilateral Fund has approved activities including industrial conversion, technical assistance, training, and capacity building worth over US $3.0 billion. Contributions to the Multilateral Fund from developed countries, or non–Article 5 countries, are assessed according to the UN scale of assessment. As of November 2015, the contributions made to the Multilateral Fund by about 45 countries (including countries with economies in transition or CEIT countries) totaled over US$ 3.44 billion (13). **Kigali Agreement: In 2016, countries committed to cut HFCs by more than 80% over 30 years under the Montreal Protocol in Kigali, Rwanda.** The ambitious phase-down schedule will avoid more than 80 billion metric tons of carbon dioxide equivalent emissions by 2050—avoiding up to 0.5° Celsius warming by the end of the century—while continuing to protect the ozone layer. The plan also provides financing to certain countries, to help them transition to climate-friendly alternatives. The final deal will divide the world economy into three tracks:
    - United States and those in the European Union will freeze HFCs by 2018, reducing them to 15% of 2012 levels by 2036.
    - Much of the rest of the world will freeze HFC use by 2024, reducing it to 20% of 2021 levels by 2045.
    - A small group of the world's hottest countries — India, Pakistan, Iran, Saudi Arabia and Kuwait — will have the most lenient schedule, freezing HFC use by 2028 and reducing it to about 15% of 2025 levels by 2047.

Key Milestones in the History of the Montreal Protocol

Figure 4 shows the key milestones in the history of adoption of the Montreal Protocol.

1974	Scientists link the emission of CFCs to the destruction of ozone in the atmosphere
1977	United Nations Environment Programme initiates the World Plan of Action on the Ozone
1985	The Vienna Convention for the Protection of the Ozone Layer is adopted
1985	Ozone hole first detected over the Antarctic
1987	**The Montreal Protocol is signed by representatives of 46 countries in Montreal, Canada**
1989	The Montreal Protocol goes into force. Developing countries are given a delayed schedule for compliance if their consumption of Ozone Depleting Substances (ODS) is low
1992	Copenhagen Amendment adds hydrochlorofluorocarbons (HCFCs), hydrobromofluorocarbons (HBFCs), and hydrobromocarbons (methyl bromide) to the phase-out schedules and formally creates the Multilateral Fund.
1994-96	After a phase-out in preceding years, a ban on CFCs and halons comes into effect in developed countries, with exceptions for essential uses
1999	**The compliance period begins for Article 5 parties (developing countries)** with the first control measure a freeze, at the average of 1995–97 levels, of production and consumption of CFCs starting July 1, 1999
1999	Beijing Amendment adds bromochloromethane to the phase-out schedules
2002	**Total phase-out of bromochloromethane in developed and developing countries**
2005	Reduction by 50% consumption and production of CFCs and halons, 85% of carbon tetrachloride (CTC), 30% of trichloroethane (TCA), and 20% of methyl bromide in developing countries
2007	Reduction of 85% consumption and production of CFCs in developing countries
2009	**Universal ratification of the Vienna Convention and the Montreal Protocol**
2010	**Total phase-out of CFCs, halons, and CTC in developing countries**
2013	Freeze, at the baseline level, of the consumption and production of HCFCs in developing countries
2014	Kigali Agreement to amend the Protocol of Montreal
2024	Freeze of HFC in developing countries to 20% of 2021 levels by 2045.
2030	**Total phase-out of HCFCs in developed and developing* countries**

*the annual average of 2.5% is restricted to the servicing of refrigeration and air-conditioning equipment existing on January 1, 2030, for the period 2030–40 and subject to review in 2015 (13).

Figure 4. Key milestones in the history of the Montreal Protocol

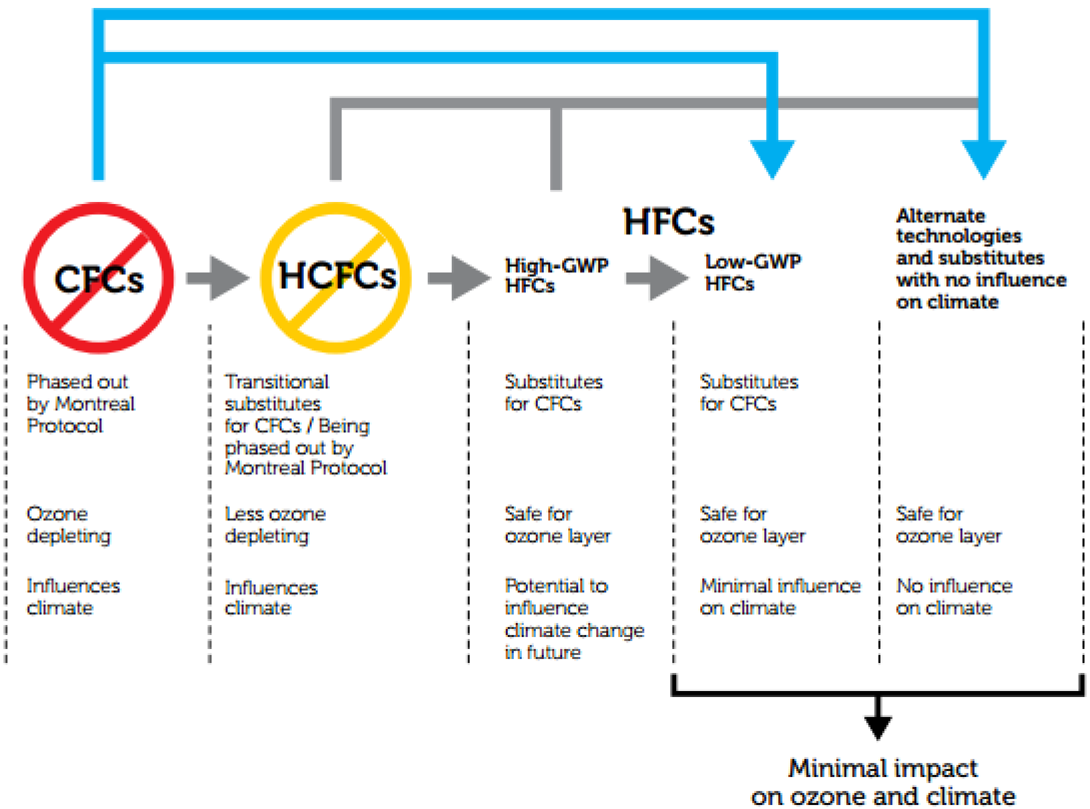

Figure 5. Status of the Montreal Protocol, as of October 2015. The general strategy following the adoption of the Montreal Protocol is to move away from using ozone-depleting substances (3).

Impact of the Montreal Protocol

The Montreal Protocol has been highly successful in reducing the emissions, growth rates, and concentrations of chlorine- and bromine-containing halocarbons, the historically dominant ODSs (14), and has limited ozone depletion and initiated the recovery of the ozone layer. By 2011, the 197 parties to the Montreal Protocol had reduced their consumption of ODSs by 98%, in accordance with its strict and binding schedules for both developed and developing countries. In fact, the Montreal Protocol has been deemed one of the most successful multilateral environmental agreements because of this rapid reduction in both the consumption and production of ODSs. The phase-out of ODSs has accomplished more to mitigate climate change than all other international environmental efforts combined, with cumulative emissions reductions of 135 billion tonnes of CO_2e between 1989 and 2013 (13).

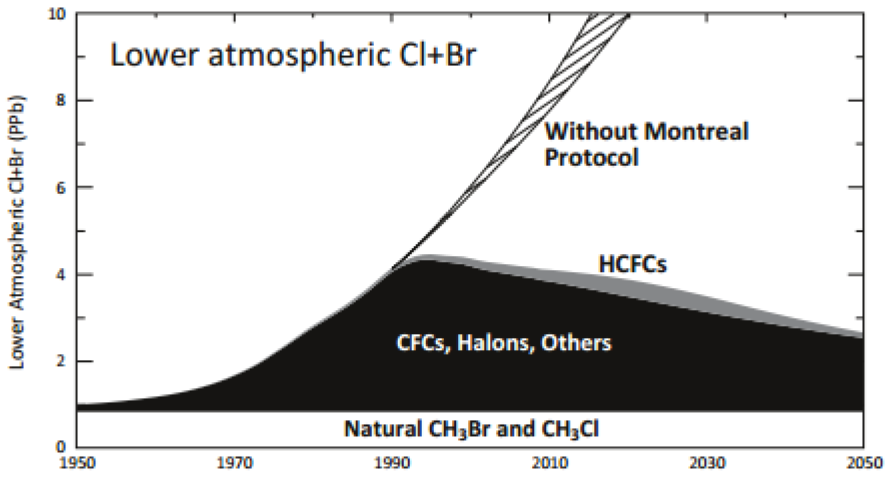

Figure 6. Change in lower atmospheric abundance (in parts per billion, ppb) of the sum of chlorine and bromine arising from ODSs as a result of the Montreal Protocol. The bromine abundance has been multiplied by a factor of 60 to account for the 60-times higher efficiency of bromine, relative to chlorine, (on a per-atom basis) in depleting the stratospheric ozone layer. The hatched region is an estimate of the atmospheric abundance of chlorine plus bromine that would have occurred without the Montreal Protocol, assuming a 2%–3% increase in annual production of all ODSs. Figure based on Velders et al. (2007) (15) (16).

Thanks to the controls implemented by the Montreal Protocol, the net change in climate forcing due to ODS gases, over the next 50 years, is expected to be about zero if the endeavor of the protocol is extended to include additional gases such as HFCs and a destruction of the CFCs and HCFCs banks (8).

II. Key Factors to Consider in Selecting a Refrigerant

Besides the environmental factors discussed above, other practical considerations need to be taken into account when selecting a refrigerant. This section outlines the key considerations.

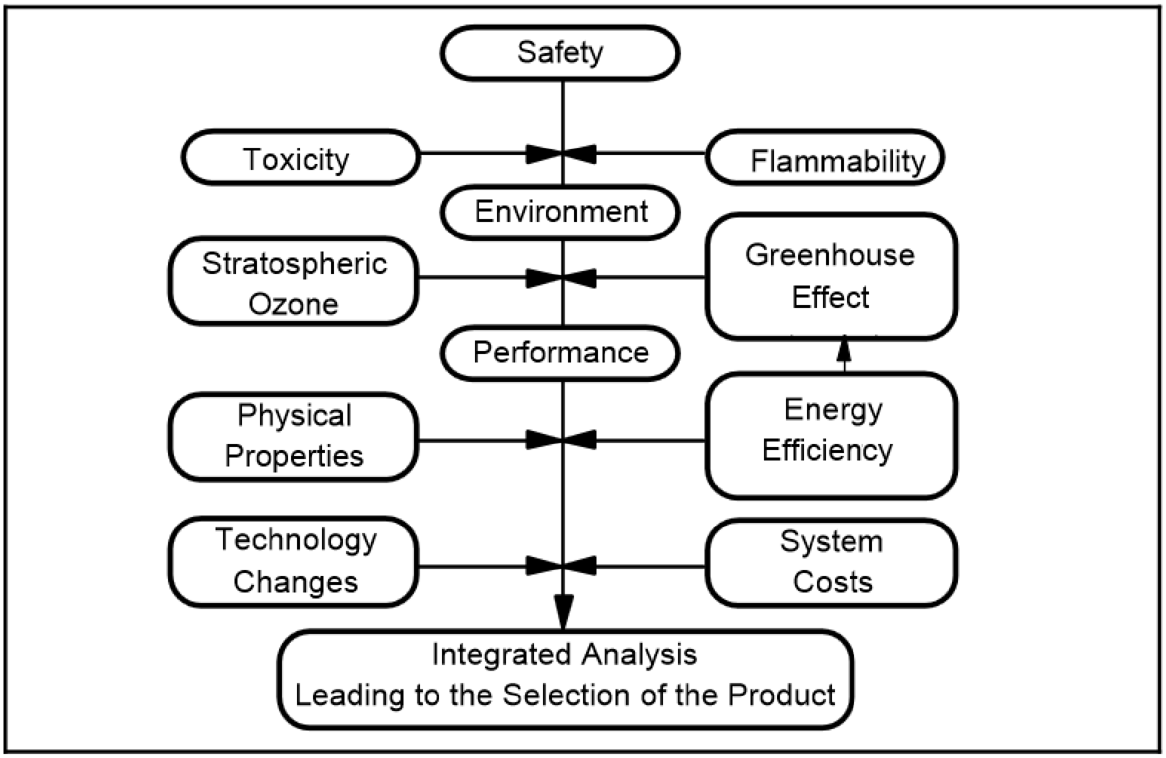

Figure 7. Factors to consider in an integrated approach to selecting an optimum solution for a given heating, cooling, or refrigeration requirement. Adapted from a 1997 report by the Oak Ridge National Laboratory of the U.S. Department of Energy (17).

A. Safety

Safety is a basic consideration that must be evaluated for refrigerant selection. Factors affecting choice include the location of the system and likelihood of hazard.

