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Availability of low GWP alternatives to HFCs

Feasibility of an early phase-out of HFCs by 2020

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EXECUTIVE SUMMARY

Fluorinated greenhouse gases, including CFCs, HCFCs and HFCs, have a significant impact on climate change. It was recently estimated that they have accounted for 12% of all radiative forcing caused by increased levels of greenhouse gases since the beginning of the industrial revolution.[1] Thanks to the phase-out of CFCs under the Montreal Protocol, atmospheric concentrations of these gases are declining, while those of HCFCs and HFCs used as replacements are rising rapidly.[2] While they do not deplete the ozone layer, many HFCs are potent greenhouse gases.

Emissions of HFCs (excluding HFC-23 by-product) currently contribute around 1% of global greenhouse gas emissions, but are growing by 8-9% annually and have the potential to increase significantly in the future. This is due to their use as replacements for HCFCs and CFCs and because of rapidly increasing demand for refrigeration and air-conditioning in emerging economies.

The European Commission is currently conducting a review of the European Union's (EU) Regulation on the Use of Certain Fluorinated Greenhouse Gases ("F-gas Regulation") and recently published a report showing that the current measures will stabilise emissions at around 110 million tonnes (Mt) CO_2-equivalent per year until 2050. Later this year the Commission will bring forward proposals to improve the performance of the Regulation, which is widely regarded as inadequate in the context of Europe's greenhouse gas targets. Against this backdrop, this report explores the availability of alternatives to HFCs and the potential for 'placing on the market prohibitions' (POMs) of HFCs in new equipment as an effective way of reducing HFC emissions.

There are two long-term technical options for eliminating the influence of HFCs on climate change:

1. *Using fluorine-free substances with low or zero-GWP*. Commercially available examples include:
    - Ammonia
    - Hydrocarbons such as propane and iso-butane
    - Dimethyl ether
    - Water
    - CO_2
    - Other substances used in various types of aerosols, foam products, refrigeration, air conditioning and fire protection systems.

2. *Alternative methods and processes* (termed 'not-in-kind' alternatives): Commercially used examples include fibre insulation materials, dry-powder asthma inhalers and building designs that avoid the need for air-conditioners.[3]

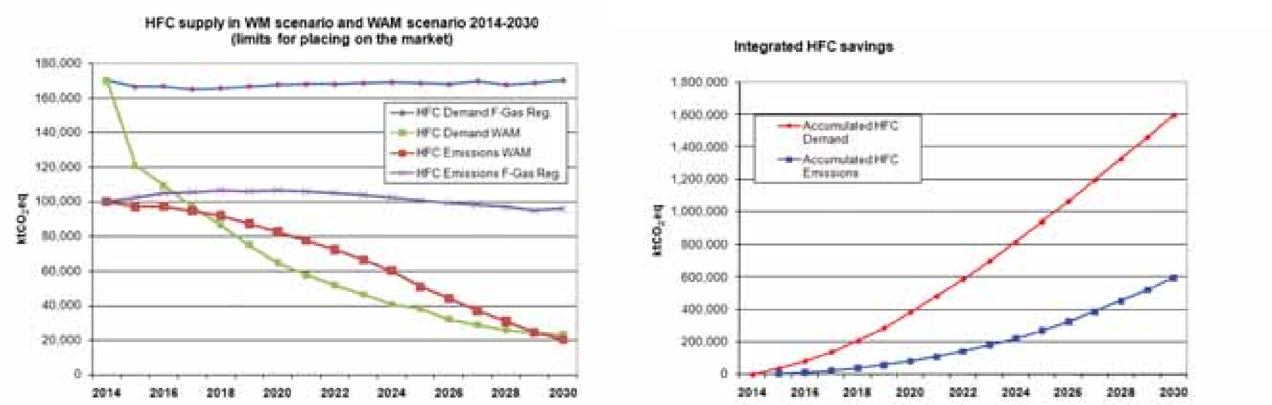
In the EU, low-GWP alternatives to HFCs have already won significant market share in some sectors, with over 90% of new domestic refrigerators/freezers and approximately 25% of new industrial air conditioners using alternatives. In other sectors however, low-GWP technologies remain minor players, although their share of the market could also increase dramatically under the right conditions.

As well as offering lower direct emissions from the refrigerants used, many alternative technologies also provide additional indirect emissions savings through increased energy efficiency, as compared to traditional HFC technologies.

Some barriers to the adoption of alternative technologies exist in some sub-sectors, for example regulations and standards that inhibit the use of flammable and/or toxic alternatives, insufficient supply of components, increased investment costs, and lack of relevant skills among technicians. However, the current use of alternatives demonstrates that these barriers can be overcome, through revised technical standards, training and technical assistance, infrastructure developments and financial subsidies. Perhaps most important is the political will to move away from HFCs through legislation, as demonstrated by Denmark, which has banned the use of HFCs in some sectors in addition to a tax on HFC refrigerants.

This report shows that the use of POM prohibitions (bans) of HFCs in new equipment is the most effective way of reducing the emission of HFCs. The report outlines a clear timetable, setting out the dates by which the use of HFCs can be banned in new equipment for each sub-sector, with a complete phase-out possible in 20 sub-sectors by 2020. The introduction of POM prohibitions alongside measures to capture the maximum technically feasible transition to alternatives up to the prohibition dates will prevent emissions of 75.4 Mt $C0_2$-equivalent per year by 2030. This represents a cumulative reduction in HFC emissions of 600 Mt CO_2-eq. and a cumulative reduction in demand of 1.6 Gt $C0_2$-eq. HFCs by 2030 (right hand figure).

HFC demand (consumption) in kt CO_2 eq. with current F-Gas Regulation (F-Gas Reg.) and the maximum technically feasible which could be achieved with additional measures (WAM) (left) and the resulting cumulative amount of HFC consumption and emission in kt CO_2 eq. which could be avoided by these measures (right). Figures are produced with data kindly provided by Öko-Recherche.



HFC demand (consumption) in kt CO_2 eq. with current F-Gas Regulation (F-Gas Reg.) and the maximum technically feasible which could be achieved with additional measures (WAM) (left) and the resulting cumulative amount of HFC consumption and emission in kt CO_2 eq. which could be avoided by these measures (right). Figures are produced with data kindly provided by Öko-Recherche.

Crucially, there is no single alternative that will replace HFCs in all applications, just as there is no single fluorinated greenhouse gas that can be used in all applications. The low-GWP technology that is most appropriate will depend on a number of factors including the local economic and regulatory situation, as well as climatic and other factors. Nonetheless the evidence is clear that the use of HFCs can be phased out in the majority of sectors by 2020, with safe, affordable and energy efficient alternatives.

1. INTRODUCTION

Water vapour, carbon dioxide (CO_2), methane, nitrous oxide and ozone are the main gases from natural sources responsible for the global warming effect which makes life on earth possible. Without these greenhouse gases the temperature would be about 30 degrees colder and all water would be frozen to solid ice. Most of these gases are also products from our own activity: water vapour is emitted from large cooling towers of power plants; carbon dioxide is produced when burning organic fuels – fossil (coal, oil and gas) as well as biomass; and methane is released from cattle as well as rice farms. We call them manmade greenhouse gases and describe their effect on the climate in terms of their Global Warming Potential (GWP), which compares the amount of heat trapped by a certain mass of the gas in question over a certain time period, compared to the number one climate gas, CO_2. As the reference gas, CO_2 is given the GWP of one. The GWP is calculated over a certain time period, usually 20, 100 or 500 years. So for example, the 100 year GWP of methane is 25, which means that if the same mass of methane and CO_2 were released to the atmosphere, that methane will trap 25 times more heat than CO_2 over the next 100 years.

There is one family of very potent manmade greenhouse gases, produced for special purposes - hydrofluorocarbons, or HFCs. HFCs are manufactured for use in certain applications such as refrigeration or foam blowing. Eventually the HFCs leak out into the atmosphere, either immediately on use (as in aerosol spray cans) or gradually (e.g. in refrigeration and air conditioning as well as firefighting systems) or at the end of product life-time (e.g. enclosed insulation foams). Another HFC emission source occurs during the manufacturing process of HCFCs in the chemical plant.

HFCs were developed as a replacement for CFCs and HCFCs, which are being phased out under the Montreal Protocol due to their destructive impact on the ozone layer. In total, halocarbons[4] (CFCs, HCFCs and HFCs) have been shown to account for 12% of the radiative forcing caused by the increased levels of globally mixed long-lived greenhouse gases throughout the years 1750 to 2009.[5] Due to the phase-out of CFCs under the Montreal Protocol, atmospheric concentrations of CFCs are declining, while those of HCFCs and HFCs are rising rapidly.[6] Even though HFCs have a lower GWP than many of the CFCs and HCFCs they are replacing, their GWP is still very high – in the range of hundreds to thousands of times greater than that of CO_2. The heat trapping part of the HFCs are the Fluorine (F) atoms. The more fluorine and the more stable the molecule is, the higher the atmospheric lifetime and the GWP value becomes. Some HFCs break down relatively quickly in the atmosphere – namely those with a double carbon bond – resulting in a short atmospheric lifetime of e.g. 11 days for HFC-1234yf and implicated low GWP[7] of 4.4 while others have an extremely long atmospheric life e.g. HFC-23 with a lifetime of 270 years resulting in a very high GWP of 14,800.[8]

Although their current contribution to climate forcing (excluding HFC-23 by-product) is around 1% of all greenhouse gases combined (0.4 Gt CO_2 eq.), HFC emissions are currently growing by 8-9% annually and have the potential to become very large in the future.[9] Global HFC emissions in 2050 (5.5–8.8 Gt CO_2-eq yr) will be equivalent to 9–19% (CO_2-eq. basis) of projected global CO_2 emissions in business-as-usual scenarios.[10]

The areas of application for HFCs are primarily: *(market share[11])*

- Stationary and mobile refrigeration and stationary air-conditioning applications (as refrigerant) *(~55% of total HFC use in 2010, expressed in CO_2 eq.)*;
- Mobile air conditioning applications (as refrigerant) *(~24%)*;
- Insulating materials/foam plastics (as blowing agent) *(~11%)*

Other sources of HFC emissions are:

- Aerosols (as propellant gas) *(~5%)*;
- Use as fire extinguishing agent *(~4%)*;
- Use as a solvent *(~1%)*;
- Formation of HFC-23 (not included in Figure 1.1). HFC-23, which has a GWP_{100} of 14,800, is formed as a by-product of the production of HCFC-22. HFC-23 emissions are estimated to be 127 $MtCO_2$eq./yr, which corresponds to 25% of all HFC emissions.[12]
- HFC-23 in semiconductor production as etching gas estimated at ~ <1% *(not included in Figure 1.1)* The use of HFCs is increasing rapidly as a result of CFC and HCFC replacement, global economic development and world population growth, Figure 1.1.

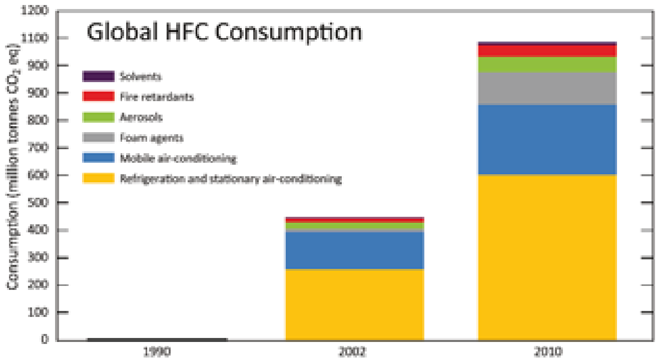


Figure 1.1
Estimated global consumption of HFCs by various sectors, expressed in CO_2-equivalent, for 1990, 2002 and 2010.[13]

This sharp increase can also be seen in the atmospheric concentrations of the two HFCs measured by the World Meteorological Organisation (WMO) since 1995 (see fig. 1.2) which suggests that most of the HFCs produced – with some time delay – end up in the atmosphere where they contribute to global warming. It is estimated that under current practices HFC emissions will increase to 5.5–8.8 $GtCO_2$-eq./yr by 2050, equivalent to 9-19% of the CO_2 emissions based on the Intergovernmental Panel on Climate Change's (IPCC) business-as-usual scenario, and equivalent to 28-45% of CO_2 emissions compared with projected CO_2 emissions in a 450 ppm CO_2 stabilisation scenario.[14] HFC emissions in 2050 will thus largely offset the climate benefits already achieved by the Montreal Protocol through the phase-out of CFCs.[15]

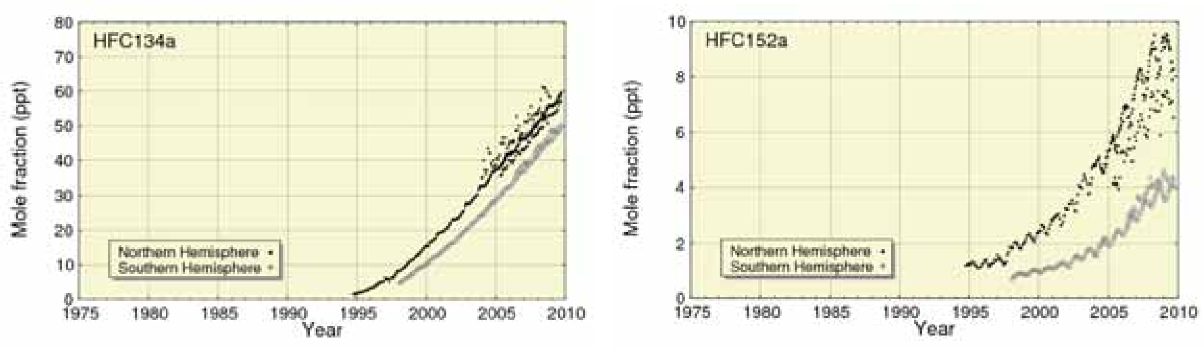


Figure 1.2
Time series of the monthly mean mole fractions in parts per trillion (i.e. one part per 1,000,000,000,000 parts or one part in 10-[12]*) of HFC-134a and HFC-152a. Solid circles show mole fractions measured in the Northern Hemisphere and open circles show mole fractions in the Southern Hemisphere.*[16]

2. AVAILABLE ALTERNATIVES

Alternatives to HFCs can be (1) other fluids used in the same processes, cycles or products or (2) alternative processes, cycles or products. An example for the change of the fluid would be a refrigeration system using propane as refrigerant working as vapour compression cycle similar to the original HFC system. Absorption refrigeration systems or thermo-electric (Peltier) systems on the other hand would be considered alternative cycles or processes. Fibre insulation material replacing polyurethane foam would be an alternative product. This report deals mainly with the application of alternative fluids, especially such fluids occurring naturally in nature, i.e. ammonia, CO_2, and hydrocarbons, as these are the main replacements for HFCs in the original process or cycle.

When discussing replacement fluids one has to bear in mind that refrigeration and air conditioning systems usually contribute to global warming in two ways:

- Direct emissions of potent greenhouse gases like HFCs;Indirect emissions due to energy consumption and the CO_2 emissions associated with the energy conversion.

Depending on the application, refrigerant charge, leakage rate and annual energy consumption, the CO_2 emissions associated with the energy consumption of refrigeration or air conditioning systems can contribute more to greenhouse gas emissions than the refrigerant emissions. Energy consumption for most refrigeration and many air conditioning applications can be reduced by improved insulation or shading of the cooled space.

2.1 Available substitute fluids

Ideal replacement fluids should have properties as close as possible to those of the original HFCs, if no or only minor changes are to be made to the original process, system or product. Among other properties this will mean:

- Low global warming potential (GWP);
- Zero ozone depleting potential (ODP);
- Allow refrigeration and air conditioning systems to perform with high energy efficiency;
- High insulation properties over lifetime in the case of foam insulation;
- Excellent flame extinguishing properties for fire extinguishing systems;
- Chemically stable in order to prevent decomposition, e.g. during high temperature and pressure at the end of compression in a refrigeration system or in an insulation material;
- Non-flammable and non-toxic as well as non-corrosive;
- Inexpensive and available in any country.

It is clear that no fluid is able to meet all requirements. Among a number of possible fluids, the most appropriate one must be selected in accordance with the application or the system's design. Table 2.1 contains an overview of possible replacement fluids together with some of their properties.

Table 2.1
Properties of selected replacement fluids. HFC-134a is included for reference purposes.

	Boiling temperature at atmospheric pressure in °C	Critical temperature in °C	Saturation pressure in bar at boiling temperature of			Flammable	Toxic	GWP* [IPCC AR4, except water and ammonia]
			-30 °C	0 °C	40 °C			
HFC-134a	-26.1	101.1	0.8	2.9	10.2	no	no	1,430
Isobutane	-11.7	134.7	0.5	1.6	5.3	yes	no	3.3
Propane	-42.1	96.7	1.7	4.7	13.7	yes	no	3.3
Propylene	-47.6	91.1	2.1	5.9	16.5	yes	no	1.8
Pentane	36.1	196.6	0.05	0.25	1.16	yes	no	3.3
Ammonia	-33.3	132.3	1.2	4.3	15.5	(yes)	yes	0
Water	100	373.9	Ice	6 mbar	0.0738	no	no	0
CO_2	(-78.4)**	31.0	14.3	34.8	not applicable	no	< 10% no	1

** Related to CO_2 with a 100 year time horizon   ** Triple point of CO_2 at 5.18 bar and –56 °C*

2.1.1 Hydrocarbons

Hydrocarbons are essentially less expensive than synthetic refrigerants, foam blowing agents and aerosol propellants. They have global warming potentials below 20 and no ozone depleting potential, are non-toxic, nearly odourless and accomplish many of the specifications required for refrigerants, foam blowing agents and aerosol propellants. However, they are flammable (see Table 2.2). Nevertheless, they are prevalent in technical aerosols, insulation foam blowing in household appliances and sandwich panels with flexible facing (CFF) as well as European and Asian household refrigerators and commercial stand-alone cabinets with HC refrigerant charges of up to 150 g, which is defined as the upper limit in IEC 60335-2-89.[17] For larger charges special requirements are stipulated concerning flammability. Typically a refrigeration system initially designed for HFC will need about 40% to 50% of that charge when operating on hydrocarbons.[18] Current plug-in refrigeration units with refrigerant charges below 150 g may achieve refrigeration capacities up to approximately 1,000 Watt.[19] Hoehne et al. suggest 50 g per kW refrigeration capacity as a limit within reach and hence 3 kW refrigeration capacity without changes in safety standards.[20]

In many refrigeration systems, most of the refrigerant is contained in the heat exchangers, especially in the condenser. Most central multiplex supermarket refrigeration systems use round tube-and-fin heat exchangers with tube diameters of around 15 mm as evaporators and condensers. The refrigerant charge inside the heat exchangers can be reduced by up to 80% using minichannel heat exchangers already well known within the automotive air conditioning industry. The automotive air conditioning industry has developed from large round tube condensers (12 mm diameter) in the 1970s to small round tubes (7 mm diameter) and finally to Multi-Port-Extruded all aluminium brazed heat exchangers, with a fourfold increase in heat transfer coefficient on the refrigerant side together with a tremendous decrease in refrigerant charge.[21] This development is yet to take place in stationary refrigeration and air conditioning equipment. One major American air conditioning manufacturer already offers its chillers with minichannel condensers with noticeably reduced refrigerant charge. The rest of the refrigeration and air conditioning market is expected to follow. This is mainly relevant to new systems, not a measure that can be applied to existing systems.

Table 2.2
Ignition limits and ignition temperatures of some hydrocarbons.[22] Electric sparks are sufficient as ignition source – the required ignition energy is about 0.25 mJ.

	Lower and upper ignition limits in dry air in Vol.-%	Ignition temperature in °C
Isobutane (R600a)	1.3 – 9.8	543
Propane (R290)	1.7 – 10.9	470
Propene (R1270)	2.0 – 11.1	460
For comparison: gasoline	ca. 1.1 – 7.0	ca. 300

The hydrocarbons used as refrigerant are heavier than air. Ignitable blends with air are therefore formed in low areas. When larger refrigerant charges are used, appropriate gas sensors and air removal devices need to be installed at floor level.

Hydrocarbons mix very well with mineral oils. The hygroscopic synthetic oils used with HFCs can be avoided, making construction and service of refrigeration systems much easier.

Isobutane (HC-600a) is the standard refrigerant for European and many Asian domestic refrigerators and freezers. Over 40 million appliances are produced annually with isobutane worldwide.[23] Isobutane is also used for smaller commercial plug-in units, e.g. chest freezers for ice cream. Due to lower pressure levels and pressure ratios of isobutane, isobutane refrigeration units run more silently than comparable HFC-134a units.

Propane (HC-290) is used by some producers for plug-in bottle coolers, chest freezers and food service cabinets. Those units usually have higher refrigeration capacities than household refrigerators requiring the higher pressure refrigerant propane. When the statutory requirements for safety are met (i.e. IEC 60335-2-89), propane is the ideal refrigerant for such units. It can be used together with available components, is well mixable with mineral oils and causes lower compression end temperatures and often has 10% to 15% better energy efficiency than the comparable HFC unit.[24] Furthermore, the pressure ratios and pressure differences are lower than with HFC resulting in lower noise emissions.

Propene (HC-1270) or propylene is a hydrocarbon with one unsaturated carbon bond (double carbon bond). Correspondingly, it is less stable than e.g. propane. In the middle of the 1990s, propene was used for indirect supermarket refrigeration systems[25] due to claimed slightly better performance than propane.

Pentane (HC-601) is mainly used for foam blowing. Cyclopentane, cyclopentane/isopentane and cyclopentane/isobutane blends are globally the most used blowing agents for foam in domestic refrigeration equipment.[26]

Mixtures of any of the above mentioned hydrocarbons – possibly together with other hydrocarbons – are typically used as foam blowing agents.

2.1.2 Ammonia

Ammonia (R717) has the lowest GWP (0) of all refrigerants suitable for large refrigeration systems. Ammonia refrigeration systems also usually achieve higher energy efficiency than HFC refrigeration systems. Although ammonia is toxic (maximum-workplace-concentration value (MAC) is 50), it has a pungent odor and thus a high warning effect. Certain ammonia air mixtures can be ignited. Ignition limits lie between 15 and 30 per cent by volume in air.

Ammonia is an alkaline gas. Gaseous ammonia is susceptible to react very strong with nitrogen oxides and strong acids. In connection with water the well-known liquid ammonia water (ammonium hydroxide) is created. In connection with carbon dioxide, ammonium carbonate is formed. Steel is the most commonly used material used for ammonia refrigeration systems, since ammonia-water mixtures are corrosive to copper and brass. Copper- and zinc-free aluminium alloys can also be used since aluminium is resistant to ammonia-water-mixtures with water contents of up to 10%.[27]

In refrigeration systems, ammonia causes high compression end temperatures, so refrigeration systems for low temperature applications must be designed in two stages with intermediate cooling between both compression stages. Ammonia is not miscible with mineral oil, consequently ammonia refrigeration systems must be planned and installed very carefully with respect to their oil balance. Ammonia has been the standard refrigerant for industrial refrigeration systems for more than 125 years. Because of its toxicity, it is only used with indirect systems in public access areas, e.g. systems with liquid and evaporating secondary refrigerant for the medium temperature and/or low temperature range. Recently ammonia has also been used as the higher temperature stage in CO_2 cascade refrigeration systems.

2.1.3 Carbon dioxide

Carbon dioxide (CO_2 or R744) is used as a refrigerant, as foam blowing agent and as a fire extinguishing gas. CO_2 is a colorless and odorless gas which is non-flammable and heavier than air. Although it is the largest contributor to manmade global warming, its use in technical applications is usually considered environmentally sound because the CO_2 used in refrigeration or firefighting systems is a waste product which otherwise would escape directly to the atmosphere. CO_2 is non-toxic in low concentrations, but can be harmful in higher concentrations. The maximum allowable concentration (MAC) for a workplace is 5,000 ppm or 0.5%. Immediate danger to health and life (IDHL) exists for CO_2-concentration over 4 vol. % in air (40,000 ppm). Above 10 vol. % in breathing air, CO_2 has a numbing effect and is immediately lethal above 30 vol. %.[28]

CO_2 operates with significantly higher pressures than other refrigerants (see Table 2.1). In plug-in bottle coolers CO_2 achieves pressure levels up to 130 bar on the high pressure side. The high operational pressures require stronger materials and/or larger wall thicknesses. On the other hand, the volumetric refrigeration capacity of CO_2 is much higher than that of traditional refrigerants, allowing system designs with smaller volumes. This also holds true for other components. Smaller cylinder displacement still provides adequate system capacity. Thus, despite the larger wall thicknesses due to increased pressure, the use of material for piping is less.[29] Pressure drops lead to significantly smaller temperature losses and thus to smaller losses in energy efficiency. Due to higher heat transfer coefficients, e.g. evaporation temperatures can be increased by about 2 K compared to HFCs.[30]

The critical temperature of a refrigerant is an important parameter in the effectiveness and efficiency of equipment unless explicitly designed for transcritical operation (as is often the case with CO_2 systems). In the conventional vapour-compression cycle equipment, the condensing temperature is kept well below the critical temperature, because thermodynamic properties and principles result in declining capacity and efficiency as heat-rejection (refrigerant condensing) temperatures increase and approach the critical temperature.