Refrigerant classification for safety consists of two alphanumeric characters (for example, A2); the capital letter corresponds to toxicity and the digit to flammability.

Toxicity

Refrigerants are divided into two groups, according to toxicity:

1. Class A signifies refrigerants for which toxicity has not been identified at concentrations less than or equal to 400 parts per million (ppm);
2. Class B signifies refrigerants for which there is evidence of toxicity at concentrations below 400 ppm.

In other words, Class A refrigerants are less toxic than Class B refrigerants.

Flammability

Refrigerants are divided into three main groups and a sub-group, according to flammability based on ISO 817 and ISO 5149:

1. **Higher flammability**: Class 3 indicates refrigerants that are highly flammable as defined by a lower flammability limit of less than or equal to 0.10 kilograms per cubic meter (kg/m^3) at 21°C and 101 kiloPascals (kPa), or a heat of combustion greater than or equal to 19 kilojoules per kilogram (kJ/kg) (18).
2. **Flammable**: Class 2 indicates refrigerants with a lower flammability limit of more than 0.10 kg/m^3 at 21°C and 101 kPa and a heat of combustion of less than 19 kJ/kg.
3. **Lower flammability**: Class 2L indicates lower flammability than Class 2 refrigerants.
4. **Not flammable**: Class 1 indicates refrigerants that do not show flame propagation when tested in air at 21°C and 101 kPa.

In other words, Class 1 refrigerants are not flammable, and Class 3 refrigerants are the most flammable. The commonly used refrigerant R-22 is assigned a safety rating of A1, while the safety rating of R-32 is B2. Many of the new refrigerants are blends or mixtures. The commonly used, blended refrigerant R-410A has a safety rating of A1, while R-411A is rated A2.

B. Environmental Impact (ODP and GWP)

ODP and GWP have already been defined. The target should be to have a zero ODP value and a low GWP.

C. Performance

Physical Properties

Desirable physical properties of refrigerants include a low freezing point, low condensing pressure, and high evaporator pressure, among others.

Energy Efficiency

Refrigerants that are more energy efficient have a higher heat-transfer coefficient, which requires a smaller area and lower pressure drop.

Technology Changes

New blends are being introduced to the market to help lower the environmental impact of refrigerants. New technologies and systems are also being introduced that use new and improved refrigerants.

System Costs

Some of the newer types of systems have a significantly different price compared with older technologies.

While most performance factors other than system cost and energy efficiency are to be considered by manufacturers, all these factors need to be considered by the construction industry in an integrated fashion to select a “good” refrigerant.

III. High Environmental Impact Refrigerants (Bad)

Most common refrigerants used in the market today have a large negative impact on the environment. The main types of refrigerants and their respective environmental impacts are introduced in this section. They are divided into two groups: those controlled by the Montreal Protocol (and that are thus already being phased out), and those that are not. This section is followed by a section on refrigerants with a minimal impact on the environment.

A. Compounds Controlled by the Montreal Protocol and its Amendment "Kigali Agreement"—CFCs, HCFCs, HFCs

The first cooling fluids used for industrial applications included chloromethane (CH3Cl), sulphur dioxide (SO2), ammonia (NH3), acetylene (C2H2), 1,2-Dichloroethene (C2H2Cl2), dichloromethane (CH2Cl2) and hydrocarbons (HCs). These offered good refrigerating performance, but were flammable and toxic. These were not approved for use in cooling systems for buildings.

Chlorofluorocarbons (CFCs)

The first-generation refrigerant compounds approved for use in buildings were CFCs, which contain chlorine, fluorine, and carbon atoms. Such compounds include R-11 and R-12, commonly known by their brand name, Freon®-11 and -12 (an invention of the DuPont company). Other trade names include Honeywell's "Genetron" and Arkema's "Forane." **Chlorine is the damaging element in these compounds**. Scientists have found that when CFCs are exposed to intense solar radiation in the upper layer of the atmosphere (the stratosphere), they decompose and release their chlorine molecules. This chlorine reacts with and destroys ozone (O_3) gas molecules in the stratosphere, decomposing into other gases, such as oxygen and chlorine monoxide. Because chlorine atoms can stay in the stratosphere for more than a century and get recycled through the reactions, one chlorine atom can destroy up to 100,000 molecules of stratospheric ozone (5).

The manufacture of CFC chemicals is now banned in all countries that have signed the Montreal Protocol, which makes the ban practically universal. CFCs and HCFCs (described next) together contribute approximately 11% of the warming effect of well-mixed greenhouse gases (WMGHG). Although emissions have been drastically reduced for CFCs, their long lifetime means that reductions take substantial time to affect their concentrations. The warming impact from CFCs has declined since 2005 (mainly due to a reduction in the concentrations of CFC-11 and CFC-12), whereas the warming impact from HCFCs is still rising (mainly due to HCFC-22) (19).

Hydrochlorofluorocarbons (HCFCs)

The second-generation refrigerants such as Freon®-22,[3] or R-22, belong to a family of refrigerants called HCFCs. HCFCs contain hydrogen, fluorine, chlorine, and carbon atoms—similar to CFCs except for the additional hydrogen atoms. HCFCs are also greenhouse gases as well as ozone depleting substances. However, these refrigerants have a shorter lifespan and therefor a lower ODP than CFCs, and have been introduced as temporary replacements for CFCs.

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[3] A registered trademark of the Chemours company, previously known as DuPont.

HCFCs are currently being phased out under the Montreal Protocol. A complete phase-out is scheduled by 2040. The primary HCFC refrigerants are R-22 (used in a broad range of applications and currently the most widely used refrigerant) and R-123 (the most commonly used refrigerant in centrifugal chillers). Others include R-124 and R-142b, both primarily as blend components (20).

Hydrobromofluorocarbons (HBFCs)

HBFCs are chemically similar to Hydrochloroflurorcarbons (HCFCs), Chlorofluorocarbons (CFCs) and halons and therefore display some similar properties. HBFCs are also part of a group of chemicals known as volatile organic compounds (VOCs). HBFCs have never been as widely used as the chemically similar HCFCs, CFCs, and halons. Their use in developed countries has been phased out since the mid-1990s, and since 2002 their use is not permitted at all. The main uses of HBFCs have been as solvents, cleaning agents, fire suppressants, and (sometimes) refrigerants. Compared to other similar groups of chemicals, HBFCs are particularly potent ozone depleters and have a very high GWP (21).

Hydrofluorocarbons (HFCs)

Newer refrigerants such as Puron®[4] and Suva®410A[5] are marketing brand names for the refrigerant R-410A. This is one of several types of HFCs, the third-generation refrigerants that have been most often substituted for ODSs. HFCs do not deplete the ozone; however, they are powerful GHGs. In fact, among GHGs, they are cause for great concern and can potentially undo the progress made by the Montreal Protocol.

As the previous generation of refrigerants (HCFCs) have been phased out, HFCs were developed to replace them and are increasingly being used globally, as illustrated in Figure 8. . They form a large family of man-made **fluorinated gases** developed and commercialized for use primarily in refrigeration, air conditioning, foam blowing, and fire suppression, and as aerosols and solvents. Each type of HFC gas consists of different combinations of hydrogen, fluorine, and carbon. They do not contain chlorine, and therefore do not deplete the ozone.

[4] A registered trademark of the Carrier Corporation.
[5] A registered trademark of the Chemours Company, previously known as DuPont.

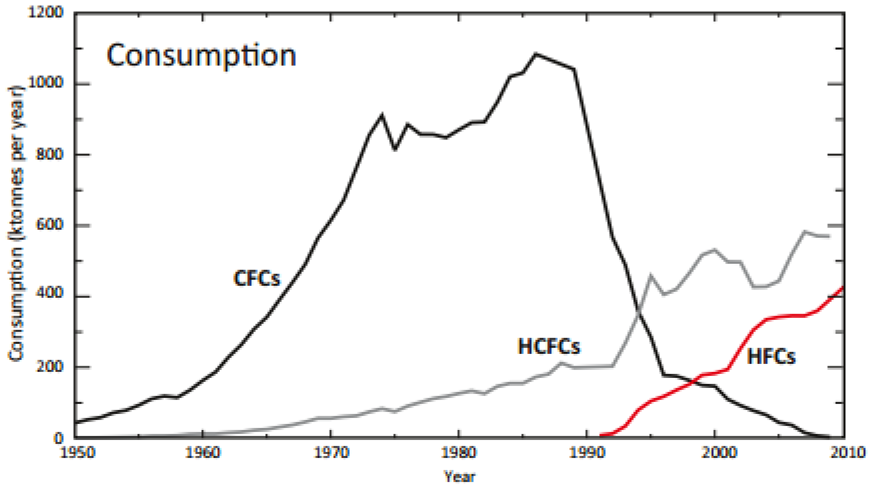


Figure 8. Global consumption (in kilotonnes per year) of ozone-depleting CFCs and HCFCs. The phasing-in of HFCs as replacements for CFCs is evident from the corresponding decrease in CFC usage concomitant with the increasing usage of HFCs. HCFCs, which also increased corresponding with the decrease in CFCs, are partially being replaced by HFCs, as the 2007 Adjustment to the Montreal Protocol on HCFCs continues to be implemented. Thus, HFCs are increasing primarily because they are replacing CFCs and HCFCs (15).

However, some of them are powerful GHGs, with GWPs hundreds to thousands of times more damaging to the climate than CO_2. For example, HFC-404A, commonly used in commercial refrigeration, is almost 4,000 times more damaging to the climate than CO_2. To put this in context, just 1 kg of HFC-404A leaking into the atmosphere equates to the climate impact of 4 tonnes of CO_2. There are 19 different HFCs, with GWPs ranging from under 100 to nearly 15,000 (22) (2). In October 2016, the 197 parties to the Montreal Protocol agreed to amend the protocol to phase down HFCs (23).

KEY HFCs	GWP
R-404A	3,922
R-410A	2,088
R-407C	1,774
HFC-134a	1,430

Figure 9. Global warming potential (GWP) of the four key HFC refrigerants used in the refrigeration and air-conditioning market. The first three represent 90% of the global consumption of HFCs when expressed in terms of their GWP weight (2).

As ODSs were phased out under the Montreal Protocol, HFCs were among the most important chemicals selected as replacements (2). As a result, HFCs are the fastest-growing source of GHG emissions in much of the world, and after only two-and-a-half decades of commercial production, they represent about 1.7% of all global GHG emissions. HFC emissions are growing rapidly, at a rate of about 7% each year, with growth rates in developing countries at or exceeding 20% annually. The growth rate in developing countries is higher due to a combination of economic growth, a phase-out of ODSs, and a lack of strict climate change policies (23).

If action is not taken, global HFC emissions could reach 5.5 billion–8.8 billion tonnes of CO_2e per year by 2050, equaling 9%–19% of projected global CO_2 emissions under a business-as-usual (BAU) scenario (24).

The amendment to the Montreal Protocol to phase down HFCs would avoid an estimated 105 gigatonnes of CO_2e by 2050, and mitigate up to 0.4°C of potential global warming by the end of the century, while continuing to protect the ozone layer. On the other hand, BAU would undo the gains made so far by the Montreal Protocol by 2050 (23).

See Figure 10 and Figure 11 for an illustration of the impact of HFCs.

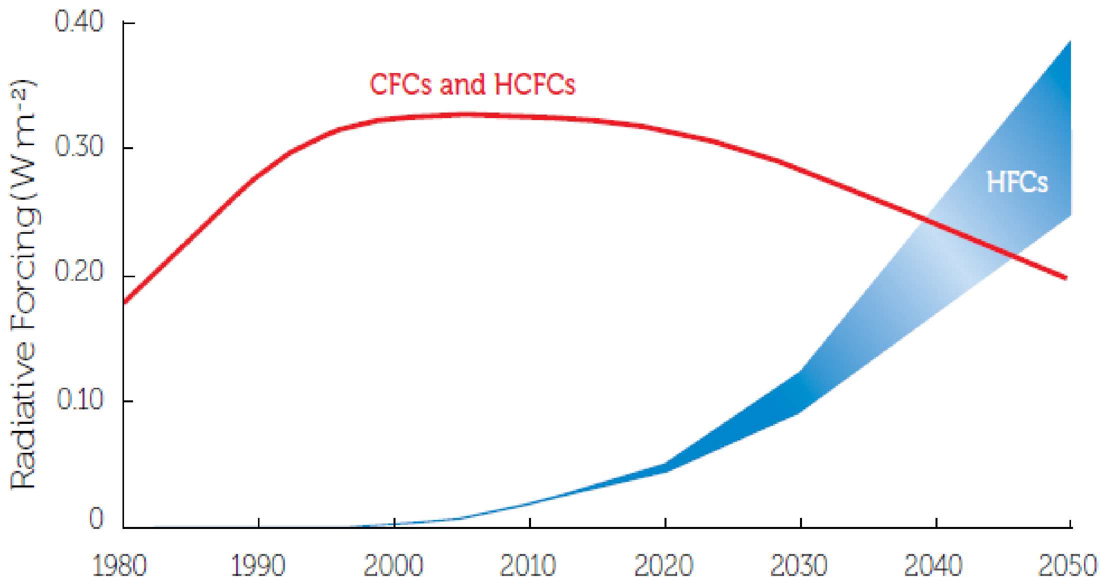


Figure 10. The impact of CFCs and HCFCs (red line), as measured by their radiative forcing (a measure of net energy change, with implications for climate change), from 1980 to 2050. While the contributions of CFCs and HCFCs are set to decrease, the continued use of high-GWP HFCs could offset the gains made by phasing out ODSs, as shown by the blue area. Alternatives to low-GWP HFCs—both in-kind and not-in-kind replacements—would maintain the gains made by the Montreal Protocol toward climate change (3).

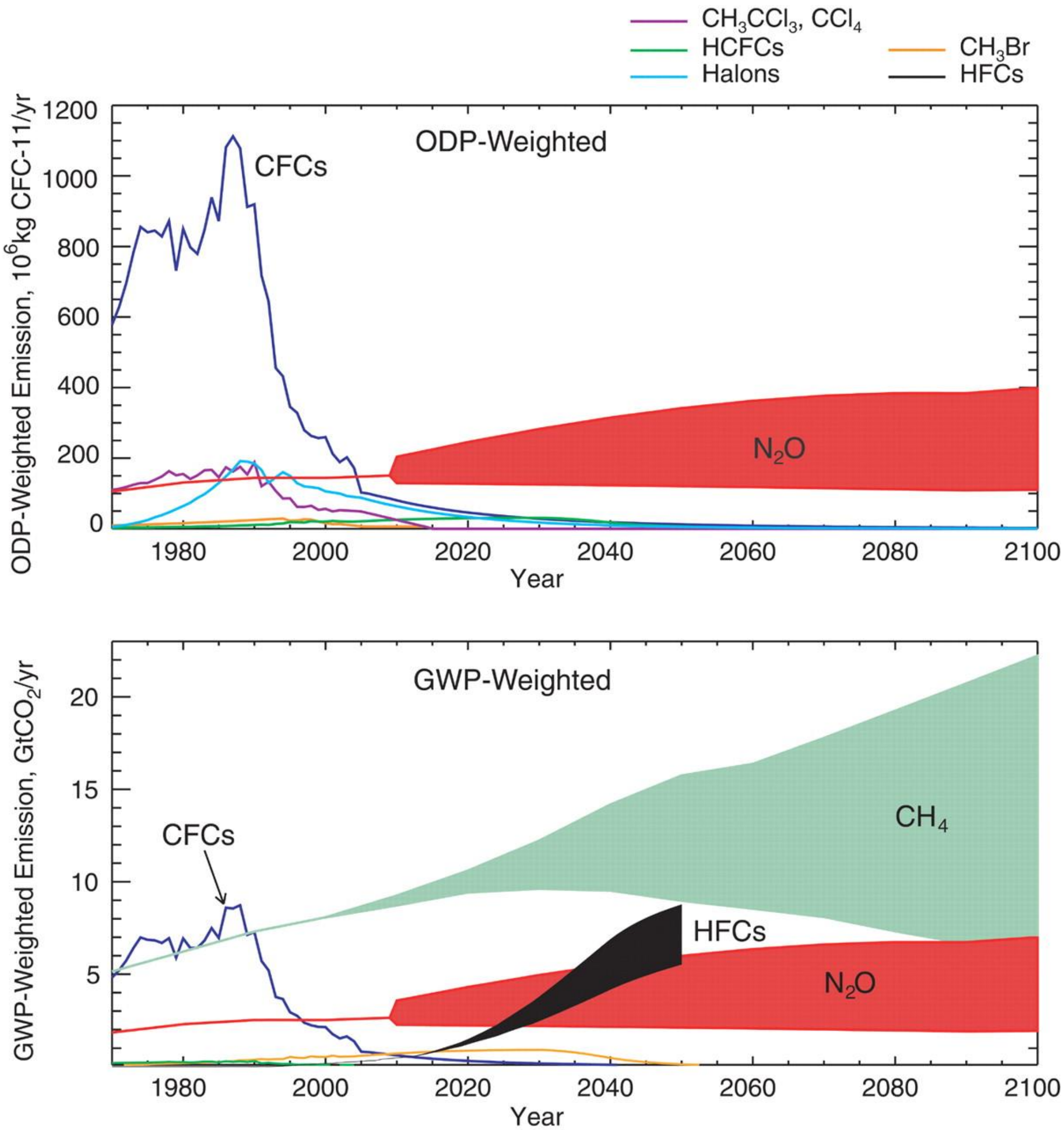


Figure 11. Historical and projected ODP- and GWP-weighted emissions of the most important ODSs and non-CO_2 greenhouse gases (25).

Figure 11 shows the historical and projected emissions of the most important ODSs and non-CO_2 GHGs. The upper plot shows the projection weighted by the ODP and the lower plot by the GWP. In this plot we can clearly see that the GWP reductions achieved by the Montreal Protocol during the phasing out of CFCs will be offset by emissions from HFC substances.

As a response to this, developed countries are already starting to phase out HFCs even before the Kigali agreement. In April 2014, the European Union (EU) adopted ambitious regulations to control fluorinated gases; the consumption of HFCs is planned to be phased down by nearly 80% by 2030, and it is banned in particular sectors. Other countries are following suit and driving the market toward HFC-free equipment and products.

Developing countries would do well to leapfrog from HCFCs to environmentally superior technology. For example, the least-cost substitute for some HCFCs is HFC-134a, with a GWP of 1,440. However, a slightly more costly HFO-1234yf—with a GWP of 4—would be far preferable (26).

IV. Low Environmental Impact Solutions (Better)

The low-impact alternative solutions include **natural refrigerants, not-in-kind (NIK)** solutions, and new **low-impact refrigerant blends**.

Natural Refrigerants

Natural refrigerants include CO_2, hydrocarbons, ammonia, water, and air. These climate- and ozone-friendly refrigerants are increasingly available for some RACHP applications. Safety measures will need to be carefully put in place for some of these refrigerants that are toxic or flammable.

In specific applications, RACHP systems with natural refrigerants are not only better for the climate, they can be more energy efficient, and they also keep operation and maintenance costs to a minimum (27). Systems using natural refrigerants have been found to have lower operating costs due to less refrigerant leakage, which also leads to lower overall maintenance requirements.

Alternative refrigerants used in the industry have a considerable share of the market in industrialized countries and developing countries. Figure 12 lists the share of alternative refrigerants by sector.

Sector	Examples of Alternatives to high-GWP HFCs	Use of Alternatives in Sector		
		Industrialized Countries	Developing Countries	Global Total
Industrial refrigeration systems (a)	Ammonia, CO_2, hydrocarbons	92%	40%	65%
Industrial air-conditioning systems (a)	Ammonia, CO_2, hydrocarbons	40%	15%	~25%
Domestic refrigerators (compressors) (b)	Hydrocarbons	51%	22%	36%
Foam in domestic refrigerators (c)	Hydrocarbons	66%	68%	67%
Foam in other appliances (c)	Hydrocarbons	38%	<1%	28%
Polyurethane foam boards and panels (c)	Hydrocarbons	82%	21%	76%

Figure 12. Examples of sectors that use a substantial percentage of alternative refrigerants (15) where (a) is refrigerants used in new installations annually, (b) is annual production of new equipment, and (c) is annual consumption of blowing agents

Carbon Dioxide (CO_2)

CO_2 goes by the refrigerant name R-744. As the gas to which other compounds are normalized, the GWP of CO_2 is 1.0 mass unit CO_2equivalent. This is thousands of times lower than conventional refrigerants.

CO_2 systems have high operating pressures, even higher than R-410a, and need to be designed accordingly. Care must be taken to ensure that CO_2 levels do not rise in occupied spaces because of the toxicity aspect.

CO_2 is well suited as a low-temperature refrigerant, both for industrial freezing applications and for commercial freezer display cases. CO_2 is also a uniquely well-suited gas for heat pump applications. CO_2 can replace HFCs in a cascade[6] in combination with any high-stage refrigerant, or in a CO_2-only system.

Highly feasible applications include: cold storage, small and large scale; all supermarket refrigeration systems; blast, spiral, and plate freezers; and industrial, commercial, and domestic heat pumps (28).

Hydrocarbons (HCs)

HC refrigerants are natural compounds that are generally available at a low cost and have excellent thermodynamic properties. HCs have been widely used in petrochemical applications, where the use of flammable substances is well understood. They are chemically stable and their application outside the petrochemical area is rapidly growing. Domestic refrigeration is an obvious application; here, safe systems are easy to achieve because the system charges are small (smaller than contained in a cigarette lighter, in many cases). Many small and medium commercial applications are also feasible for various HC refrigerants, where safety requirements are adhered to (28).

HC refrigerants include propane, butane, ethane, isobutene, and isopentane. These refrigerants (e.g., propane and propylene) have been used for over 10 years in small capacity chillers (up to 200 kilowatts [kW]) in Article 5 countries and in some non-Article 5 countries (15). The recent development of domestic refrigerators and freezers using HCs as refrigerants has contributed to the use of these refrigerants in small air-conditioning units. Air-conditioning units using HC technology have a high energy-efficiency rating and can be designed to achieve good safety measures (29).

Unsaturated HFCs or Hydrofluoroolefins (HFOs)

HFOs are called fourth-generation refrigerants and are essentially unsaturated HFCs with shorter atmospheric lifetimes in the order of days to weeks. Consequently, their GWPs (for a 100-year span) are around 20 or less; they are thus called low-GWP HFCs. HFOs are becoming available as refrigerants and for some foam-blowing applications. At present, a few low-GWP HFCs are being either phased in or proposed as substitutes for HCFCs and for some of the high-GWP HFCs (with lifetimes from several to tens of years). Examples include HFC-1234yf, as a substitute for the refrigerant HFC-134a; HFC-161, as a substitute for the refrigerant HCFC-22; and trans-HFC-1234ze, as a substitute blowing agent for some thermal insulating foams. Some of these low-GWP HFCs are so short-lived that the concept of GWP may

[6] A cascade system has two (or more) refrigerant circuits, each with a compressor, condenser and evaporator, where the evaporator of one circuit cools the condenser of another circuit.

not be applicable to them. For the purpose of comparison, they are estimated to be a hundred to a thousand times less potent as GHGs as the substances that they are expected to replace (15).

Ammonia (NH_3)

Ammonia is widely used in industrial applications because of its excellent thermodynamic performance. Building, fire, and hazardous material codes set limitations on its use because of safety concerns (11) (also see Absorption Chillers in the next section).

Water (H_2O)

Water is used for making ice in limited industrial applications. Because of its very low vapor pressure, its machine size per unit capacity is of an order of magnitude larger than current building machinery. Although it is the main gas responsible for the absorption of infrared radiation in the atmosphere, its very short atmospheric lifetime (nine days) makes any anthropogenic emission completely benign (also see Absorption Chillers in the next section).

Not-in-Kind (NIK) Solutions

Alternative solutions that do not merely replace the refrigerant but change the strategy for addressing the requirement for refrigeration are called not-in-kind (NIK) solutions.

Improved Building Shell

In most climates, the outer shell of a building (the building envelope) can be designed to suit the climate so that the need for refrigeration is minimized. For example, in a predominantly hot and dry climate, a building shell of mostly glass will serve as a greenhouse, trapping solar heat. On the other hand, a well-shaded and well-insulated building shell with optimized windows would require much lesser cooling. Similarly, in a hot and humid climate, a well-shaded building shell that allows for cross-ventilation when outside temperatures are mild can significantly reduce the amount of cooling required. In all climates, strategies that combine historic and local knowledge of climate adaptation with new technology and aesthetics can result in buildings that drastically cut down the need for refrigerant-based cooling.

Evaporative Coolers

In dry climates, evaporative cooling or “swamp cooling” provides cool air using much less energy than air conditioning. An evaporative cooler uses the outside air’s heat to evaporate water inside the cooler. The process of evaporation draws heat out of the air and the cooled air is blown into the space by the cooler’s fan. There are two types of evaporative coolers: direct and indirect. Direct evaporative coolers, also called swamp coolers, work by cooling outdoor air by passing it over water-saturated pads, causing water from the pads to evaporate into the warm and dry air. The cooler air is then directed into the home or building, and warmer air is pushed out through the windows. Indirect evaporative coolers have a heat exchanger that prevents humidity from entering the building. Efficiency tends to be lower than that of direct evaporative coolers (32).