As the critical temperature of CO_2 is low (31ºC), the CO_2 system will operate in a transcritical cycle most of the time in high ambient temperatures. Heat rejection then takes place by cooling the compressed fluid at supercritical high-side pressure. The low-side conditions remain subcritical. Usually, the energy efficiency of transcritical refrigeration systems is lower than that of conventional refrigeration. This characteristic can be partially compensated by application of an internal heat exchanger, which has a greater positive impact on energy efficiency in the transcritical CO_2 process than with other refrigerants. The choice of the high side pressure has an equally critical impact on the energy efficiency. There is an optimal high side pressure for every CO_2 gas cooler exit temperature, i.e. the high side pressure has to be adjusted depending on the temperature of the cooling air or water in order to achieve optimum performance. The control of a CO_2 refrigeration system must account for this characteristic and constantly adjust the high side pressure in order to ensure low energy consumption. Electronic control is able to secure over a wide range that the system is operating with the lowest possible energy consumption.[31]

At ambient temperatures around 26 °C an air-cooled CO_2 refrigeration system achieves comparable energy efficiency to an HFC direct evaporation refrigeration system. At lower ambient temperatures (below 24 °C), the CO_2 system achieves even better energy efficiency.[32]

As CO_2 provides very good energy efficiency at low condensing and evaporation temperatures, it is often the choice for the low temperature stage in commercial and industrial cascade refrigeration systems alongside e.g. ammonia or hydrocarbons. Large refrigeration system manufacturers offer such cascade systems as part of their standard product range,[33] and they are competitive in relation to investment costs incurred, especially for large supermarkets. In the context of these applications, typical condensing temperatures of the CO_2 system are at about 0 °C. In Switzerland, the construction of equipment for refrigeration, air conditioning and heat pumps containing more than 3 kg of refrigerants stable in the air – mainly hydrofluorocarbons (HFCs) – has been subject to licensing since 1 January 2004. Commercial refrigeration systems typically use CO_2 for low temperature circuits.[34]

Unlike condensing refrigerants, the transcritical CO_2 releases approximately the same amount of heat during the entire gas cooling process at continuously reducing temperature, with enormous potential for heating water or air (heat recovery).[35] For this reason, CO_2 has been widely used as a refrigerant in heat pumps in Japan, supported by government subsidies.[36]

2.1.4 Water

Water (R718) is the perfect fluid from an environmental point of view and the most commonly used liquid as a heat transfer fluid in secondary refrigeration and air-conditioning. It is one of the most common fluids in firefighting and is also used in foam blowing processes. The thermophysical properties of water (very low vapour pressure and freezing point at 0 °C) limit its use as refrigerant to applications above 0 °C, where it can be used in larger chillers with good energy efficiency.[37]

2.1.5 Unsaturated HFCs

Unsaturated HFCs – molecules with double carbon bonds, also called hydrofluoro-olefins (HFO) – have been developed as alternatives to HFCs. Unsaturated HFCs are either used as single substance, e.g. HFC-1234yf for automotive air conditioning systems, or in mixtures with HFCs, where they reduce the GWP of the blend. Unsaturated HFCs have high reactivities and therefore shorter lifetimes in the troposphere resulting in low GWPs.

There are concerns about the potential environmental impact of large-scale use of HFOs. Trifluoroacetic acid (TFA), for example, is a common by-product when other HFCs break down, however HFC-1234yf yields more than 90% TFA (4-5 times as much as HFC-134a).[38] Simulations by Luecken et al. (2010) have shown that *" automobile air conditioning HFC-1234yf emissions are predicted to produce concentrations of TFA in Eastern U.S. rainfall at least double the values currently observed from all sources, natural and man-made"*.[39] Henne et al. (2012) forecast a tenfold increase in TFA mixing ratios if HFC-1234yf is used in all European passenger cars.[40] Calculations show that annual global TFA deposition from HFC-1234yf emissions of all European MACs would be 18,600 tonnes. The largest annual mean TFA concentrations in rainwater were over the Mediterranean and Northern Africa, up to 0.0025 mg/L. The highest modelled daily TFA concentrations in rainwater reached 0.013 mg/L, approximately a factor of ten below the no-effect level of TFA in water for the most sensitive algae (which is 0.120 mg/l).

TFA is extremely stable in the environment and therefore accumulates in closed aquatic systems after deposition.[41] The phytotoxic effects of TFA have been demonstrated at rather low concentrations and can act as a co-stress factor on various plants *"TFA may introduce considerable constraints on crops as well as natural vegetation. TFA exposure in combination with drought stress may prove to have disastrous effects on crops and natural vegetation if the reduction in root growth is considered"*.[42] Therefore, even if low GWP-HFCs are not a threat to the global climate, massive emissions of low-GWP HFCs may be a threat for aquatic environments and plants rather than the atmosphere.

The processes and by-products involved in the manufacture of unsaturated HFCs are not well known. For example, it is well known that HFC-23, with a GWP of 14,800, is produced in large quantities during manufacture of HCFC-22, which itself is a feedstock for other fluorinated products. In some production sites, HFC-23 by-product is vented to the atmosphere and has contributed a large share of the current HFC climate impact. While the production process of HFC-1234yf is not known, the production process of tetrafluoropropene (HFC-1234), an isomer of HFC-1234yf, produces HFC-23 as a by-product during its manufacturing process.[43]

The influence of unsaturated HFCs on health is also unclear. Unsaturated HFCs have a low global warming impact because they are rather unstable due to the double carbon binding. This same instability makes them break up into new chemicals inside living organisms.[44] According to a Mexichem Fluor review of their potential use in pharmaceutical propellants: *"The toxicology of the HFOs is found to be quite variable, but in all cases reviewed here, some level of activity was reported, sometimes quite significant. Furthermore, there are major gaps in the data, such as the absence of 2-year chronic exposure studies."*[45]

Another concern relates to the combustion products of the flammable unsaturated HFC. The decomposition of unsaturated HFC during a fire and subsequent recombination can create decomposition products, e.g. hydrogen fluoride (HF), which are toxic to humans – just like decomposition products of any other HFC. The LC_{LO} value (lowest concentration of a HF in air reported to have caused the death of animals or humans) for HF is 50 ppm.[46]

Therefore unsaturated HFCs are not considered a long term alternative in this report and are only mentioned where no other alternative appears feasible with current technology.

2.1.6 Secondary refrigerants

In indirect, or secondary loop refrigeration systems, two fluids are used: a primary refrigerant and a secondary heat transfer fluid (HTF). These systems use a much smaller refrigerant charge than traditional direct expansion refrigeration systems and therefore can significantly decrease refrigerant charges and emissions. The perfect HTF needs to meet many requirements: good thermophysical properties enabling the transport of large refrigeration capacities with only a small temperature change and little volume flow; high heat transfer coefficients to limit temperature differences in the heat exchanger; and low viscosity in order to reduce the work required by the pumps. In addition, the HTF must not cause corrosion of materials, must be non-toxic, environmentally friendly, non-flammable, easy to handle and affordable. The HTF that meets all of these requirements does not exist. For any application, one therefore has to select the most appropriate secondary refrigerant.

HTFs can be divided into single-phase liquids, which generally have relatively low energy content, and secondary refrigerants, with melting or evaporating phase change which facilitates higher energy content. Traditionally, in refrigeration systems single-phase liquids are used where the freezing point must lie below the application temperature. Recent developments are looking at melting HTFs, so-called ice slurry, or evaporating secondary refrigerants, e.g. carbon dioxide.

The most commonly used water-based HTFs are water alone or mixed with ethylene glycol, propylene glycol, ethanol, methanol, glycerine, ammonia, potassium carbonate, calcium chloride, magnesium chloride, sodium chloride, potassium acetate and potassium formate. Melting secondary refrigerants (ice slurries) can be made on the basis of any of these water-based HTFs. To date, the most extensive experience has been made with ethanol and glycol as additive, as well as with sodium chloride (sea water).

2.2 Examples of sectors already using a significant proportion of alternative technologies

The UNEP (2011) synthesis report *"HFCs: A critical Link in Protecting Climate and the Ozone Layer"* gives a good summary of sectors where alternatives already make up a substantial part of the market.[47]

Table 2.3
Examples of sectors which already use a substantial percentage of alternatives.[48]

Sector	Examples of alternatives	Use of alternatives in sector		
		Industrialised countries	Developing countries	Global total
Industrial refrigeration systems[a]	Ammonia, CO_2, HC	92%	40%	65%
Industrial air conditioning systems[a]	Ammonia, CO_2, HC	40%	15%	~ 25%
Domestic refrigerators (vapour compression cycle)[b]	HC	51%	22%	36%
Foam in domestic refrigerators[c]	HC	66%	68%	67%
Foam in other appliances[c]	HC	38%	< 1%	28%
Polyurethane foam boards and panels[c]	HC	82%	21%	76%
Fire protection systems[d]	water, foams, dry chemicals, inert gases	-	-	75%
Asthma medication[e]	Dry powder inhalers	-	-	~ 33%
Solvents[f]	aqueous, no-clean, alcohols, others	> 90%	> 80%	> 80%

Sources: FTOC 2010; RTOC 2010; TEAP 2009ab; TEAP 2010a.
The percentages in this table refer to: [a] refrigerants used in new installations annually; [b] annual production of new equipment; [c] annual consumption of blowing agents; [d] usage or market; [e] annual medical doses; [f] market penetration in solvent applications.

The availability of alternatives in each major sector, i.e. refrigeration, air-conditioning, foam blowing, aerosols, fire protection, solvents, HFC-byproduct, and semiconductor production is given below. Due to the broad view on each sector, details are omitted and only those alternatives being mainly used are described. Comments on energy efficiency and technical feasibility of the various alternatives are also given.

The following sections refer to the future penetration rates(i) estimated by Schwarz et al. (2011) to describe the potential technical feasibility of alternatives to HFCs. Penetration rate is defined as the "maximum market potential of a technical choice (i.e. an abatement option) to replace new products or equipment relying upon HFCs in a particular sector."[49] As its basic guiding principle, the abatement options must achieve "at least the same level of efficiency as the existing refrigerants".

2.3 Refrigeration

Safe, reliable and affordable refrigeration was the main driving force in the development of synthetic refrigerants in the 1930s and is a key HFC consuming sector. Low-GWP refrigerants suitable for refrigeration include ammonia, CO_2, hydrocarbons (mainly isobutane and propane) and water. For certain low temperature applications, air in an air cycle could be a good alternative.

Due to the wide variety of applications and systems developed over many decades, it is best to divide refrigeration systems into individual categories. Categories used in the UNEP Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (RTOC) assessment reports namely domestic, commercial, industrial and transport refrigeration, are well proven categories and will therefore also be applied here.

2.3.1 Domestic refrigeration

Domestic refrigerators are a good example of an application where a natural refrigerant is widely and successfully used due to several advantages offered by the hydrocarbon isobutane (HC-600a). Isobutane is the standard refrigerant for European domestic refrigerators and freezers. When the statutory requirements for safety are met (e.g. IEC 60335-2-89), isobutane is the ideal refrigerant for such units, giving about 10-30% higher efficiency than HFC-134a while at the same time reducing noise level of the unit.[50] Worldwide over 37 million appliances each year are produced with isobutane – 25 million of them in Europe.[51] Legal concerns have so far limited the use of isobutane in the United States of America, but on December 14, 2011 U.S. Environmental Protection Agency (EPA) approved isobutane and a butane-isobutane-propane-ethane blend (R441A) under EPA's Significant New Alternatives Policy Program (SNAP) for household and small commercial refrigerators and freezers. North American manufacturers have started production of high-end products with HC-refrigerants – two decades after Germany did the same. Figure 2.1 shows the transition in European household refrigerators from CFC-12 to HFC-134a (initially) and HC-600a, which outnumbers the HFC-134a unit production since 1999.[52] The total reduction in GWP-weighted CO_2-eq. tonnes (left vertical axis) is quite evident. Figure 2.1 also shows the development in energy efficiency of domestic refrigerators/freezers (right vertical axis).[53] As household refrigerators are manufactured in a wide variety of sizes, the annual energy consumption is normalized to 100 litre internal volume of the refrigerator (kWh per 100 litre). A part of that energy reduction can be attributed to the shift to HC-600a. Together, increased energy efficiency and isobutane refrigerant have drastically reduced the climate impact of household refrigerators.