Desiccant Drying (Dehumidification)

A desiccant is a substance, such as calcium oxide or silica gel, which has a high affinity for water and absorbs moisture from the air, thus reducing the latent load on cooling equipment. Two types of desiccant systems are available for meeting the latent cooling load in building air-conditioning applications. One of these is based on solid desiccants in rotating wheels, and the other on liquid desiccants pumped between various components in the circuit. This solution is more common in applications such as supermarkets, hospital operating rooms, and other niche markets requiring low humidity. The efficiency, cost, size, reliability, and life expectancy of desiccant components and systems are key considerations for the commercial air-conditioning market. Integrated systems that combine desiccant-based components with more conventional air-conditioning equipment are available. System efficiency is greatly enhanced if the desiccants are at least partially regenerated with waste heat from other system components (15).

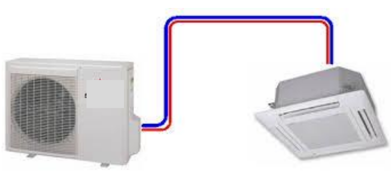
Absorption Chillers

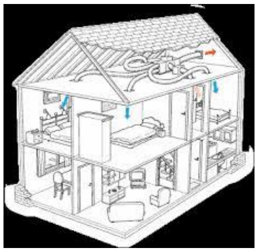
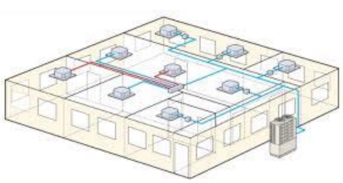
Absorption chillers use heat rather than electricity as their energy source. Natural gas is the most common heat source for absorption cooling (earning it the nickname gas-fired cooling). Other potential heat sources include propane, solar-heated water, or geothermal-heated water. Mainly used in industrial or commercial settings, absorption chillers are also commercially available for large residential homes. The refrigerant fluid used in absorption chillers is usually water. Other fluids commonly used as an “absorbent” include lithium bromide and ammonia. Because absorption chillers can make use of waste heat, they can essentially provide free cooling in certain facilities (33).

V. Building Systems and Low-impact Solutions

Building refrigeration, air-conditioning and heat pump (RACHP) systems use a majority of the substances with high global warming potential. This section provides a ready reference of low-impact alternatives to the refrigerants commonly used in RACHP systems. The final selection of the right refrigerant requires good expertise in refrigeration engineering, so it must be undertaken with care by a suitable expert. It might be noted that changing a refrigerant may require changing the refrigeration system itself. Even for refrigerants that are considered "drop-in" replacements, refinements such as refrigerant charge optimization and adjusting the size of the thermal expansion device are needed.

Figure 13 shows the various types of refrigeration, air-conditioning and heat pump equipment used in buildings, with their respective refrigerants and low GWP alternatives.

Equipment Type	Equipment Characteristics	
Refrigerators and Freezers 	Used for: storage of chilled and frozen food and drink products Small hermetically sealed refrigeration system used in appliance insulated with PU foam.	
	Refrigerant charge (kg): 0.05 to 0.3	Cooling capacity (kW): 0.1 to 0.5
	Common ODS refrigerants: CFC-12	
	Common HFC refrigerants: HFC-134a	
	Example low GWP alternatives: HC-600a (iso-butane) HFO-1234yf	
	Comments: Iso-butane is already widely used in many countries. HFO-1234yf and HFO-1234ze not currently used for domestic refrigerators and freezers, but can be considered if local standards prohibit the use of hydrocarbons.	
Small room split air-conditioning 	Used for: room air-conditioning. Single or multi-split configurations. Can be reversible (for heating via air source heat pump in winter).	
	Refrigerant charge (kg): 1 to 10	Cooling capacity (kW): 2 to 40
	Common ODS refrigerants: HCFC-22	
	Common HFC refrigerants: HFC-410A HFC-407C	
	Example low GWP alternatives: HFC-32 blends of HFCs/ HFO (e.g., HFC-446A, HFC-447A, HFC-452B	
	Comments: Propane being offered by a few manufacturers, but higher flammability remains a barrier HFC-32 already in widespread use for small split air-conditioning in Japan and Europe Blends such as HFC-454B recently introduced	

<table>
<tr><td rowspan="6">Ducted air-conditioning
</td><td colspan="2">Used for: cooling of whole dwelling, via an air cooling unit, with cooled air ducted to each room. Can be reversible (for heating via air source heat pump in winter).</td></tr>
<tr><td>Refrigerant charge (kg):
1 to 3</td><td>Cooling capacity (kW):
2 to 12</td></tr>
<tr><td colspan="2">Common ODS refrigerants: HCFC-22</td></tr>
<tr><td colspan="2">Common HFC refrigerants: HFC-410A HFC-407C</td></tr>
<tr><td colspan="2">Example low GWP alternatives: HFC-32, R-290,HFC-446A, HFC-447A, HFC-452B</td></tr>
<tr><td colspan="2">Comments: Refrigerant charge in ducted systems usually too large for safe use of propane. HFC-32 and HFC-454B can be used as alternatives to HFC-410A, with compact compressors and can have very good efficiency
If a non-flammable refrigerant is required, HFC-513A and HFC-450A have characteristics similar to HFC-134a – a larger compressor is required than for HFC-32</td></tr>
<tr><td rowspan="6">Heating-only heat pump
</td><td colspan="2">Used in cool climates for space heating</td></tr>
<tr><td>Refrigerant charge (kg):
2 to 5</td><td>Cooling capacity (kW):
4 to 20</td></tr>
<tr><td colspan="2">Common ODS refrigerants: HCFC-22</td></tr>
<tr><td colspan="2">Common HFC refrigerants: HFC-410A HFC-407C</td></tr>
<tr><td colspan="2">Example low GWP alternatives: HFC-32, HFC-446A, HFC-447A, HFC-452B</td></tr>
<tr><td colspan="2">Comments: Many heat pumps are located outdoors – propane can be used safely in such locations
If the equipment is indoors a lower flammability refrigerant such as HFC-32 can be used</td></tr>
<tr><td rowspan="6">Multi-room VRF air-conditioning
</td><td colspan="2">Systems connecting multiple indoor units to an outdoor condensing unit.</td></tr>
<tr><td>Refrigerant charge (kg):
10 to 100</td><td>Cooling capacity (kW):
40 to 150</td></tr>
<tr><td colspan="2">Common ODS refrigerants: HCFC-22</td></tr>
<tr><td colspan="2">Common HFC refrigerants: HFC-410A</td></tr>
<tr><td colspan="2">Example low GWP alternatives: HFC-32, HFC-446A HFC-447A, HFC-452B</td></tr>
<tr><td colspan="2">Comments: VRF systems can provide very efficient air-conditioning and can also provide heating to parts of a building if required. However, with larger refrigerant charge it is more difficult to use lower flammability (2L) refrigerants in VRF units than in smaller split systems. They can be used in some applications with appropriate safety precautions e.g. leak detectors and automatic ventilation. If a non-flammable refrigerant is required it is possible to use ducted systems and a refrigerant such as HFC-513A</td></tr>
</table>

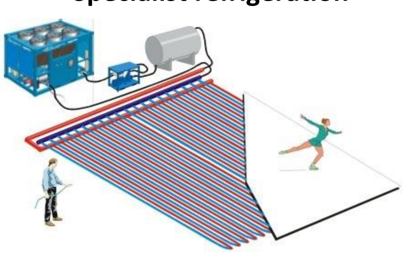
Water chillers for central air-conditioning 	Used for: large air-conditioning systems e.g. in university buildings Integrated unit for chilling of water in shell and tube heat exchanger and water cooled condenser	
	Refrigerant charge (kg): 50 to 500	Cooling capacity (kW): 200 to 2,000
	Common ODS refrigerants: HCFC-22 HCFC-123	
	Common HFC refrigerants: HFC-134a HFC-410A	
	Example low GWP alternatives: HFO-1234ze, HFO-1234yf, HFO-1233zd R-717 (ammonia)	
	Comments: Ultra-low GWP alternatives already available. Newly commercialised HFO-1234ze quickly becoming available as a replacement for HFC-134a in medium pressure chillers. HFO-1233zd recently commercialised and becoming available as a replacement for HCFC-123 in low pressure chillers. Ammonia a possibility but high toxicity may limit applicability and increase cost. Propane a possibility but high flammability may limit applicability and increase cost.	
District cooling 	Large chilled water systems serving several buildings	
	Refrigerant charge (kg): 1,000 to 10,000	Cooling capacity (kW): 2,000 to 20,000
	Common ODS refrigerants: HCFC-22 HCFC-123	
	Common HFC refrigerants: HFC-134a	
	Example low GWP alternatives: HFO-1234ze HFO-1233zd, HFO-1234yf, R-717 (ammonia)	
	Comments: These are usually based on very large water chillers located in a dedicated building. Any of the safety issues (e.g. toxicity or flammability) can be dealt with in the design of the plant room. The chillers for district cooling should always use an ultra-low GWP refrigerant.	
Specialist refrigeration 	Used for various applications such as ice rinks and ski centres	
	Refrigerant charge (kg): 50 to 500	Cooling capacity (kW): 100 to 1,000
	Common ODS refrigerants: HCFC-22	
	Common HFC refrigerants: HFC-134a HFC-404A	
	Example low GWP alternatives: HFC-513 A, HFO-1234ze, HFO-1234yf, R-717 (ammonia R-744 (CO_2)	
	Comments: Ammonia is widely used for ice rinks. CO2 has been introduced more recently.	

Figure 13. Examples of different types of RACHP equipment and their respective refrigerants for use in buildings.

Besides the common refrigerants mentioned above, some other refrigerant types are also available. The following tables group refrigerants by type and application and provide their GWP, ODP, and flammability (these characteristics are explained in Sections I and II). Each table is followed by explanatory notes that are referenced in the rightmost column of the tables.

Air-conditioning systems

Figure 14 lists the high-impact refrigerants and their low-impact alternatives for all air-conditioning systems – small and large – in buildings. The options are presented in the following categories (see columns under System Type to the right of the table):

1. S = Small self-contained systems
2. SPL = Small split systems
3. L = Large air-to-air systems
4. CH = Water chillers

REFRIGERANT OPTIONS for AIR CONDITIONING SYSTEMS (Small and Large)

Type	Refrigerant	GWP	ODP	Flammability	SYSTEM TYPE				Note #
					S	SPL	L	CH	
CFC	CFC-11	4660	1						
	CFC-12	10200	1						
	CFC-13	5820	0.8						
HCFC	HCFC-22	1810	0.055						
	HCFC-141b	782	0.11						
	HCFC-142b	1980	0.065						
Blend	R-404A	3922	0						
	R-410A	2088	0						
	R-407C	1774	0						
HFC	**HFC-134a**	1430	0						
	HFC-32	675	0	2L					1
HC	R-441A (HCR188C)	6	0	3					2
	Propane (HC-290) (R-290)	3	0	3					3
	HC-1270	1-5	0	3					4
Blend	R-432A, B, C	1-5	0	3					5
	R-436A, B	1-5	0	3					5
	R-447A	582	0	2L					6
	R-446A	460	0	2L					6
	R-454B	460	0	2L					6
	Blends awaiting ASHRAE number	250 to 700	0	2L					7
	R-450A	601	0	1					8
	R-513A	631	0	1					8
	R-513B*	596	0	2L					8
	R-451A	140	0	2L					8
	R-451B	150	0	2L					8
	Blends awaiting ASHRAE number	150 to 700	0	2L					9
CO2	CO2 (Carbon Dioxide) (R-744)	1	0	1					10
HFO	HFO-1234yf	4	0	2L					11
	HFO-1234ze	7	0	2L					11
	HFO-1233zd	5	0	1					12
	HFO-1336mzz	9	0	1					12
Water	R-718 (Water)	0	0	1					13
NH3	R-717 (Ammonia)	0	0	2L					14

LEGEND 1:
- High GWP
- Med GWP
- Low GWP

LEGEND 2:
- **S** Small Self-contained
- **SPL** Small Split
- **L** Large Air-to-Air
- **CH** Water Chillers

Not In Kind Solutions
- Improved Building Shell
- Evaporative Coolers
- Desiccant Drying
- Absorption Chillers

Figure 14. Refrigerant alternatives for air-conditioning systems (small and large) (2) (34). Related notes are on the next page.

Note 1. HFC-32 is a lower flammability refrigerant with characteristics similar to R-410A and a much lower GWP. HFC-32 has been used for small split air conditioning in East Asia and India since 2012 and in Europe since 2013. It is also suitable for multi-splits, variable refrigerant flow (VRF), and ducted systems, subject to compliance with refrigerant charge restrictions in safety regulations. Several major air-conditioning manufacturers now have a number of HFC-32 models available. HFC-32 is suitable for small- and medium-sized chillers.

Note 2. Hydrocarbons (HCs) are being used in small self-contained air-conditioning units, where, in most cases the refrigerant charge is low.

Note 3. HCs suitable for small- and medium-sized chillers. Available widely in Europe.

Note 4. HC-290 and HC-1270 have been used for small split air-conditioning units in Europe for several years and in East Asia and India since 2012. Suitable for small- and medium-sized chillers. Available widely in Europe. In spite of their high flammability, HCs can be considered for use in some equipment in this sector, depending on refrigerant charge, indoor unit location, and room size.