[1] Penetration rate is a measure of the amount of adoption of a product compared to the total theoretical assumed market for that product. Penetration rate can be used with regards to the total actual sales of a product or to the total number operated in the market. For example, if there are 104 million domestic refrigerators produced worldwide in 2008 and 37 million of them are manufactured with HC-600a [RTOC, 2010, p. 56], the placement on the market penetration rate in new units in 2008 is approximately 36%. Whereas total numbers placed on the market until 2008 (1,200 million) compared to the total number of HC-600a units (290 million) sold until that year, assuming a lifespan of 15 years, results in a 24% market share of the installed basis. Penetration rates used in Schwarz et al (2011) always refer to the penetration rate of actual sales, i.e. placing on the market.

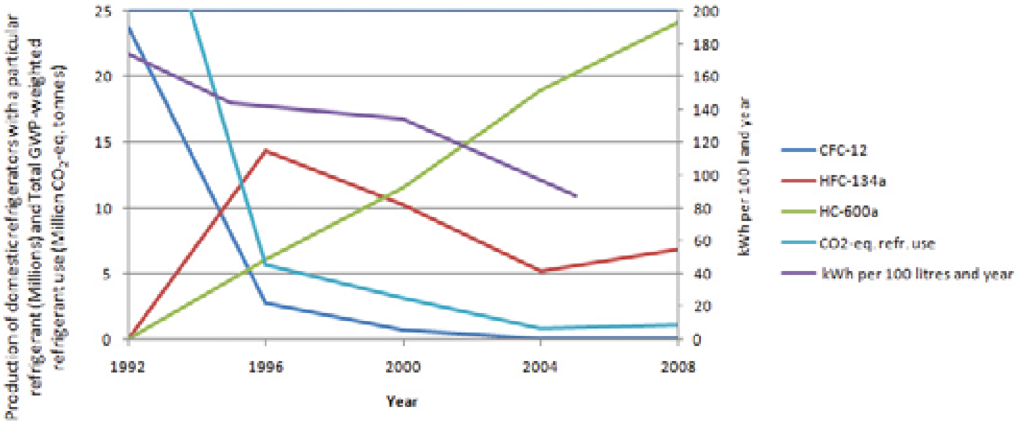


Figure 2.1
Annual European production of domestic refrigerators and freezers in million units and the CO_2-equivalent weighted refrigerant consumption as well as specific energy consumption[54] *of combined refrigerator-freezers.*[55]

According to Schwarz et al. (2011) only 230,000 HFC-134a units are manufactured currently in five of the EU-27 countries,[56] suggesting a significant reduction from the almost 3.6 million HFC-units quoted to have been manufactured in 2008 in Western Europe.[57]

Energy efficiency of hydrocarbon household refrigerators and freezers is at least 10% better than with HFC units.[58] The use of hydrocarbons is deemed technically feasible for all appliances, but due to internationally accepted safety standards stating 150 g of hydrocarbons as the upper limit to be used safely (IEC 60335-2-89), refrigeration capacity has so far been limited to a few hundred Watts, which is sufficient for most European refrigerators and freezers. Due to the almost complete shift to hydrocarbons, HFC consumption for the manufacturing of new units is rather limited, although increasingly HFC-refrigerators are imported, resulting in a continued HFC emission forecast[59] shown in fig. 2.2. The lifetime of household refrigerators is estimated to be 15 years.[60]

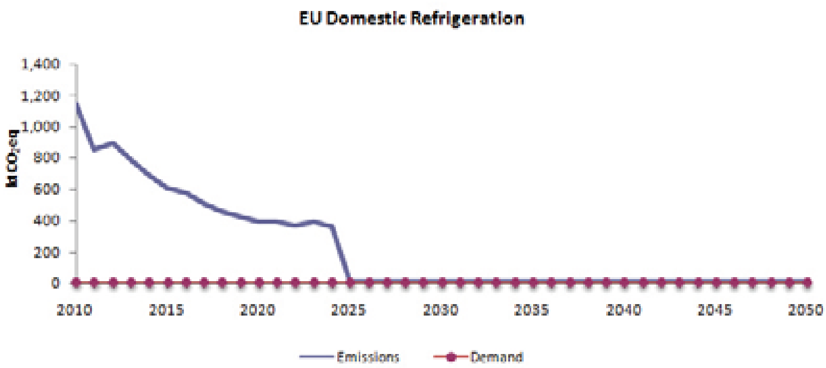


Figure 2.2
HFC demand and (end-of-life) emissions in the EU under the current F-Gas Regulation assuming full implementation for domestic refrigeration 2010-2050. In Europe, household refrigerators and freezers use hydrocarbons as refrigerants. Demand for domestic manufacturing will be of negligible size from 2010 onwards. Emissions from disposal will likewise decrease to marginal amounts from 2025.[61]

With additional measures (WAM) – i.e. exceeding the current F-Gas Regulation –it is deemed technically feasible to shift completely to hydrocarbons in all new units by 2015 within the EU.[62]

Other alternatives for domestic refrigeration are CO_2, used for bottle coolers[63] by one soft drink manufacturer.

2.3.2 Commercial refrigeration

Commercial refrigeration can be divided into three main equipment categories: self-contained or plug-in units (similar to domestic refrigerators) with refrigeration capacities from a few hundred Watts to almost 5 kW, condensing units with refrigeration capacities from a few kW to almost 100 kW and large centralized supermarket refrigeration systems with refrigeration capacities up to 1,500 kW and HFC charges up to 3,000 kg. Different HFC alternatives are being used depending on the category and the food storage temperature (LT – low temperature and MT – medium temperature) served by two main levels of evaporating temperatures: -40 to -32 °C for frozen food (and ice-creams) and -15 to -3 °C for fresh food (dairy, meat etc.).

The application of CFCs and HCFCs has been prohibited in the EU since 2000. Due to the equipment lifetime of plug-in units (10 years) centralized systems (12 years) and condensing units (15 years), most of the commercial refrigeration units in the EU are running on HFCs. The EU F-Gas Regulation places strict requirements regarding leakage check and containment on all refrigeration systems with more than 3 kg refrigerant charge, thus increasing service cost for larger HFC systems. Annual leakage rates of centralized commercial refrigeration systems are expected to decrease from their current 15% to 9% due to the F-Gas Regulation while those of condensing units are expected to decrease from 10% to 6%, if the Regulation is fully implemented.[64] However, the F-Gas Regulation is not expected to decrease the total demand of HFCs in the commercial refrigeration sector even by 2050 as can be seen from Figure 2.3.

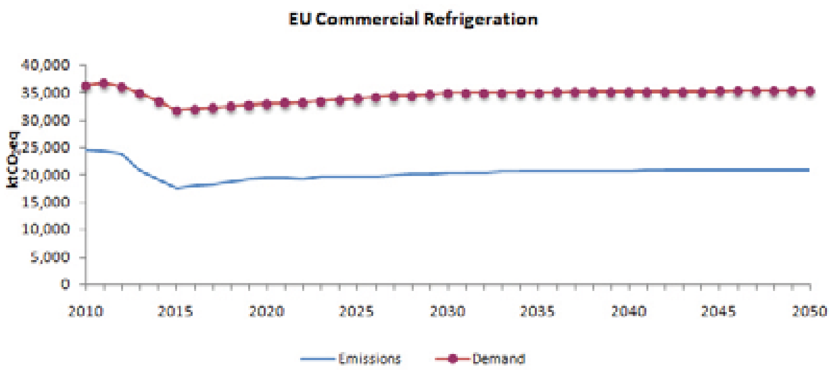


Figure 2.3
Projected HFC emissions and demand (kt CO_2 eq) in commercial refrigeration (2010-2050), for EU-27 under the current F-Gas Regulation assuming full implementation. After reductions in 2010-2015, constant long term levels for emissions and demand are projected.[65]

Alternatives to HFCs exist in all three sub-sectors of commercial refrigeration. In countries where they are required by law, e.g. Denmark (systems with more than 10 kg refrigerant charge, see 5.3.1) or Luxembourg, Sweden and Switzerland, they have successfully replaced HFC systems. Even without legislation, commercial refrigeration is increasingly using alternatives to HFCs, since systems are demonstrating increased energy efficiency e.g. in plug-in chest freezers with hydrocarbons or centralized CO_2 systems for providing low temperature refrigeration. In addition cost savings achieved due to reduced energy consumption mean economic advantages to the user despite the often higher investment cost for the equipment.

2.3.2.1 Stand-alone (plug-in) units

Stand-alone units are built with HC-600a, HC-290 and CO_2. The energy efficiency of hydrocarbon units is approximately 10-15% better than that of a comparable HFC-unit.[66] An estimated 800,000 HC-units have been manufactured so far.[67] CO_2 units achieve slightly better energy efficiency than HFC-units under moderate and indoor climate.[68] Several thousand units with CO_2 have been produced mainly as bottle coolers.

Both options are technically feasible and commercial hydrocarbon plug-in units have been manufactured in several hundreds of thousands with refrigerant charges up to 150 g for most manufacturers. Some European brands commercialize equipment with hydrocarbon charge up to 1 kg and even 2.5 kg depending on national regulation.[69] Figure 2.4 shows the maximum technically feasible phase-out of HFCs in commercial plug-in units in the EU, provided additional measures are implemented (WAM), and the expected mix of alternative technologies with their estimated growth.[70]

Fig. 2.4 also shows the equipment lifetime. Starting at the earliest end of use date, it visualizes when HFC consumption for existing equipment will end.

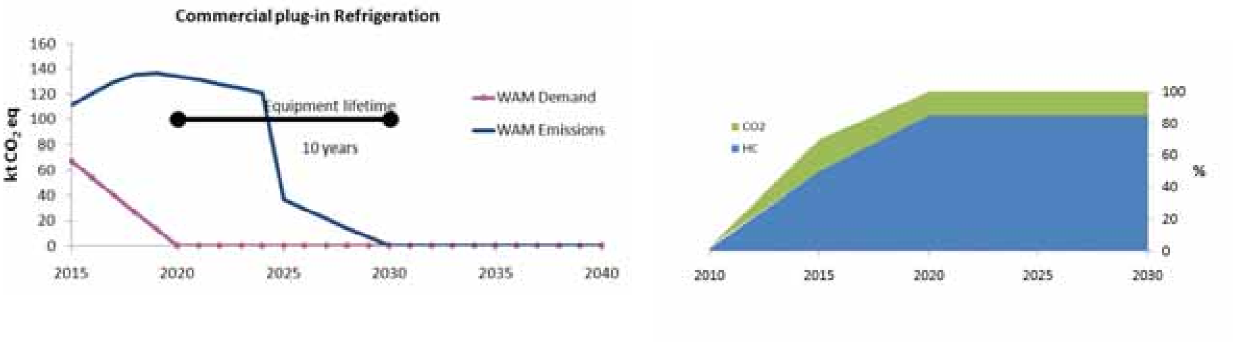


Figure 2.4
Estimated maximum technically feasible phase-out of HFCs in new commercial stand-alone units in the EU provided additional measures are implemented (WAM), and the expected mix of abatement options. Data from Schwarz et al. (2011).[71]

Case Studies Commercial Stand-alone Units

In 2000, the world largest ice cream producer Unilever made a commitment to implement by 2005 a non-HFC purchasing policy for ice cream freezer cabinets in all countries where commercially viable alternatives can be legally used.[72] Unilever has chosen propane as the replacement for HFCs in this application. Since 2003, propane cabinets have been rolled out globally, and by mid-2008 about 270,000 units were operating in the field, representing 15% of the global Unilever fleet.[73] Data from the field and from climate room tests reconfirm that there is no difference in safety, reliability and performance between cabinets with HC-290 or HFC refrigerants, and that the HC-290 cabinets are more energy efficient.[74] Similar considerations have lead most of Germany's discount shop operators to only order propane chest freezers. Equipped with variable speed compressors, these units save approximately 25% energy compared to their HFC counterparts.[75]

Nestlé states it has *"phased out more than 90% of refrigerants with high global warming potential from their industrial operations and focuses now on smaller refrigeration systems such as ice cream freezers. In Switzerland, all new ice cream freezers now use HC refrigerants under controlled conditions, and from 2011 onwards, we will test a further 2,400 HC freezers in Australia, Spain, Malaysia, Chile and the United States. Our new HC freezers have enhanced safety features, making it safer than those currently available in the trade. They are also equipped with high-efficiency fans, improving the energy efficiency of this component by 80%. We estimate that the reduction in greenhouse gas emissions from these freezers will be around 10,000 tonnes of CO_2 equivalent over their expected 10-year lifetime"*.[76]

2.3.2.2 Condensing units

Worldwide approximately 34 million condensing units are used mainly in small shops and for individual cold rooms.[77] HFC alternatives for condensing units are also hydrocarbons and CO_2. While hydrocarbons (mainly HC-290) are only feasible in direct evaporation (DX) in smaller systems due to safety concerns (1.5-25 kg HC charge maximum in non-public areas depending on the national regulations), CO_2 can be used universally. From a technical point of view, hydrocarbons could cover the entire range of condensing units with 5-10% lower energy consumption than HFC condensing units.[78] Due to the flammability of the hydrocarbon refrigerants, special precautions like leak detectors and ventilation have to be taken, resulting in up to 25% higher initial investment cost.[79]

If hydrocarbons are to be used in areas with public access, e.g. in a grocery store, secondary loop systems (also called indirect refrigeration systems) are the selection of choice for larger refrigeration capacities. Such indirect systems can operate efficiently in the medium temperature range while they tend to use more energy in the low temperature range when operating with liquid secondary refrigerant. Using CO_2 as evaporating secondary refrigerant allows the use of hydrocarbon condensing units that are also energy efficient for low temperature applications. The special CO_2 pumps required for this are available worldwide.

CO_2 can also be used as the sole refrigerant. Such CO_2 condensing units are expected to operate with greater energy efficiency than HFC condensing units in cold and moderate climates, while they are expected to consume more energy in warm climates. All three options are technically feasible and proven in a few installations for CO_2 to several hundred installations for small direct and indirect systems with hydrocarbons. Any of the alternative systems can achieve similar energy efficiency as the HFC systems. Wallace claims 20% higher efficiency for a hydrocarbon condensing unit with direct expansion.[80]

Figure 2.5 shows the maximum technically feasible phase-out of HFCs in commercial condensing units in the EU (WAM), and the expected mix of alternative technologies with their estimated growth.[81] Although 100% of all new commercial condensing units can be HFC-free by 2020, the demand will continue for some years for servicing of existing equipment as the equipment lifetime is approximately 15 years.

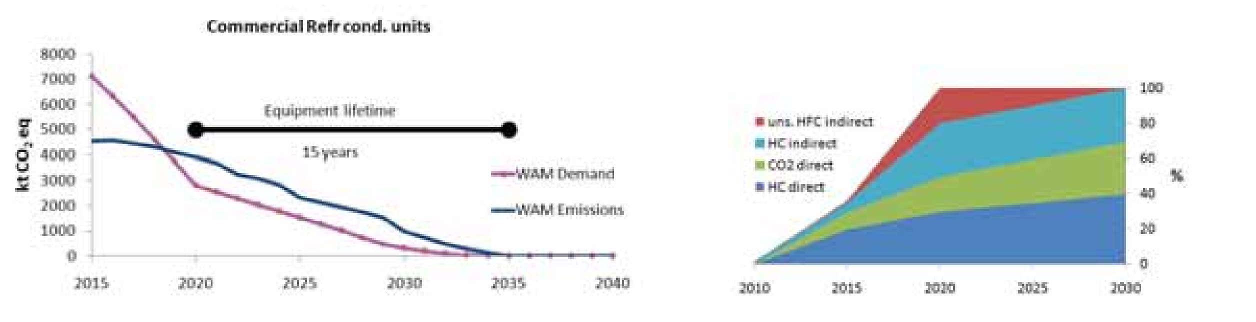


Figure 2.5

Estimated maximum technically feasible phase-out of HFCs in new commercial condensing units in the EU and the expected mix of abatement options. Data from Schwarz et al.[82]

Case Studies Condensing Units

"SANYO has been pursuing R&D for a CO_2 condensing unit, based on its adoption as a FY 2008 Non-fluorocarbon Energy-saving Refrigeration/Air-conditioning System Project by the New Energy and Industrial Technology Development Organization (NEDO). In August 2009, test installation of the system was begun at 'Maxvalu Express Rokugodote Ekimae' a supermarket by AEON Retail Co., Ltd. (Shohei Murai, President; headquartered in Chiba City, Chiba), a subsidiary of AEON Co., Ltd. (Motoya Okada, President; headquartered in Chiba City, Chiba). Thanks to the split cycle and the rotary two-stage CO_2 compressor, the energy consumption has been reduced by about 10% during refrigeration operation, compared to previous HFC refrigeration systems. In addition, the weight of the necessary copper piping can be reduced by about 37%, thereby contributing to the saving of resources."[83]

Wallace (2008) describes a direct expansion hydrocarbon installation for a 135 m³ refrigerated cold room for fruit and vegetable storage in Perth, Australia. The hydrocarbon condensing unit has 18 kW refrigeration capacity and uses approximately 20% less energy than its HCFC-22 counterpart.[84]

2.3.2.3 Centralized systems

Centralized systems are the preferred option in supermarkets, because they usually achieve better energy efficiency than plug-in cabinets and condensing units. They operate with racks of compressors installed in a machinery room, typically using HFC in direct expansion refrigeration systems. Because all cabinets/evaporators are connected to all compressors in one compound system, HFC charges are quite high – up to 3,000 kg for hypermarkets – with resulting high emissions in the case of component failure like pipe rupture due to excessive vibration. In addition the thousands of joints of large systems are prone to constant leakage, hence such systems often have HFC leakage rates in the order of 15%.[85]

For centralized supermarket refrigeration systems, alternative refrigerants used are ammonia, CO_2 and hydrocarbons, mainly propane (HC-290) and propene (HC-1270). While CO_2 can be used inside the sales area, all other alternatives are confined to the machinery room or an outdoor installation due to toxicity (ammonia) or flammability (HC-290 and HC-1270) of the refrigerant.

With CO_2 as the only refrigerant in a remote DX-system, annual energy consumption in moderate climates is usually lower than that of an HFC-system.[86] The energy efficiency of CO_2 systems is better than that of comparable HFC-systems at temperatures below 22 °C, about equal at temperatures between 22 and 26 °C and lower at higher ambient temperatures.[87] The technical feasibility is well proven with more than a thousand such systems spread throughout Europe. Installation of CO_2 systems has also begun in Asia, America and Australia. Shifting from HFCs to CO_2 can reduce the carbon footprint of supermarkets by 25%.[88] With new developments like economized systems (two-stage expansion with recompression of the flash gas), ejector systems and expander systems, the efficiency of CO_2 systems may in future be improved to the extent that such systems will be more energy efficient even in warmer climates.[89]

Ammonia and hydrocarbons require secondary loop (indirect) systems in the areas with public access. Traditionally liquid (water based) fluids – see 2.1.6 – have been used for both medium (MT) and low temperature (LT) applications. Due to the high viscosity of water based fluids in the LT-application, energy consumption is higher for indirect LT-systems. Therefore liquid secondary fluids are mainly applied in MT-applications where they achieve similar energy efficiencies as HFC direct expansion systems at 10 to 30% higher cost. The LT-loop of an indirect ammonia or hydrocarbon system is now usually built as a cascaded CO_2-system, achieving better energy efficiency than HFC-systems. All indirect systems as well as the CO_2 cascade solution are technically feasible and well over 1000 such supermarket systems can be found all over the world, with concentrations in Scandinavia, Luxemburg and Canada. Indirect systems are also aining significant market share in the USA.[90]

Distributed systems, whereby the compressors are installed close to the display cases either inside or very close to the sales area (rather than in a separate machine room), are also popular in the USA. If installed inside the sales area, compressors are housed in sound proof boxes and condensers are cooled by a water loop. These systems can significantly reduce refrigerant charge and, provided the necessary safety precautions are taken, can also use hydrocarbon refrigerants. Distributed systems (with HFC refrigerant) account for 40% of new installations in the USA.[91] As well as reducing refrigerant charge, the close proximity of the compressors to the cases and coolers allows the systems to use considerably less piping than traditional direct expansion systems.

Figure 2.6 shows the maximum technically feasible phase-out of HFCs in commercial central refrigeration systems in the EU provided additional measures are implemented (WAM), and the expected mix of alternative technologies with their estimated growth.[92]

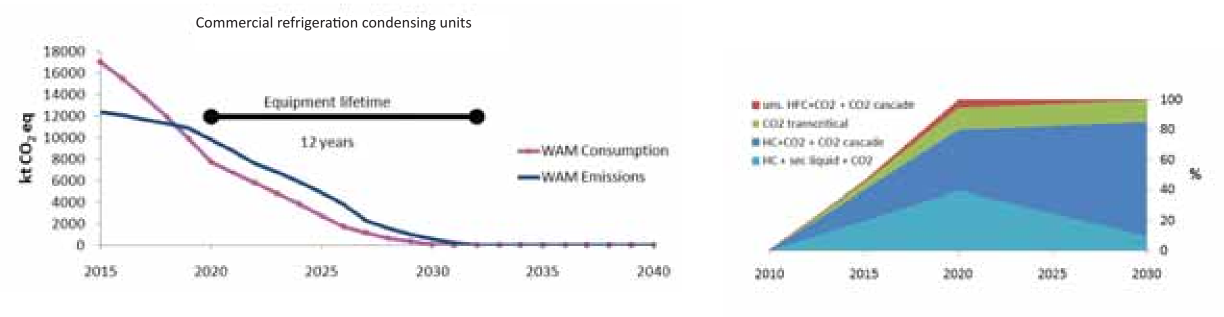


Figure 2.6

Estimated maximum technically feasible phase-out of HFCs in new commercial central refrigeration systems in the EU and the expected mix of abatement options. Data from Schwarz et al. (2011), however the final penetration mix has been adjusted. According to Schwarz et al. (2011), penetration of CO_2 transcritical decreases to zero % after 2020 with 90% of penetration met through hydrocarbons with 10% CO_2 cascade system. However the author believes that transcritical CO_2 systems will remain a viable option, meeting around 15% of the market for new products.[93]

Case Studies Central Commercial Refrigeration Systems

The German food discount chain, Aldi Süd, announced in December 2009 that as of January 2010 the company will only install CO_2 refrigeration systems in all new stores in Germany. The company opens around 150 new stores each year.

At Marks and Spencer's "from 2010 all new installations will use CO_2 secondary systems wherever possible".[94] By 2030, the company plans to manage without HFCs completely, using CO_2 and hydrocarbons as refrigerants instead. The company is training technicians in developing countries in the use of natural refrigerants.[95]

With the express desire to reduce energy consumption, the South African supermarket chain Pick 'n' Pay has converted the refrigeration systems to natural refrigerants in two supermarket stores in climatically different zones of South African (Johannesburg and Cape Town), with the help of German GIZ. *"The new technology is a cascade system with ammonia as the primary system located in a machine room off the sales area and a glycol-water solution for distribution inside the store. The secondary CO_2-cascade provides the cooling for the low temperature applications. The two stores were opened in December 2009 during the summer season in the southern hemisphere and are now fully operational. After more than one year of monitoring, energy savings of 19-26% are demonstrated."*[96]

2.3.3 Industrial refrigeration

Industrial refrigeration systems are characterized by heat extraction rates in the range 10 kW to 10 MW, typically at evaporating temperatures from –50 °C to +20 °C. About 75% of all industrial refrigeration capacity is installed in the food industry, the rest in industrial processes and leisure applications.[97] Over 90% of the large industrial refrigeration installations use ammonia (R717) whereas the market share of ammonia is only 5% (India and China) to 25% (Europe and Russia) for smaller industrial refrigeration systems.[98] Industrial ammonia systems are in general 15% more energy efficient than their HFC-counterparts and 40% of the European industrial refrigeration systems use ammonia.[99] While industrial refrigeration systems using ammonia are very tight due to the pungent smell of ammonia, HFC systems in the EU show current leakage rates of 8-10%.[100] Without additional measures, the current F-Gas Regulation is not expected to decrease emissions of HFCs in the industrial refrigeration sector (fig. 2.7).