Note 5. HCs can be considered for some equipment in the small split systems sector, depending on refrigerant charge, indoor unit location, and room size.

Note 6. Newly developed lower-flammability HFO/HFC blends with characteristics similar to R-410A. These are a possible alternative for multi-splits, VRF, and ducted systems, subject to compliance with refrigerant charge restrictions in safety regulations. Being considered for small- and medium-sized chillers.

Note 7. Blends under development with properties similar to R-410A.

Note 8. Newly developed blends with properties similar to HFC-134a. The non-flammable options are possible alternatives for ducted and packaged rooftop units. The lower flammability options may also be suitable for these applications subject to compliance with refrigerant charge restrictions in safety regulations. Suitable for medium-sized chillers using screw compressors. These options are not considered suitable for multi-split and VRF systems, due to their negative impact on capital cost and efficiency.

Note 9. Blends under development with properties similar to R-410A or HFC-134a.

Note 10. R-744 can be used for larger air conditioning typically in ducted-type systems. Efficiency is acceptable only in cool weather conditions.

Note 11. These HFOs also have properties similar to HFC-134a and could be considered for ducted and rooftop units, subject to compliance with refrigerant charge restrictions in safety regulations.

Note 12. New fluids suitable for low-pressure centrifugal chillers as an alternative to HCFC-123. HFO-1233zd models are commercially available.

Note 13. Water can be used as a refrigerant in chiller systems, but requires very large compressor swept volume.

Note 14. Suitable for medium- and large-sized chillers with screw compressors. More commonly used for industrial chillers but can also be used in air conditioning.

Heating-Only Heat Pump Systems

Figure 15 shows high-impact refrigerants and low-impact alternatives for heating-mode-only heat pumps. Heat pump types include those for space heating, water heating, and district heating.

REFRIGERANTS for HEATING ONLY HEAT PUMP SYSTEMS

Type	Refrigerant	GWP	ODP	Flammability	SYSTEM TYPE			Notes #
					Space	**DHW**	**District**	
CFC	CFC-11	4660	1					
	CFC-12	10200	1					
	CFC-13	5820	0.8					
HCFC	HCFC-22	1810	0.055					
	HCFC-141b	782	0.11					
	HCFC-142b	1980	0.065					
Blend	R-404A	3922	0					
	R-410A	2088	0					
	R-407C	1774	0					
HFC	**HFC-134a**	1430	0					
	HFC-32	675	0	2L				1
HC	HC-600A	1-5	0	3				2
	Propane (HC-290) (R-290)	3	0	3				2
	R-432A, B, C	1-5	0	3				2
	R-436A, B	1-5	0	3				2
	R-441A (HCR188C)	6	0	3				2
	R-447A	582	0	2L				3
	R-446A	460	0	2L				3
	R-454B	460	0	2L				3
	CO2 (Carbon Dioxide) (R-744)	1	0	1				4
	HFO-1234ze	7	0	2L				5
	HFO-1233zd	5	0	1				6
	HFO-1336mzz	9	0	1				
	R-717 (Ammonia)	0	0	2L				7

LEGEND 1:

High GWP

Med GWP

Low GWP

LEGEND 2:

Space Space Heating

DHW Domestic Hot Water Heating

District Large District Heating System

Figure 15. Lower-GWP alternatives for heating-only heat pumps (2).

Note 1. Lower flammability refrigerant with characteristics similar to R-410A and much lower GWP. For heat pumps, lower flammability refrigerants can be considered for both outdoor and some indoor locations. HFC-32 was recently introduced in Japan for water heaters.

Note 2. When air-source heat pumps are located completely outdoors and situated safely, higher-flammability refrigerants can be used efficiently.

Note 3. Newly developed lower-flammability HFO/HFC blends with characteristics similar to R-410A are also being considered.

Note 4. R-744 is well suited to water heating because of the large temperature range of the water being heated (e.g., from 10°C to 70°C, heated in one step). Several million are in operation in Japan, but subsidies were provided. R-744 water heaters are not common outside Japan.

Note 5. Being considered for heat pumps with large centrifugal compressors as an alternative to HFC-134a.

Note 6. Newly introduced fluids suitable for low-pressure centrifugal compressors. May be used in large heat pumps, especially with a high delivery temperature (e.g., as an alternative to HFC-245fa).

Note 7. Used in a number of large district heating and space-heating installations, especially in Northern Europe.

Refrigerators—Commercial, Industrial, and Residential

These represent systems used for the storage and display of products in the food and drink retail market, wholesale food storage, and domestic systems.

The commonly used refrigerants in **commercial refrigerators** are R-404A (GWP 3,922) and HFC-134a (GWP 1,430); both have a high GWP. The GWP of alternative refrigerants varies: natural refrigerants like NH_3 have 0 GWP, while new blends with similar properties to HFC-404A have a GWP in the range of 460–582 (35).

Larger **industrial refrigerator** systems, normally used in the non-residential sector for the storage of food, use R-404A (GWP 3,922) as the main refrigerant. Relevant to EDGE buildings are only small and medium-sized systems (10 to 100 kg refrigerant charge), because of the relative high refrigerant charge. The use of low-GWP refrigerants has been difficult due to their flammability risk. The use of R-744 technology developed for the supermarket sector could present an alternative solution for small and medium industrial refrigerator systems (36).

The most common refrigerant used in **domestic refrigerators** is HFC-134a (GWP 1,430). The leakage rate of these appliances is lower than 0.5% (37). The larger emission share occurs at the end-of-life of the appliance. An alternative refrigerant used in this sector is HC-600a (GWP 3).

REFRIGERATION (COMMERCIAL, INDUSTRIAL, RESIDENTIAL)							
Type	Refrigerant	GWP	ODP	Flammability	NEW	RETROFIT	NOTES
CFC	CFC-12	10,900	1				
Blend	R-502	4,657	0.334				
	R-507A	3,985	0				
	R-404A	**3,922**	**0**				1
	R-407A	2,107	0				2
	R-407F	1825	0	1			2
	R-407H*	1495	0	1			3
	R-442A	1888	0	1			3
	R-448A	1387	0	1			3
	R-449A	1397	0	1			3
	R-449B	1412	0	1			3
	HFC-134a	**1,430**	**0**				4
HC	Propane (R-290) (HC-290)	1-5	0	3			5
	HC-600a	1-5	0	3			5
	HC-1270	1-5	0	3			5
HC Blends	R-432A, B, C	1-5	0	3			5
	R-436A, B	1-5	0	3			5
	R-441A	1-5	0	3			5
	CO2 (R-744)	1	0	1			6
	Ammonia (R-717)	0	0	2L			7
HFO	HFO-1234yf	4	0	2L			8
	HFO-1234ze	7	0	2L			8
	R-450A	601	0	1			9
	R-513A	631	0	1			9
	R-513B*	596	0	1			9
	R-451A	140	0	2L			9
	R-451B	150	0	2L			9
	R-454A	239	0	2L			10
	R-455A*	145	0	2L			10
	R-446A	460	0	2L			11
	R-447A	582	0	2L			11
	R-454B	466	0	2L			11
	HFC-32	675	0	2L			12
	Blends awaiting ASHRAE number	150 to 600	0	2L			13

LEGEND 2:

Space Space Heating

DHW Domestic Hot Water Heating

District Large District Heating System

LEGEND 2:

NEW New Equipment

Retrofit Repair of Existing Equipment

Figure 16. Low-GWP alternatives for refrigeration equipment—commercial, industrial, and residential. Related notes are on the next page.

Note 1. R-404A is a common refrigerant used in commercial refrigerators.

Note 2. Better than R-404A.There has been significant use of these blends in Europe as R-404A alternatives (both for new systems and for retrofits). Can have higher efficiency than R-404A systems.

Note 3. Newly developed blends with properties similar to R-404A, but with a lower GWP. As of this writing, their commercial application is limited.

Note 4. The most common refrigerant in both domestic and commercial refrigerators.

Note 5. HCs are suitable for stand-alone equipment (e.g., in ice cream freezers and bottle coolers) and are already used widely in both Article 5 and non-Article 5 countries. HCs may be used in very small condensing units, subject to safety regulations, and as a primary refrigerant in chillers in indirect systems and cascade R-744 systems. They are also used in large supermarkets with multiple stand-alone units rejecting heat into a water circuit.

Note 6. Good for small and medium industrial refrigerators systems (38). For stand-alone systems, they are used in bottle coolers and other equipment condensing units, though capital cost is a barrier in the case of small condensing units. In centralized systems, there is significant use of R-744 in new systems in both transcritical and cascade configurations.

Note 7. Used in indirect systems, but energy efficiency can be low if liquid secondary refrigerants are used.

Note 8. Not currently used, but being considered for stand-alone systems and medium-temperature (MT) condensing units.

Note 9. Newly developed blends with properties similar to HFC-134a. Being considered for MT systems. The non-flammable blends can be considered for large systems. The lower flammability (2L) blends may be suitable for condensing units.

Note 10. Newly developed blends with properties similar to R-404A. Being considered for low-temperature (LT) and MT condensing units.

Note 11. Newly developed blends with properties similar to R-410A. Being considered for condensing units.

VI. Additional Strategies to Minimize Impact

Some immediate and cost-effective steps to reduce emissions from existing refrigeration and air-conditioning equipment in the near term include leak detection and control, and the purchase of certified reclaimed refrigerants. Many types of refrigeration and air-conditioning equipment have leak rates of 10%–25% a year, or higher (22).

Leak Detection and Control

In the RACHP sector, the use of HFCs to top up leaks is estimated to represent 55% to 65% of total HFC consumption. There are excellent opportunities to reduce leakage (3). Significant benefits can be realized from enacting the best refrigerant management practices. When a system is low on refrigerant, the motor has to work harder to provide the necessary heat exchange and cooling, thus requiring more energy than if the equipment is properly charged. General leak rates in the supermarket industry average about 25% of the equipment's refrigerant charge per year; however, industry leaders routinely achieve leak rates under 10%. Benefits of refrigerant management practices include: cutting annual refrigerant costs, increasing the energy efficiency of existing systems and decreasing energy use, and drastically decreasing emissions of HCFCs and HFCs, as well as indirect emissions of CO_2, because of reduced energy use (22).

Leak detection systems are of two types: area monitors and leak pin-pointers. Area monitors signal when a leak has occurred in a specific area, such as an equipment room, while a leak pin-pointer is used by a professional to check individual joints or components of a system once the area monitor has found a leak. Fluorescent additives can also be injected along with oil into the system to allow to be detected using a UV lamp. Several companies manufacture leak detection systems (22).

Purchase of Certified Reclaimed Refrigerants

Refrigerants that have reached their end-of-life or require recharging due to leaks can be recharged using either "new" or "certified reclaimed" refrigerant gas. As old equipment reaches its end-of-life it is important to recover the old refrigerants. This reduces end-of-life emissions and creates an opportunity to reclaim the recovered refrigerant for re-use. Using a reclaimed refrigerant outside a "phase-down quota system" can be an important way to encourage end-of-life recovery (3).

HCFCs are being phased out, but a certified reclaimed refrigerant can be used to service old equipment. Though HFCs are still abundantly available, reclaimed refrigerants are often cheaper than new refrigerants. It is recommended that reclaimed refrigerants be used; this displaces the production of new refrigerants, thus reducing overall emissions (22).

VII. Potential Global Impact of Adoption by EDGE Users

In this section we estimate the CO_2e emissions savings potential that might be achieved by a transition to low-GWP refrigerants in EDGE-certified buildings. The underlying assumptions of the analysis are also included.

For a quick comparison of CO_2e emissions on the RACHP market we selected a list of equipment based on the UNEP's Fact Sheet series. This list (see Figure *17*) offers a quick overview of the emission-savings potential of this market. It displays the refrigerants used for various types of equipment and their corresponding GWP. It also includes the typical refrigerant charge, its cooling duty, as well as the expected leakage rate. We make use of these data to create a BAU scenario for a quick estimation of the saving potentials of CO_2e through the adoption of alternative refrigerants in the RACHP market in EDGE-certified buildings. The saving potential, by equipment type, is computed based on available alternative refrigerants used in this type of equipment.