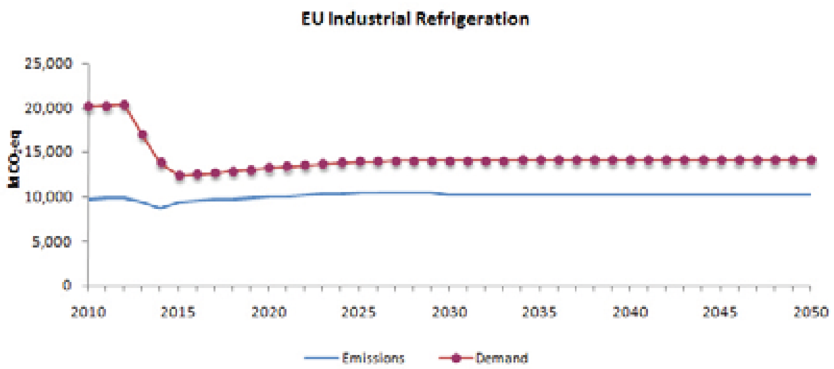


Figure 2.7

HFC emissions from industrial refrigeration are forecast to remain constant from 2010 to 2050 despite the drop in emission factors due to the F-gas Regulation. The high demand values from 2010 to 2015 result from the accelerated phase-out of HCFC-22, which is substituted in existing equipment by HFCs.[101]

Alternatives to HFCs include ammonia, which is already widely used, hydrocarbons, CO_2 and air for very low temperatures.

A replacement of a 3.2 MW HCFC-22 refrigeration system by one using ammonia resulted in 40% reduction of energy consumption.[102] As the new plant utilizes heat recovery and water heating by means of an additional heat pump, the total annual cost savings are more than £1.4 million, resulting in a payback time of 2.7 years.[103] Applying improvement levers such as reduced condensing temperature, increased evaporation temperature, variable speed compressors and multistage systems, the energy consumption of the ammonia plants can be drastically reduced.[104]

Hydrocarbons are not widely used, other than in situations where safety measures are already required, e.g. in a petrochemical plant. *"They offer excellent efficiency, and compatibility with most materials and lubricants. However the precautions required to prevent ignition are significantly more expensive than those required for ammonia systems."*[105]

CO_2 is used with excellent efficiency in systems as the low temperature stage to a cascaded upper ammonia system especially in the food industry where the refrigerant has to evaporate in freezing equipment in the factory. According to Gerwen (2011) *"The use of CO_2 as a refrigerant in the low pressure stage of a cascade refrigeration system, with ammonia in the high stage, could be an opportunity for further improvement"*.
In colder climates CO_2 is energy efficient as the sole refrigerant.

Air can be used with good energy efficiency in low temperature applications, namely below -60 °C. At least one manufacturer is offering such systems.[106]

Figure 2.8 shows the maximum technically feasible phase-down of HFCs in industrial refrigeration systems in the EU, provided additional measures are implemented (WAM), and the expected mix of alternative technologies with their estimated growth.[107]

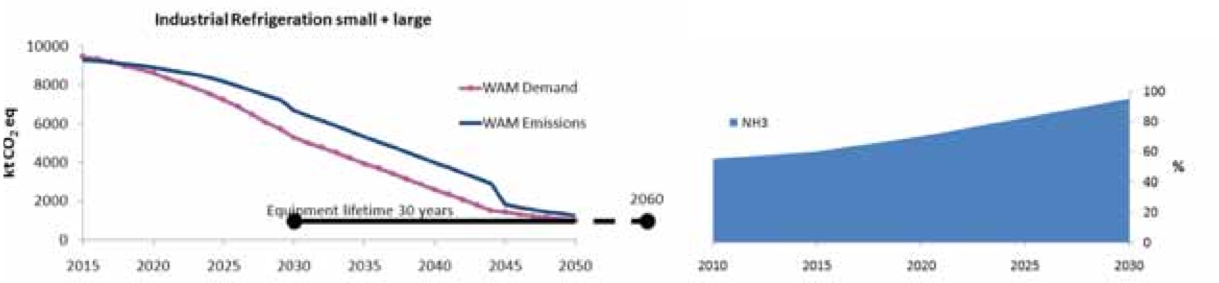


Figure 2.8
Estimated maximum technically feasible phase-down of HFCs in new industrial refrigeration systems in the EU and the expected mix of abatement options. Data from Schwarz2011 – small and large industrial combined.[108]

Case Study Industrial Refrigeration

According to Unilever: *"The refrigerant choice for industrial refrigeration is ammonia, using an optimised standard core design concept and an appropriate safety management system."*[109]

Nestlé committed to the use of natural refrigerants in 2001, and has since also supported the use of CO_2/NH3 systems: "*As already publicly stated in 2001, Nestle reiterates its commitment to the use of natural refrigerants that are environmentally friendly. Especially and whenever feasible, carbon dioxide (C02) in combination with ammonia (NH_3) must be used for all low temperature applications. Beyond many technical and economical advantages carbon dioxide is safer for the environment, people and goods."*[110]

2.3.4 Transport refrigeration

"Technical requirements for transport refrigeration systems are extremely complex. The equipment has to operate over a wide range of ambient temperatures and weather conditions (wind, solar radiation, rain, sea water spray, etc.). The equipment has to be able to carry any one of a wide range of cargos with different temperature needs and even different temperatures simultaneously in different compartments (more than 20% of the European market for truck and trailers)."[111]

The refrigerant of choice for transport refrigeration systems within the EU is HFCs, with refrigerant charges from less than 1 kg (refrigerated vans) to more than several kg (trucks, trailers and reefer containers) to 3,000 kg on board large fishing vessels.[112] Leakage rates are typically 20% for trucks/trailers, 30% for vans and up to 40% for fishing vessels.[113] As transport refrigeration equipment is not subject to Article 3 containment measures or Article 4 recovery measures of the F-gas Regulation (2006), HFC emissions are expected to rise in this sector, fig. 2.9.

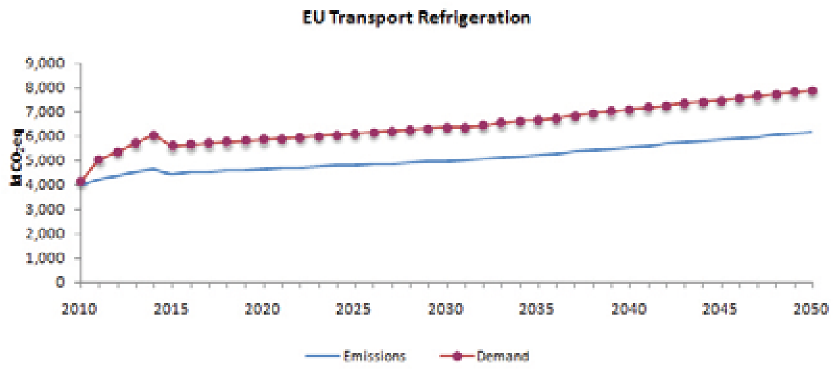


Figure 2.9
HFC refrigerant demand and emissions in European refrigerated transport sectors under the current F-Gas Regulation scenario. Emission reduction measures are not included for this sector in the present F-Gas Regulation. Therefore continuous increase in emissions and demand is assumed from 2010 onwards. The peak in 2014 results from HCFC-22 replacement by HFC blends in existing fishing vessels.[114]

Natural refrigerants have been commercialized to a small extent aboard marine vessels worldwide (ammonia, CO_2).[115] For European fishing vessels highly efficient ammonia-CO_2-cascade systems are the systems of choice, using approximately 6% less energy.[116]

Initial field tests with small fleets of containers using CO_2have started. Hydrocarbons are not deemed a technically feasible option for reefer containers.

Current and previous tests with trucks using CO_2 suggest that larger scale introduction of CO_2 will take place when more efficient compressors with more than one compression stage, which are under development, are commercially available.

The use of HC-290 in truck refrigeration units has been tested with a small number of vehicles both in the UK and Germany. Safety concerns have until now prevented a wider application, even though many trucks are equipped with an auxiliary heating system running on hydrocarbons, making the fear of hydrocarbon refrigerants somewhat difficult to understand. A new refrigerated truck with propene (HC-1270) was developed by a German company and is now in field tests for a supermarket chain in Germany. The refrigeration unit uses innovative inverter technology and is very energy efficient. It was awarded with the German Refrigeration Award in 2011.[117] For a broader market introduction, manufacturers and customers still see a need for specific legal rules and standards for hydrocarbons in mobile applications. From an energetic point of view hydrocarbons are the preferred choice as they result in at least 20% lower energy consumption. Calculations show an even higher energy saving potential for hydrocarbons.[118] CO_2 systems should achieve comparable energy efficiency as HFC-systems.[119]

Cryogenic or open loop systems which evaporate the liquid CO_2 or nitrogen (N_2) charged to an insulated container aboard the truck are a low maintenance alternative to the standard vapor compression cycle. Besides the possibility of high local CO_2 or N_2 concentrations with the associated risk of asphyxiation, they usually need more energy as the liquefaction of the cryogenic liquid takes place at much lower temperatures than the normal evaporation temperature of a vapor compression system. Furthermore the systems need frequent refilling, consequently the user needs to provide storage and refilling infrastructure for the liquified gases. Thus, open loop systems are usually only used for local distribution.

Figure 2.10 shows the maximum technically feasible phase-out of HFCs in transport refrigeration systems (vans, trucks and fishing vessels) in the EU provided additional measures are implemented (WAM), and the expected mix of alternative technologies with their estimated growth.[120] Container data are not considered EU specific in Schwarz (2011) as container fleets are operated worldwide. The expected abatement options and their penetration rates are also shown in fig. 2.10 together with the equipment lifetime.

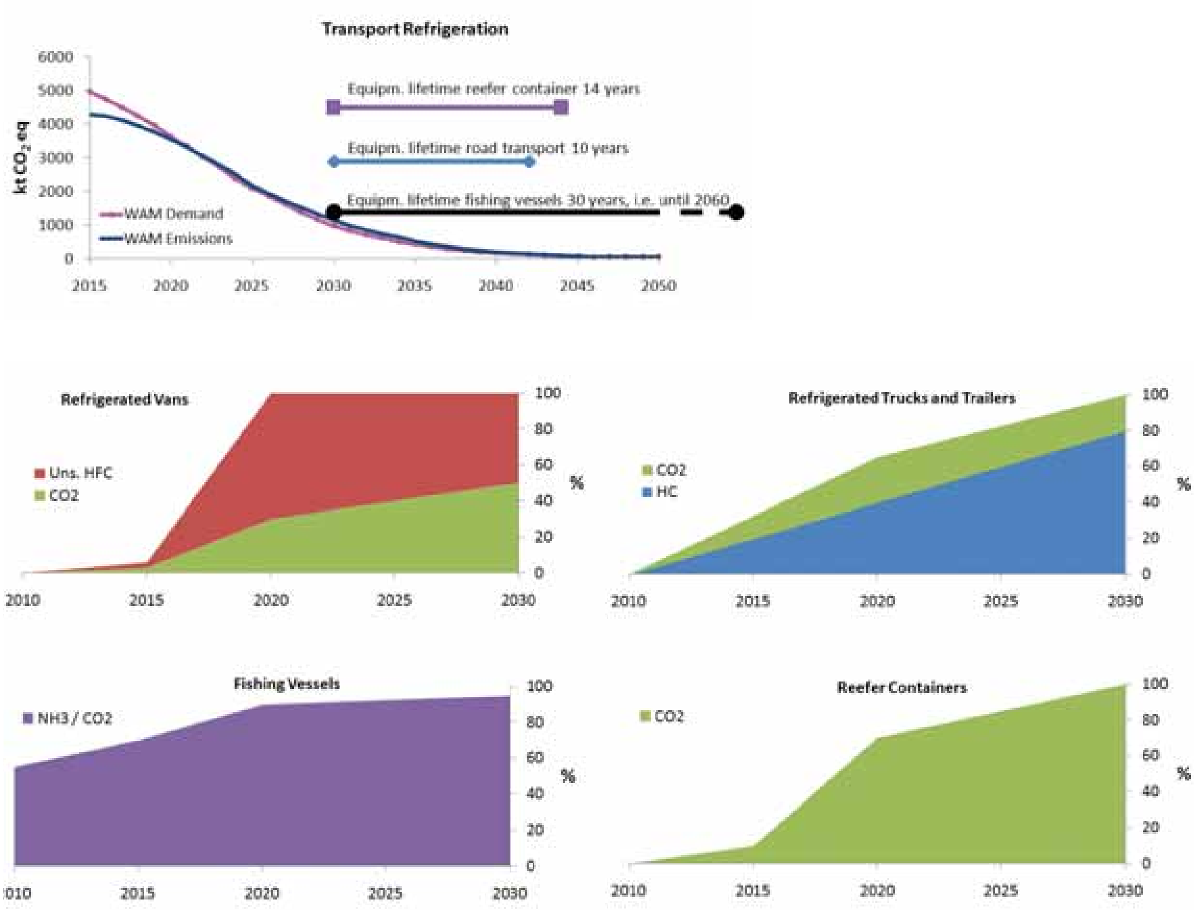


Figure 2.10
Estimated maximum technically feasible phase-down of HFCs in new transport refrigeration systems in the EU and the expected mix of abatement options according to Schwarz et al. (2011) – consumption and emission curves (upper graph) show refrigerated vans, trucks and fishing vessels combined. The EU sector sheet of Schwarz et al. (2011)[121] states the potential penetration rate of CO_2 in refrigerated vans is 65% by 2030 (as opposed to 50% shown in the above penetration mix). Due to the energy efficiency constraints of CO_2 systems in Southern Europe and the current choice of refrigerant for the air conditioning system of vans, i.e. HFC-1234yf, this was limited by Schwarz et al. to 50%.