#		Type	Refrigerant Charge (kg)	Cooling Load (kW)	HFC	GWP	Leakage Rate
1		Portable	0.2 to 2	2 to 7	R-407C R-410A	1,774 2,088	< 1%
2		Small single split	0.5 to 3	2 to 12	R-407C R-410A HFC-32	1,774 2,088 675	1% to 4%
3		Large single- and multi-split	3 to 10	10 to 40	R-407C R-410A	1,774 2,088	1% to 4%
4		Variable refrigerant flow (VRF)	5 to 100	12 to 150	R-407C R-410A	1,774 2,088	1% to 5%
5		Ducted	5 to 100	12 to 200	R-407C R-410A	1,774 2,088	2% to 6%
6		Water chiller	20 to 250	50 to 750	R-407C R-410C	1,774 2,088	2% to 4%
			250 to 6,000	750 to 10,000	HCF-134a	1,430	2% to 4%

Figure 17. *Defined BAU equipment and used refrigerant.*
Source: UNEP HFC Management Documents*: Technical* Fact Sheets 1,4,7,8,9,10, and 11 *(39)*

To assess the savings potential, it is important to define a BAU scenario in which alternative refrigerants are used for the same equipment. In this exercise, only direct emissions from a refrigerant transition are considered; end-of-life, installation, and maintenance emissions are not considered. Also, only cooling equipment is included in the analysis (domestic or commercial refrigerators are not included, although the EDGE certification program takes into account the energy efficiency of both domestic and commercial refrigerators). The EDGE certification program includes five building types: (1) residential, (2) hotels, (3) offices, (4) hospitals, and (5) retail. We have chosen different assumptions for each building type; see Figure 20 in the next section for an overview of the assumptions made by building type and geographical region.

For each equipment type and refrigerant, we compute a BAU scenario, expressed as CO_2e emissions per kW cooling duty, E_{HFC}.

$$E_{HFC} = (m_{HFC} \times GWP_{HFC} \times Life \times LQ_{HFC}) \div Q_{HFC}$$

Where m is the refrigerant charge (kg), GWP is the global warming potential (CO_2e), $Life$ is the life span used for the computation (10 years), LQ is the yearly leakage rate of the equipment (%), and Q is the cooling duty of the equipment.

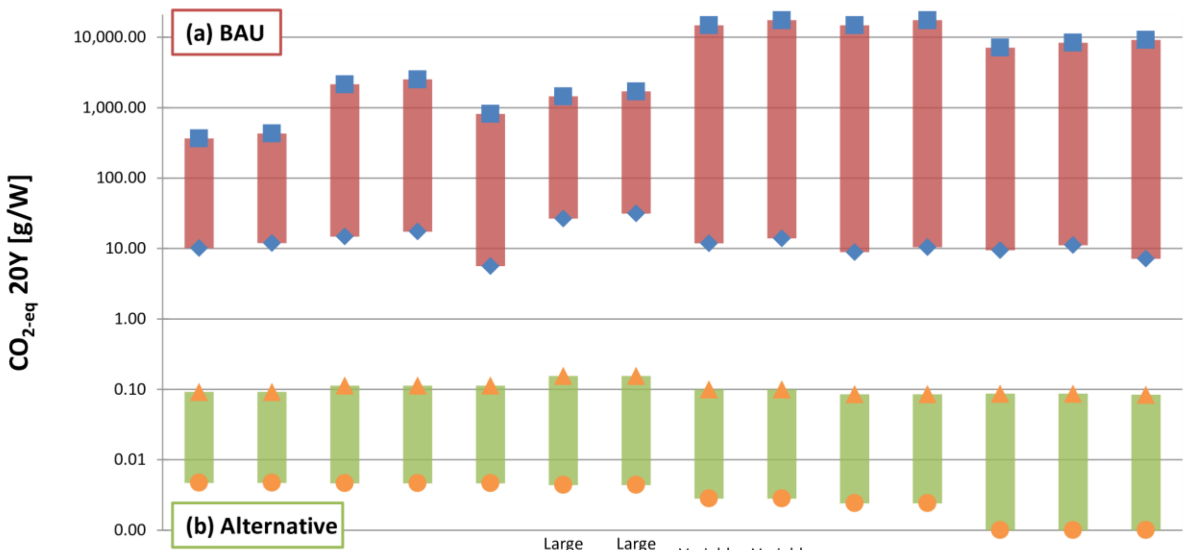
The savings potential of alternative refrigerants is computed using the same equation, but with the GWP of the alternative refrigerants listed in Figure 18. For each selected equipment and each defined alternative refrigerant, we recomputed the CO_2e emissions. Because of the large range of the assumptions, the results also range widely. The estimation could be improved by using more accurate data to define the assumptions.

The savings potential is then computed for each HVAC equipment type as the difference between the BAU scenario and the alternative scenarios. The potential is expressed as potential CO_2e emissions savings per cooling duty. This simple computation aims to capture the possible savings that can be achieved through the use of alternative refrigerants in the building sector.

		Equipment type (See Table 1)					
Refrigerant	**GWP**	**1**	**2**	**3**	**4**	**5**	**6**
R-717 (ammonia)	0						X
R-718 (water)	0						X
R-744 (CO_2)	1			X	X	X	
HC-1270	2		X				X
HC-290	3	X	X				X
HFO-1234yf	4			X	X	X	
R-432A,B,C	5		X				
R-436A,B	5		X				
HFO-1233zd	5						X
R-441A	6	X	X				
HFO-1234ze	7			X	X	X	X
HFO-1336mzz	9						X
R-451A	140			X	X	X	
R-451B	150			X	X	X	
R-454B	460	X	X	X	X	X	X
R-447A	582	X	X	X	X	X	X
R-513B	596			X	X	X	X
R-450A	601			X	X	X	X
R-513A	631			X	X	X	X
R-446A	640	X	X	X	X	X	X
HFC-32	675	X	X	X	X	X	X
Blends awaiting ASHRAE number	700	X	X	X	X	X	

Figure 18. Alternative refrigerants for the defined equipment types.
Source: UNEP HFC Management Documents: Technical Fact Sheets 1,4,7,8,9,10, and 11 (39)

Figure 18 lists the GWP of alternative refrigerants. An "X" indicates the equipment type in which the defined refrigerant can be used. This assumption adds another layer of uncertainty to the computation because of the large GWP range of refrigerants. To address this uncertainty, we estimate the emissions for each possible alternative refrigerant. We present the result as the minimum and maximum emissions, by equipment type. These results are depicted in Figure 19. To visualize the computed emissions under: (a) the BAU scenario (red) and (b) the alternative scenario (green), we had to plot the values on a logarithmic scale. The columns in the plot represent the possible range of emissions by equipment with different leakage rates, cooling loads, and different refrigerants.



	Portable R-407C	Portable R-410A	Small single split R-407C	Small single split R-410A	Small single split HFC-32	Large single- and multi-split R-407C	Large single- and multi-split R-410A	Variable refrigerant flow (VRF) R-407C	Variable refrigerant flow (VRF) R-410A	Ducted R-407C	Ducted R-410A	Water chiller R-407C	Water chiller R-410C	Water chiller HCF-134a
BAU Max E	354.80	417.60	2,128.80	2,505.60	810.00	1,419.20	1,670.40	14,783.3	17,400.0	14,783.3	17,400.0	7,096.00	8,352.00	9,152.00
BAU Min E	10.14	11.93	14.78	17.40	5.63	26.61	31.32	11.83	13.92	8.87	10.44	9.46	11.14	7.15
Alternative Max E	4.00	4.00	5.83	5.83	5.83	10.50	10.50	4.67	4.67	3.50	3.50	3.60	3.60	3.38
Alternative Min E	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.00

Figure 19. CO_2 emissions per cooling load for various types of equipment using (a) business-as-usual refrigerants or (b) alternative refrigerants with a low GWP.

Figure 19 depicts the possible emissions, expressed as CO_2e per cooling load for a 20-year life span, resulting from both scenarios. These values are used to project the potential emissions savings of EDGE-certified buildings. These savings are computed by geographical region and building type, expressed as square meters of a certified building. This projection is presented in the next section.

Using these assumptions we compute the total required cooling load by region and building type. The resulting emissions for the BAU and alternative scenarios are computed for each year, region, and building type. The potential emissions savings are computed as the range between the maximum and minimum expected savings from a transition to low-GWP refrigerants.

Figure 17 groups the assumptions into four sections: (1) share of EDGE-certified floor space with active cooling, by building type and geographical region; (2) share of projected floor space, by geographical region; (3) share of projected floor space, by building type; (4) total projected EDGE-certified floor space until fiscal year 2023; and (5) maximum and minimum cooling loads.

(1) Percentage of floor space with cooling by region and building type

	Residential	Hotels	Offices	Hospitals	Retail
East Asia and Pacific (EAP)	65%	100%	100%	100%	70%
Latin America and the Caribbean (LAC)	50%	70%	60%	60%	50%
Africa	60%	90%	70%	80%	60%
India	70%	100%	100%	100%	90%

(2) Share of projected EDGE certifications by region

EAP	34%
LAC	4%
Africa	2%
India	60%

(3) Share of projected EDGE certifications by building type

Residential	Hotels	Offices	Hospitals	Retail
80%	5%	5%	5%	5%

(4) Projected EDGE-certified floor space by the end of FY 2023

4.08E+08	m^2 of EDGE-certified floor space by FY23
1.76E+08	m^2 of EDGE yearly certified floor space in FY23
1.00E+06	m^2 of EDGE yearly certified floor space in FY16

(5) Cooling load

min	**max**
20[W/m^2]	50[W/m^2]

Figure 20. Assumptions for the calculation of savings in emissions if EDGE users were to adopt low-impact refrigerants.

As a result of the large range of the initial assumptions, the resulting savings potential of the alternative scenarios also ranges widely. Figure 18 shows the projected emissions savings for:

Scenario A: Minimum projected savings, and

Scenario B: Maximum projected savings,

The difference between Scenarios A and B is greater than three orders of magnitude.

In the Minimum projected savings scenario (Scenario A), the savings are dominated by the residential sector; this is because the improvement in refrigerants in all sectors is considered to be minimal, so the large share of projected floor space allocated to the residential sector has the predominant impact. The residential sector does not dominate in the Maximum projected savings scenario (Scenario B), because the savings potential per unit of floor space is higher in the non-residential sector because of the large equipment used in this sector which use refrigerants with a large GWP value.

The results of this quick estimation reflect the uncertainties surrounding the equipment used across building types and regions. The large GWP range of refrigerants also contributes to the uncertainty. More accurate results would require empirical data from certified projects in specific regions.

Factors not considered in this projection are: (1) end-of-life emissions, (2) maintenance or installation emissions, and (3) improvements in equipment efficiency over time. The consideration of these emissions would only increase the level of uncertainty of the analysis.

The values for leakage rates were taken from UNEP fact sheets describing various equipment types. Shah (40) uses an annual operation leakage of 10% for a mini-split air-conditioning unit using R-410A as a refrigerant. In this report we use a range between 1% and 4% for the same equipment. Using a fixed leakage rate for the estimation of emissions is a viable way to reduce uncertainty. A variation in the leakage rate has a direct effect on the estimated emissions. In this analysis we consider a leakage rate between 1% and 4%; increasing the leakage rate to 10% would only expand the difference between the maximum and minimum estimated emissions.

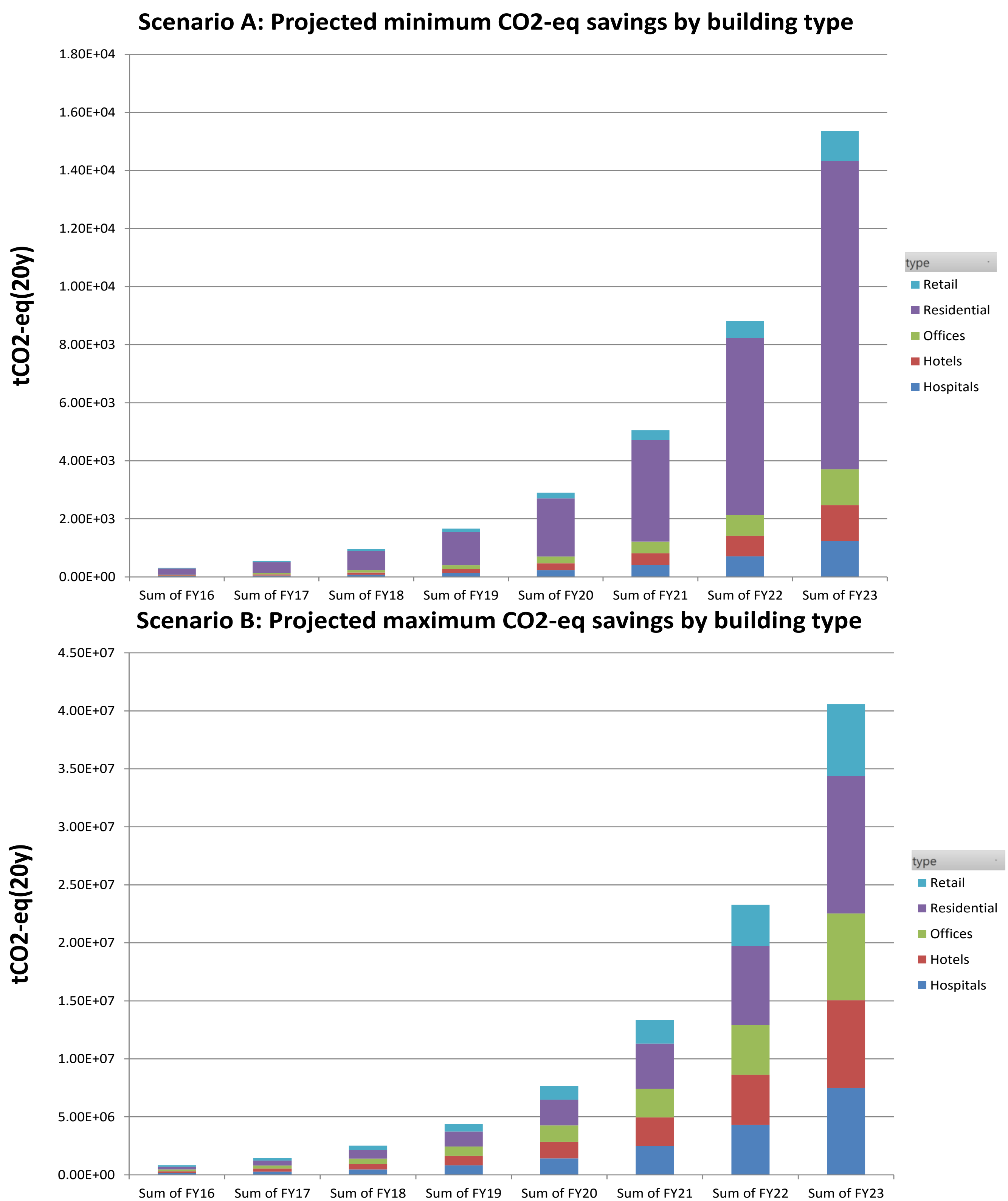


Figure 21. Projected CO_2 savings (minimum and maximum), by building type

As seen in

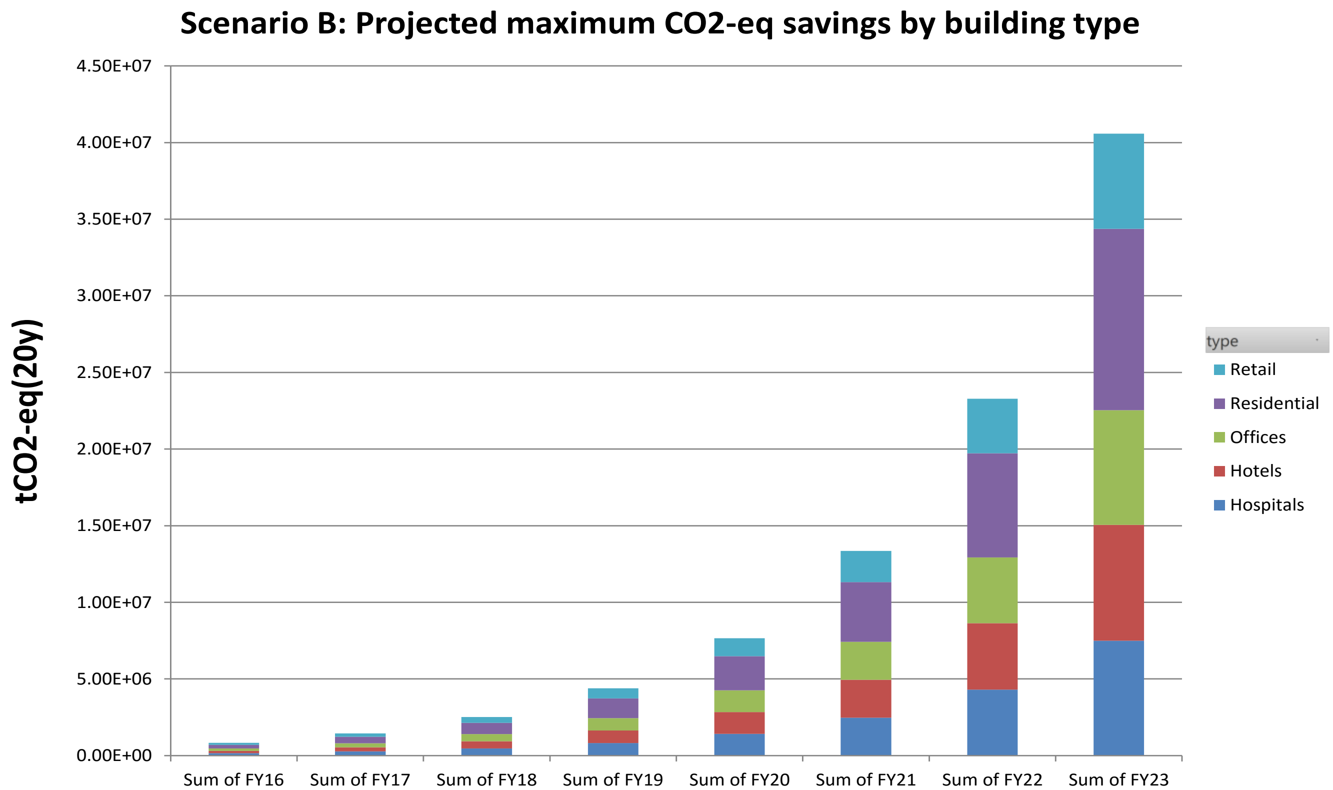


Figure 21, if all EDGE users were to follow this guidance, a projected 40 million tonnes of CO_2e emissions could be avoided by 2023. To put this in perspective, global GHGs (in equivalent tonnes of CO_2 emissions) are about 35 billion tonnes per year (1).

VIII. Resultant Addition to the EDGE User Guide

After studying the impact of refrigerants on the environment, the possible alternatives, and the requirements of various countries (Annex C) and of other green-building rating systems—such as Leadership in Energy and Environmental Design (LEED), the Building Research Establishment Environmental Assessment Methodology (BREEAM), and Green Star (Annex D)—the following guidance is provided for the use of refrigerants in EDGE-certified buildings.

Impact of Refrigerants

The type of refrigerants used within the building HVAC systems and of domestic or commercial refrigerators should (1) aim for a zero ODP, and (2) avoid refrigerants with a high GWP.

As recommended by the now-universal international agreement known as the Montreal Protocol, the use of refrigerants with a zero ODP and a low GWP is strongly encouraged within EDGE-certified buildings. The selection process requires good expertise in refrigeration engineering, so must be undertaken with care by a suitable expert.

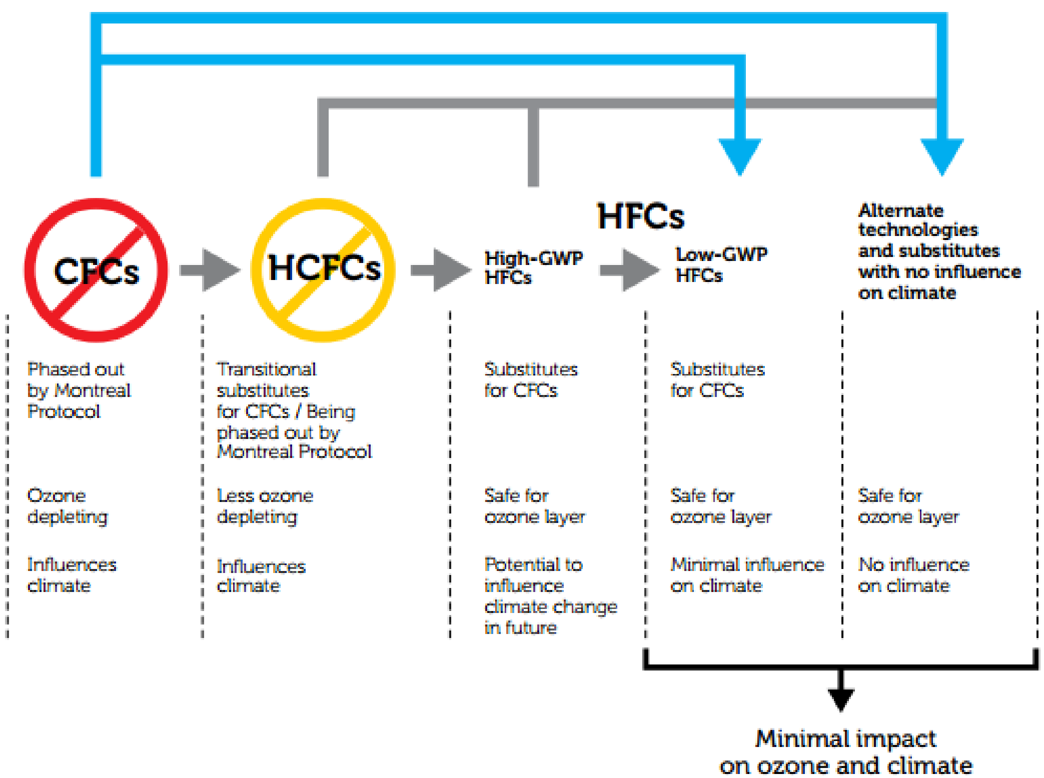


Figure 22. Status of the Montreal Protocol as of October 2015. The general strategy following the adoption of the Montreal Protocol is to move away from using ozone-depleting substances (3)

If the system envisions the use of an existing cooling system, a clear phase-out schedule for refrigerants with an ODP larger than zero or a high GWP should be developed.

If the project envisions the use of flammable or toxic alternative refrigerants, it should follow the best practice and global standards defining the management of such equipment, ensuring the safety of all building occupants.

In the case of a district cooling implementation, the guidelines listed above should be taken into account.

For suitable alternatives, users can refer to the EDGE Guidance document on coolants.

Please note that compliance with low-ODP and low-GWP refrigerants is not covered under EDGE audits of design or construction at this stage and constitutes a voluntary action of the project owner.

ANNEX A. Other Harmful Substances in Buildings (besides Refrigerants)

Besides refrigerants, some other building applications use harmful substances (especially hydrofluorocarbons, HFCs); more benign alternatives are available and are being used worldwide, as seen in Figure 23.

Sector	Examples of Alternatives	Use of Alternatives in Sector		
		Industrialized	Developing	Global Countries
Fire protection systems	Water, foams, dry chemicals, inert gases	–	–	75%
Solvents	Aqueous, no-clean, alcohols, others	>90%	>80%	>80%

Figure 23. Examples of sectors which use a substantial percentage of alternatives (15).

Foam Insulation

Foam insulation is used in buildings, in refrigerators, and as building insulation. Foam insulation is manufactured using foam-blowing agents; the blowing agent is used to convert liquid plastic resin into useable open- or closed-cell foam products. Some countries such as the United States use chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and HFCs as foam-blowing agents, while other countries have transitioned to climate-friendly alternatives. For example, in Germany, a significant portion of foam applications utilize natural foam-blowing agents, such as carbon dioxide (CO_2) and ethanol, hydrocarbons (HCs), methyl formate, and water. As concerns regarding HFCs rise, many companies have transitioned or are planning to transition to natural blowing agents. Hydrofluoroolefins (HFOs) are another alternative to foam-blowing applications, although there are other environmental concerns—toxicity in rainwater and volatile organic compound (VOC) emissions—if HFOs are used widely beyond current estimates (22).

Fire Suppression

Fire suppression using fire extinguishers or built-in systems might use halons or CFCs, both of which are banned by the Montreal Protocol. The two common types of halons are Halon 1301 (used in fire suppression systems) and Halon 1211 (in fire extinguishers). Some fire suppression products still use HFCs, though climate-friendly low-GWP alternatives are already on the market for all fire equipment types. The climate-friendly products available cover fires from ordinary combustibles, fires fueled by flammable or combustible liquids, and energized electrical fires. They use CO_2, inert gases (nitrogen, argon), water-atomizing, potassium nitrite, monoammonium phosphate, and sodium bicarbonate (22).

Aerosols and Solvents

Aerosol products are used in consumer, technical, and medical applications. Building-related aerosols include cleaning products and sprays used for commercial and industrial maintenance, including to clear dust and lint and difficult-to-reach places such as the inside of photocopiers and automated teller machines (ATMs); freeze sprays; flux removers; mold-release agents; and electronic contact cleaners used to dissolve and remove oil, grease, flux, condensation, and other contaminants quickly from delicate electronic circuitry and expensive electronic instrumentation. Natural alternatives such as HCs, dimethyl ether, CO_2, and inert gases are already in wide use in many kinds of aerosols.

Solvents are used in a variety of products, with the largest application being cleaning products, including precision electronics and metal cleaning. Alternatives exist for most solvents (22).