Case Study Transport Refrigeration

In November 2011 at Intermodal Europe Show in Hamburg Carrier Transicold exhibited one of the world's first container refrigeration systems with CO_2. By using two-stage compression, cylinder unloading and variable speed drive the CO_2 design has been engineered to deliver efficiencies equal to Carrier Transicold's best-in-class reefer container unit.[122] *"Advancing Carrier's natural leadership in environmental technologies for the marine container refrigeration market, the NaturaLINE* [trademark for the CO_2 container system] *design provides the global shipping industry with the most environmentally sound alternative for refrigerated transport,"* said David Appel, president, Carrier Transicold.[123]

The new CO_2 units reduce carbon dioxide emissions by 28% compared to HFC units. Due to high energy efficiency the CO_2 units will significantly reduce on-board power generation requirements, helping shipping lines save fuel used in generation of electricity. This, in turn, helps hold down operating costs and reduces emissions related to power generation.[124]

2.4 Air Conditioning

Air conditioning systems can be divided into stationary and mobile air conditioning systems for vehicles. Stationary systems can again be divided into unitary systems designed for air conditioning of single rooms (single split and moveable systems), multi-split systems servicing several rooms or entire buildings (often equipped with VRF technology – variable refrigerant flow) and central air conditioning systems with distribution of cold by air (central air handling units or ducted systems) or water (chillers). The refrigeration capacity varies depending on the number of rooms to be air conditioned and ranges from less than 1 kW for unitary systems to several MW for large central systems (chillers).

2.4.1 Stationary Air Conditioning

Air conditioners for cooling and heating ranging in size from 2.0 kW to 420 kW (the majority less than 35 kW) comprise a significant segment of the air conditioning market.[125] Most air conditioning systems in the EU use HFC refrigerants, with charges from a few hundred grams (factory sealed moveable units) to a few kg for split units to several tonnes for large central chillers. Leakage rates range from 2.5% for small factory sealed units to 8% for multi-split units. Due to an ever increasing demand for air conditioned spaces – triggered by the large proportion of air conditioned cars[126] – the European HFC demand in the stationary air conditioning market is expected to grow to become the largest HFC demand sector by 2035, fig. 2.11.[127]

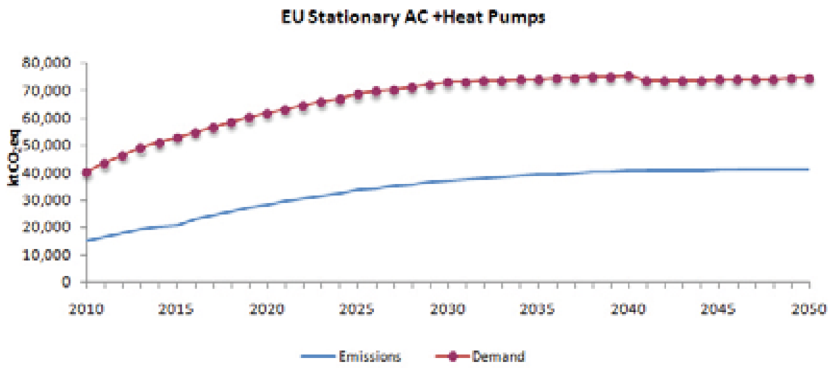


Figure 2.11
Trend of HFC demand and emissions under the current European F-Gas Regulation scenario in stationary air conditioning and heat pumps. Before 2035 where the market is saturated, considerable growth is assumed, which makes stationary air conditioning the largest individual HFC sector in Europe. The demand includes HFCs in imported pre-filled systems.[128]

"Hydrocarbons are a perfect alternative in many air conditioning and heat pumps systems. It seems that the number of producers using hydrocarbons as refrigerants has decreased during the last few years. One important reason for this seems to be the limited supply of compressors, which is at least partly a result of the new Pressure Equipment Directive. Another significant factor is the increasingly strict requirements that are specified within European and International safety standards that make it difficult to design systems with a competitive market price."[129]

2.4.1.1 Factory Sealed Units including Moveable Units

Factory sealed units are self-contained systems and single-split systems with flexible refrigerant hoses with cooling capacities of one to 10 kW. Most of them operate with HFC as refrigerant at charges of 0.3 – 3 kg.[130] HC-290 is used in several small moveable units with 5-10% higher energy efficiencies as comparable HFC-units. The cooling capacity of those units ranges from 500 to 3,200 W and the refrigerant charge is 100–500 g.[131]

Figure 2.12 shows the maximum technically feasible phase-out of HFCs in factory sealed air conditioning units in the EU provided additional measures are implemented (WAM), and the potential mix of alternative technologies with their estimated growth.[132] The EU sector sheets of Annex V of Schwarz et al. show that up to 60% of the market in 2030 can be met through hydrocarbon technologies, however the final penetration mix chosen by the Schwarz analysis includes only 40% hydrocarbons. Since the hydrocarbon systems are significantly cheaper than unsaturated HFCs (which are also flammable), the market penetration of hydrocarbons in 2030 here is increased to 60% and unsaturated HFCs lowered to 20%.

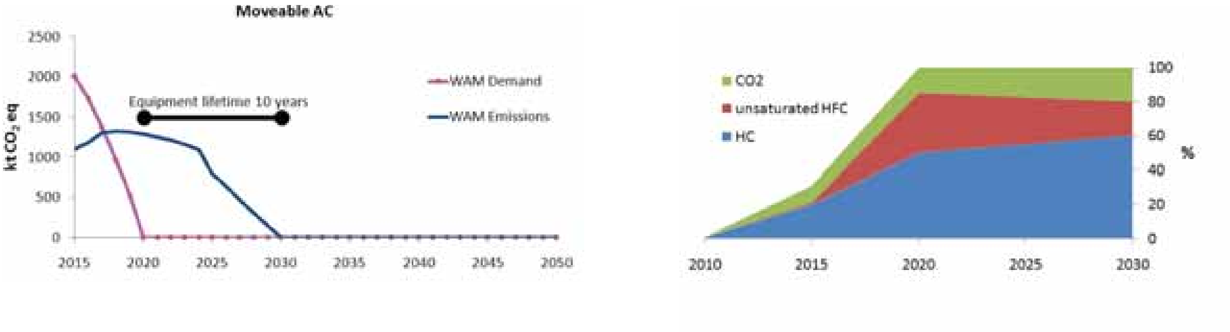


Figure 2.12
Estimated maximum technically feasible phase-out of HFCs in new factory sealed air conditioning units in the EU and the expected mix of abatement options. Data from Schwarz 2011, with market penetration of hydrocarbons increased to maximum according to Schwarz et al.[133]

2.4.1.2 Split Air Conditioners

Hydrocarbons are being used with existing safety standards, especially for wall and ceiling mounted single-split units up to approximately 7 kW cooling capacity.[134] A replacement of about 50% to 65% of all HFC refrigerant mass is technically feasible in Europe given current safety regulations.[135] The flammability risk associated with larger refrigerant charges prohibits the use of hydrocarbons in larger systems in occupied spaces under current safety regulations. Although technically feasible and even one to two percent cheaper,[136] these restrictions currently hinder the wider use of hydrocarbon refrigerants in air conditioning systems.

Figure 2.13 shows the maximum technically feasible phase-out of HFCs in single-split units in the EU provided additional measures are implemented (WAM), and the expected mix of alternative technologies with their estimated growth.[137] Fig. 2.13 also shows the equipment lifetime. Starting at the earliest end of use date in new equipment (2020), it visualizes when HFC consumption for existing equipment will end.

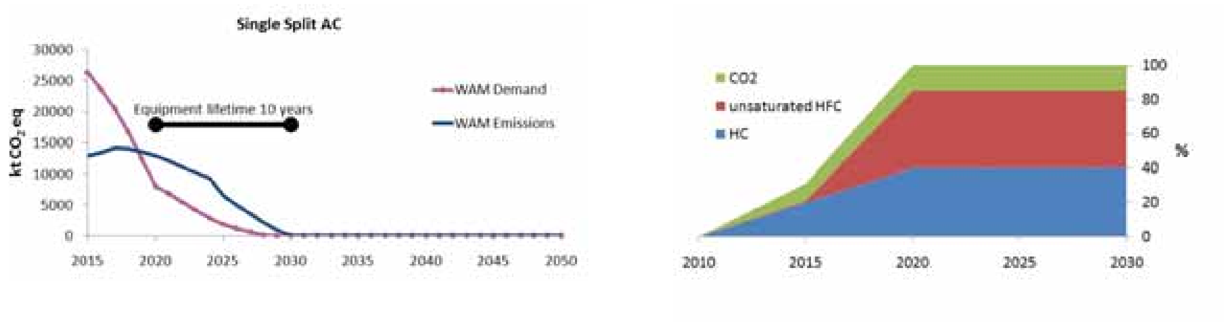


Figure 2.13
Estimated maximum technically feasible phase-out of HFCs in new single-split air conditioners in the EU provided additional measures are implemented (WAM), and the expected mix of abatement options. Data from Schwarz 2011.[138]

According to Schwarz et al. (2011), the potential penetration rates of hydrocarbons and CO_2 are as high as 50% and 30% respectively by 2030.[139] Due to energy efficiency constraints of CO_2 systems in warmer regions Schwarz et al. limited their use to 15%. Single split air conditioners can be sold to private customers in hardware stores and other shops, often resulting in home-installation by the customer (which is illegal for hydrocarbon and HFC-systems), therefore market penetration of hydrocarbons was limited by Schwarz et al. to 40%. These values are used in fig 2.13.

For larger multi-split units, current safety regulations hinder the application of hydrocarbons refrigerants in occupied spaces due to the larger refrigerant content of multi-split systems. Secondary refrigerant systems similar to those used in large centralized commercial refrigeration systems (see 2.2.2.3) could be used – the energy efficiency would then be similar to an HFC multi-split system. CO_2 might be an alternative for larger split systems showing similar energy efficiencies at least for moderate climates.[140]

Figure 2.14 shows the maximum technically feasible phase-out of HFCs in multi-split air conditioners in the EU provided additional measures are implemented (WAM), and the expected mix of alternative technologies with their estimated growth.[141] Fig. 2.14 also shows the equipment lifetime. Starting at the earliest end of use date, it visualizes when HFC consumption for existing equipment would end.