ANNEX B. Refrigerant Family Names

Generation	Fluid Family	Full Name	Examples	Comments
First	CFC	Chlorofluorocarbon	CFC-11 CFC-12	CFCs are phased out under the Montreal Protocol.
Second	HCFC	Hydrofluorocarbon	HCFC-22 HCFC-123	HCFCs are in the process of being phased out under the Montreal Protocol.
Third	HFC	Hydrofluorocarbon	HFC-134a HFC-125 HFC-32	HFCs were introduced in the 1990s as alternatives to CFCs and HCFCs.
Fourth	HFO	Hydrofluoroolefin	HFO-1234ze HFO-1234yf HFO-1233zd	HFOs are recently developed chemicals being used as low-GWP alternatives in various markets including refrigeration, air conditioning and heat pumps (RACHP), foams, and aerosols. HFOs are also referred to as unsaturated HFCs (u-HFCs). The term HFO has become widely used by users and suppliers.
	HC	Hydrocarbon	HC-290 (propane) HC-600a (isobutane)	HCs are being used as low-GWP alternatives in various markets including RACHP, foams, and aerosols.
	Blends of two or more components		R-404A R-410A R-507A	Blends are widely used in RACHP. The 400-series are non-azeotropic blends. The 500 series are azeotropic blends.
	Non-organic fluids		R-717 (ammonia) R-744 (CO_2)	R-717 and R-744 are low-GWP alternatives used mainly in RACHP applications.

Figure 24. Fluid naming conventions for refrigerants (6).

ANNEX C. Country-Specific GHG Regulations and Measures

Figure 25 lists select countries with national and sub-national **HFC** regulations (41).

Country/Region	Taxes, Levies, Fees	Economic and Market-Based Incentives	Prohibition/ Authorization	Required Practices	Voluntary Initiatives/ Education Programs	Import / Export Licensing	Reporting / Recordkeeping Requirements	Prioritization of Climate-Friendly Alternatives
Africa								
Burkina Faso	X					X		
Egypt							X	
Europe and Central Asia								
Austria			X		X			
Belgium					X			
Denmark	X		X					
Estonia							X	
France	X*			X			X*	
Germany			X	X				
Italy				X			X	
Macedonia	X		X			X		
Montenegro	X		X	X		X	X	
Netherlands		X	X	X				
Norway	X	X						
Poland	X						X	
Serbia			X	X		X		
Slovenia	X							
Spain	X							
Sweden	X		X	X				
Switzerland			X	X			X	
Turkey	X		X	X	X	X	X	
United Kingdom				X				
Latin America and the Caribbean								
Belize				X		X	X	
Chile			X	X		X		
Colombia			X	X		X		
Paraguay		X						
North America								
Canada			X	X		X	X	
United States	X	X	X	X	X		X	X
California		X		X	X		X	
Mexico					X			
Island Countries								
Australia	X	X	X	X		X	X	
New Zealand	X	X	X	X			X	
Seychelles		X	X					
East Asia								
China		X*		X				X
Indonesia								X
Japan				X	X		X	
South Korea		X						
West Asia								
Yemen				X			X	

***Proposed Legislation**

Figure 25. Select national and sub-national HFC regulations.

The following is a list of select legislation relating to the use of refrigerants in the building sector in various countries, as well as technical norms made available by various institutions.

Unites States of America

ASHRAE (2013): Safety Standard for Refrigeration Systems and Designation and Classification of Refrigerants. Standard 15-2013 (packaged w/ Standard 34-2013). Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ANSI/ASHRAE standard, 15-2013).

European Union

European Union (EU) (10/31/2009): On substances that deplete the ozone layer. Regulation (EC) No 1005/2009. In *Official Journal of the European Union* L 286/1, checked on 11/9/2015.

"The placing on the market of products and equipment containing or relying on controlled substances shall be prohibited ..." (European Union [EU] 10/31/2009, p. 7).

Refer to Annex I of EU No 1005/2009 for a list of "controlled substances" within the EU (European Union [EU] 10/31/2009, p. 5).

European Union (EU) (5/20/2014): On fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006. Regulation (EU) No 517/2014. In *Official Journal of the European Union* L 150/195, checked on 11/9/2015.

United Kingdom

Department for Environment Transport and the Regions (DETR); Department of Trade and Industry (DTI): Refrigeration & Air Conditioning CFC and HCFC Phase Out: Advice on Alternatives and Guidelines for Users, checked on 11/9/2015.

Germany

ChemOzonSchichtV (2/15/2012): Verordnung über Stoffe, die die Ozonschicht schädigen (Chemikalien-Ozonschichtverordnung—ChemOzonSchichtV). In *Bundesgesetzblatt (BGBl)* (409), checked on 11/9/2015.

DIN EN 378-2, 1/10/2014: Refrigerating systems and heat pumps—Safety and environmental requirements—Part 1: Basic requirements, definitions, classification, and selection criteria.

DIN EN 378-2, 1/10/2014: Refrigerating systems and heat pumps—Safety and environmental requirements—Part 2: Design, construction, testing, marking, and documentation.

Switzerland

Schweizerische Bundesrat (9/1/2015): Verordnung zur Reduktion von Risiken beim Umgang mit bestimmten besonders gefährlichen Stoffen, Zubereitungen und Gegenständen. ChemRRV. In *Bundesblatt (BBl)* 814.81, checked on 11/9/2015.

China

China is the world's largest producer of HCFCs. Following the targets set by the Montreal Protocol, China has started phasing out HCFCs with the help of funding from the Multilateral Fund (MLF) of the Montreal Protocol.

China's plan to phase out ozone-depleting substances (ODSs) was divided across four production sectors and five consumption sectors, and successfully met its targets (42) . The plan also involved some preparation to phase out HCFCs.

Vietnam

In 2010 the Ministry of Environment and Natural Resources of Vietnam banned the import of CFCs; it aims to stop the consumption of HCFCs in Vietnam by 2030.

Indonesia

Indonesia opted to accelerate the phasing out of ODSs, by setting a target date of December 2007 instead of January 1, 2010. By 1998, Indonesia had completed its program to phase out other ODSs. Indonesia has implemented a license system for the import of ODSs, including the import of HCFCs (43).

"On January 1, 2008, Indonesia declared zero consumption of CFC. With the issuance of Minister of Industry and Trade regulation no 229/MPP/Kep/7/1997, the import of halons was banned starting 2008. Therefore, halons consumption in Indonesia was declared zero in 2008" (43).

India

An ODS regulation and control scheme provides a comprehensive set of regulations to control and monitor production and use of ODSs. New investments in and the expansion of manufacturing facilities for the production of ODSs are prohibited.

Brazil

The Brazilian National Plan for the elimination of CFCs was developed to eliminate the consumption of CFCs by January 1, 2007—three years before the target set by the Montreal Protocol (44). Brazil also developed a programme, PBH, to eliminatethe consumption of HCFCs (República Federativa do Brasil 2012). , and controls the import and export of ODSs by setting import and export quotas and by monitoring companies working with these substances (45). The refrigeration and air-conditioning sector in Brazil consumes 60.0% (12.033,63 t) of all ODSs and 45.84% (648,9 t) in terms of ozone depletion potential (ODP) (45).

South Africa

In South Africa, the Air Quality Act, 39 of 2004, published by the Department of Environmental Affairs, came into effect on May 8, 2014. These regulations aim to define the management and phasing out of ODSs in South Africa. These regulations prohibit the use of refrigerants containing hydrochlorofluorocarbons (HCFC-22) in the construction, assembly, or installation of any new refrigeration or air-conditioning systems or equipment from January 1, 2015, onward.

Colombia

Colombia has never produced ODSs, and therefore all consumption is derived from imports. Of the total ODSs consumed in 1995, approximately 73% (1,580 t) were consumed by the refrigeration and air-conditioning sector (46). By 2002, Colombia had reduced the consumption of CFC by 50% (baseline 2002). In 1989, the country banned the use of CFC-based aerosols. In 1997, the country banned the import and production of domestic refrigerators with CFC (47)

Costa Rica

In 2010, Costa Rica managed to eliminate the import of CFCs. The biggest consumer of CFCs was the fishery industry, accounting for a 60% of all imports. In 2013, Costa Rica banned the import of Bromomethane for agricultural use. The import of HCFC is currently regulated by import quotas and is expected to be completely eliminated by 2030 (48).

Philippines

The Philippines has managed to implement a comprehensive plan to phase out ODSs through a set of incentives that include (1) the conversion of the CFC-based manufacturing sector and servicing sector to use alternative, non-CFC technologies; (2) the nationwide assessment and competency certification of refrigeration and air-conditioning service technicians; (3) the accreditation of service shops and the continuing education of the service technicians; and (4) the collection, transport, and storage of used ODSs for reuse and recycling. The import control of ODSs is controlled through registration and certification of importers (49).

Mexico

The National Plan of Mexico for the elimination of HFCs aims to reduce their consumption by 30%, relative to 2008 levels.

Nigeria

The National Ozone Office (NOO) in the Department of Pollution Control under the Federal Ministry of Environment is in charge of the implementation of the targets set by the Montreal Protocol. The country has a draft under review for the (1) protection of the ozone layer, (2) control of import and export of ODP substances, and (3) regulation of the use of ODP substances.

ANNEX D. Requirements of Comparable Green Building Rating Systems Based on the Montreal Protocol

Several green building certification systems require actions based on the Montreal Protocol. This section highlights the recommendations or requirements of six certification systems: (1) Leadership in Energy and Environmental Design (LEED), from the United States (implemented globally); (2) Minergie, from Switzerland; (3) German Sustainable Building Council (DGNB), from Germany; (4) Building Research Establishment Environmental Assessment Methodology (BREEAM), from the United Kingdom; (5) CASBEE, from Japan; and (6) Estidama, from the United Arab Emirates.

LEED (USA)

The intent of the LEED requirements for refrigerant management is to reduce stratospheric ozone depletion. LEED v4 includes a related prerequisite for LEED accreditation, that is, a requirement which does not get LEED points but without which the project will be disqualified for LEED certification. As stated in the Energy and Atmosphere category, under Fundamental Refrigerant Management, the pre-requisite is:

- Do not use chlorofluorocarbon (CFC)-based refrigerants in new heating, ventilating, air-conditioning, and refrigeration (HVAC&R) systems. When reusing existing HVAC&R equipment, complete a comprehensive CFC phase-out conversion before project completion. Phase-out plans extending beyond the project completion date will be considered on their merits.

  Existing small HVAC&R units (defined as containing less than 0.5 pound [225 grams] of refrigerant) and other equipment, such as standard refrigerators, small water coolers, and any other equipment that contains less than 0.5 pound (225 grams) of refrigerant, are exempt.

Users can get credit (LEED points) for enhanced refrigerant management. The stated intent of this credit is to reduce ozone depletion and support early compliance with the Montreal Protocol while minimizing direct contributions to climate change. The credit requirement states:

- Option 1. No refrigerants or low-impact refrigerants (1 point): Do not use refrigerants, or use only refrigerants (naturally occurring or synthetic) that have an ozone depletion potential (ODP) of zero and a global warming potential (GWP) of less than 50.
  OR

  Option 2. Calculation of refrigerant impact (1 point) based on a formula provided in the LEED Manual

Minergie (CH)

The Swiss Minergy label (Minergie-Eco) refers to the Swiss legislation for the use of refrigerants within new and existing buildings (50). The label does not restrict the use of any refrigerant.

DGNB (DE)

The German DGNB green energy building label has 14 indicators. The certification process defines 14 core criteria grouped into 6 main groups: (1) environmental quality, (2) economic quality, (3) sociocultural and functional quality, (4) technical quality, (5) process quality, and (6) site quality. Within the first criteria, “ENV1.1 Life Cycle Impact Assessment,” the label defines five indicators, among them global warming potential (GWP) and ozone depletion potential (ODP). The label does not explicitly restrict the use of refrigerants.

BREEAM (UK)

The BREEAM label attributes credits regarding the impact of refrigerants. The aim of the standard is to reduce the level of GHG emissions arising from the leakage of refrigerants of building systems (51). The label does not restrict the use of any refrigerant. BREEAM provides a list of some common refrigerant types with low GWP.

CASBEE (JP)

The CASBEE rating system provides an incentive to reduce the use of ozone-depleting refrigerants. Scoring criteria LR2 3.2.3 defines four criteria levels. The project can be attributed a Level 3 for the use of refrigerants with an ODP of 0 and Level 4 for the use of natural refrigerants with a ODP of 0 and a GWP of less than 50 (52). The label does not restrict the use of any refrigerant.

Estidama (UAE)

Estidama, the Arabic word for “sustainability,” is an initiative developed and promoted by the Abu Dhabi Urban Planning Council (UPC). The Estidama green building certification system categorically prohibits the use of any CFC refrigerants in the heating, ventilation, and air-conditioning (HVAC) systems of a building. Where existing HVAC equipment is being reused, a comprehensive CFC phase-out plan needs to be developed and implemented prior to project completion (53)

The label also requires a project to demonstrate the four following points: (1) the weighted average of all refrigerants to be installed within the project has an equivalent GWP of 10 or less; (2) the project has installed a permanent refrigerant leak detection system; (3) the project has installed an automatic refrigerant pump down system to a dedicated storage tank with isolation valves; and (4) all gaseous fire suppression systems have a GWP of 1 or less (53). The Estidama green label presents a list of refrigerants and their ODP and GWP values. Natural refrigerants with a zero GWP are also listed.

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