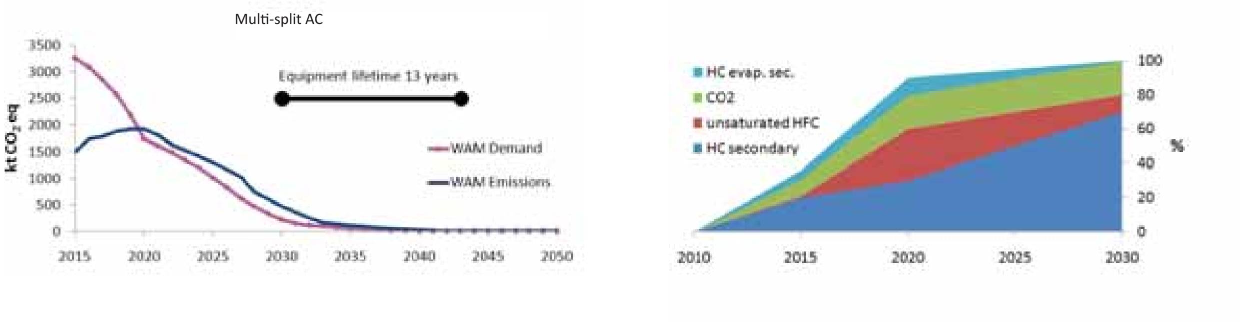


Figure 2.14

Estimated maximum technically feasible phase-out of HFCs in new multi-split air conditioners in the EU provided additional measures are implemented (WAM), and the expected mix of abatement options. Data from Schwarz 2011 indicate that CO_2 can technically cover 30% of the market in 2030 at lower costs than other abatement options. However the market penetration of CO_2 was limited to 20% by Schwarz (2011) due to energy efficiency constraints in warmer climates.[142]

Case Studies Split Air Conditioners

The Australian based company Coolquip mentions various split air conditioner projects with noticeable energy savings using hydrocarbon refrigerant: The Defence Science & Technology Agency in Singapore using a 1hp air-cooled split unit recorded 16% savings; Watson's Stores in Singapore using an air-cooled split unit recorded 24% savings; the Moomba Restaurant, Boat Quay Singapore using an 8hp Air-cooled split unit recorded 16% savings; 7-eleven Stores Kuala Lumpur recorded 24% savings; Sumiden Electronics Shah Alam in Malaysia recorded 22% savings; and Hosiden Electronics Bangi recorded 25% saving for air-cooled split air conditioner.[143]

By the end of 2010 GIZ/GTZ had converted a production line to hydrocarbon split air conditioners in a Chinese factory of one of the world's largest manufacturers of split air conditioners. The propane units achieve 10-15% higher energy efficiency. The manufacturer expects to sell 100,000 hydrocarbon split air conditioners annually with hydrocarbon charges up to 330 g for a 3.5 kW refrigeration capacity unit. One production line will produce 180,000 HCFC/HFC-free units per year. The replacement of the HCFC refrigerant will prevent 560,000 tonnes CO_2e of direct emissions during the life time of the units. Additionally, indirect emission of 320,000 tonnes CO_2e will be avoided through improved energy efficiency of the units.[144]

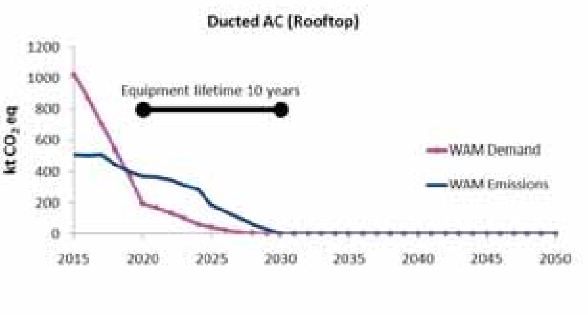
"The product is not only safe in use, it is also saving direct emissions (as the hydrocarbon refrigerant has a negligible global warming potential) and indirect emissions (energy savings of up to 15% compared with conventional appliances). This is of special importance as China is the most important production place for air conditioners worldwide (75% of world market production)".[145]

In China and India, at least five major manufacturers are now introducing HC-290 production lines. Two UK, one Australian and one Italian manufacturer have been producing such units for some time, the Italian manufacturer since 1995.[146]

2.4.1.3 Ducted Systems

Ducted air conditioning systems cover several categories including rooftop-ducted systems, central ducted systems and close-control systems. In the EU those systems typically use HFC refrigerants with charges of 5 to 150 kg. The same technical options described for multi-split systems apply to ducted systems, although due to the larger refrigerant charges, hydrocarbons will mostly be limited to indirect applications.

Figure 2.15 shows the maximum technically feasible phase-out of HFCs in ducted / packaged (roof top) air conditioning units in the EU provided additional measures are implemented (WAM), and the expected mix of alternative technologies with their estimated growth.[147] Fig. 2.15 also shows the equipment lifetime. Starting at the earliest end of use date, it visualizes when HFC consumption for existing equipment will end.



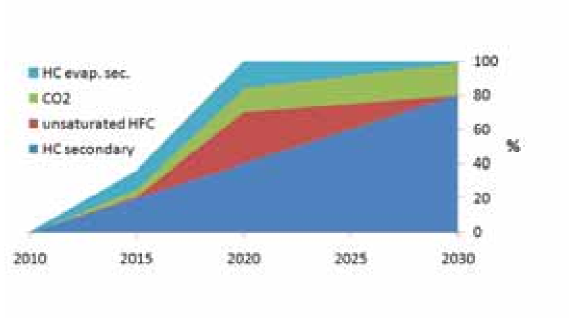


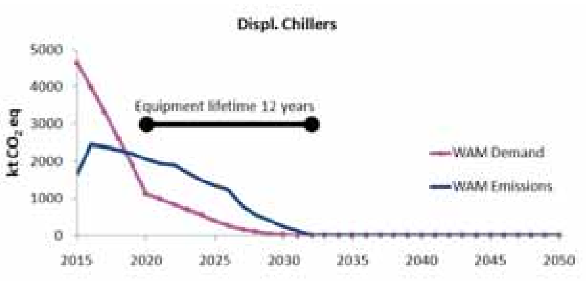
Figure 2.15
Estimated maximum technically feasible phase-out of HFCs in new ducted air conditioners in the EU provided additional measures are implemented (WAM), and the expected mix of abatement options. Data from Schwarz et al. 2011.[148]

2.4.1.4 Chillers

Chillers cool water, which is pumped throughout a building in order to provide cooling in multiple rooms. Chillers can be divided according to the compressor used, i.e. positive displacement compressors (reciprocating piston or screw) or centrifugal compressors. In the EU most of them use HFCs with charges of 5 to 10,000 kg, although there are chillers in the EU using ammonia, hydrocarbons and water.

Any alternative low-GWP refrigerants are technically feasible as the distribution in the building is via water loops. Ammonia and hydrocarbon chillers are already on the market, with increased energy efficiency of about 10% in small hydrocarbon chillers to 20% for small ammonia chillers. CO_2 is expected to have the same energy efficiency in moderate and 10% lower energy efficiency in warm climates. For large centrifugal chillers, water as refrigerant is an environmentally benign solution, with 5-10% better energy efficiency.[149]

Figure 2.16 shows the maximum technically feasible phase-out of HFCs in positive displacement compressor chillers in the EU provided additional measures are implemented (WAM), and the expected mix of alternative technologies with their estimated growth. According to the EU sector sheet ammonia has the potential to penetrate 50% of the market, however the penetration mix chosen by Schwarz 2011 only allows for 30% ammonia, despite its significantly cheaper costs compared to unsaturated HFCs.[150] Therefore unsaturated HFC could be avoided completely by 2030. CO_2 is used in the penetration mix despite its higher cost because it is the only non-flammable refrigerant among all the alternatives.[151] Fig. 2.16 also shows the equipment lifetime. Starting at the earliest end of use date, it visualizes when HFC consumption for existing equipment will end.



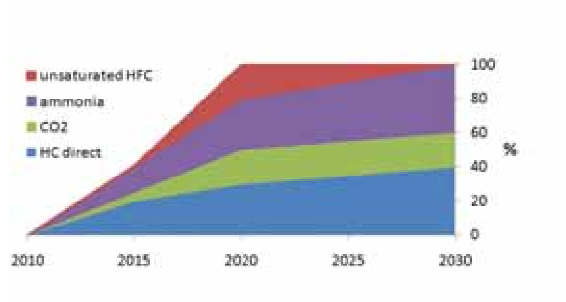


Figure 2.16
Estimated maximum technically feasible phase-out of HFCs in new positive displace¬ment compressor chillers in the EU provided additional measures are implemented (WAM), and the expected mix of abatement options. Data from Schwarz 2011 but ammonia increased by 10% to 40% in 2030.[152]

Figure 2.17 shows the maximum technically feasible phase-out of HFCs in centrifugal chillers in the EU provided additional measures are implemented (WAM), and the expected mix of alternative technologies with their estimated growth.[153] Fig. 2.17 also shows the equipment lifetime. Starting at the earliest end of use date, it visualizes when HFC consumption for existing equipment will end.

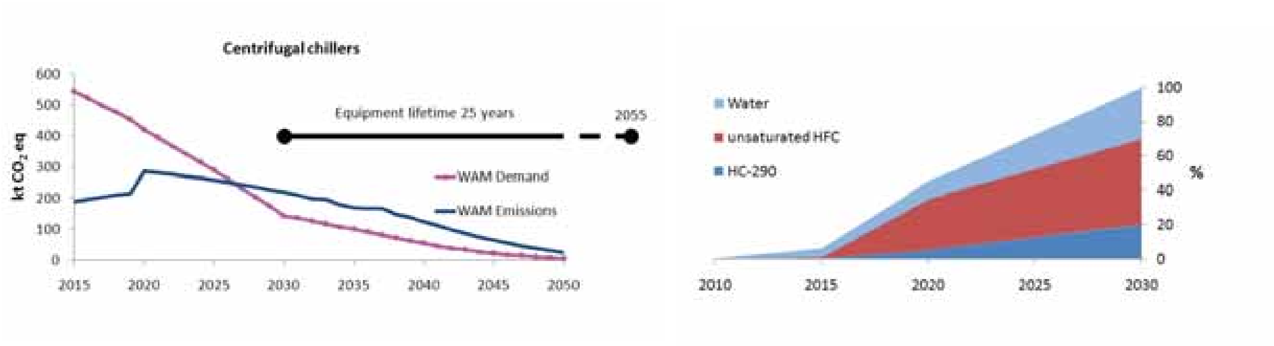


Figure 2.17
Estimated maximum technically feasible phase-out of HFCs in new centrifugal chillers in the EU provided additional measures are implemented (WAM), and the expected mix of abatement options. Data from Schwarz et al. 2011.[154]

Case Studies Chillers

GEA Grasso has developed an ammonia chiller with smaller footprint, less noise and lower energy consumption than any comparable HFC chiller. In particular the part load efficiency has been greatly improved, which is significant since most chillers operate over 90% of the time under part load condition. At 25% capacity the energy consumption is estimated to be less than half that of comparable HFC chillers. The ammonia chiller is also cheaper than an HFC unit with comparable energy efficiency.[155] Ammonia chillers are being used in many public buildings including Copenhagen airport, department stores in Aarhus and Copenhagen, and the state government building in Düsseldorf, Germany.

Chillers with hydrocarbons are readily available from various manufacturers including Earthcare Products, Frigoteam and Frigadon. Swedish SRS Frigadon reduces the hydrocarbon refrigerant charge to a minimum by building separate systems, e.g. their four circuit 210 kW cooling capacity unit has four compressors of approximately 4 kg hydrocarbon each, giving a total of 16 kg of HC-1270. These systems are 10-15% more energy efficient than HFC-chillers.[156] Installations exist in the UK, Ireland, Germany and Denmark with customers such as Sainsburys, COOP Banks, ASDA - Walmart, St. Pauls Academy, NHS Trust, Roche Pharmaceuticals, Dunnes Stores, Braehead Foods, Meadowhall Shopping Centre, Liverpool, Produce Terminal, Novo Nordisk Pharmaceuticals and Brixham Fish Market.[157]

Water as refrigerant has long been marketed by an Israeli manufacturer of centrifugal compressor desalination equipment. Systems have been installed in *inter alia* South Africa, Denmark and Japan. A recently concluded multi-year development project funded by the Danish Energy Agency involving Japanese and American companies together with a Danish research institute has resulted in two water vapor compressors of 0.8 and 1.8 MW. Depending on the system design and operating conditions, systems using the newly developed compressors can in many cases achieve energy savings in the range of 10 to 20%.[158] The German company Efficient Energy has developed a centrifugal chiller with water as refrigerant of about 5 to 15 kW capacity which the company also plans to offer as a heat pump.[159] In both cases – cooling and heating mode – Efficient Energy claims energy efficiencies much higher than HFC systems.

2.4.1.5 Not in kind alternatives to room air conditioning systems

An alternative to the vapor compression cycle used in all HFC air-conditioning systems is an absorption air-conditioning system which is used quite frequently in large buildings in big cities with electrical grid limitations in the summer. The absorption system uses the principle that some gases will be absorbed by certain liquids. Typical pairs are water (refrigerant) and lithium bromide (absorbent), or ammonia (refrigerant) and water (absorbent). The water/lithium bromide pair is usually used in absorption air conditioning systems. Instead of using an electrically driven compressor, such systems facilitate the pressure lift by a liquid pump pumping a mixture of the refrigerant and absorbent, i.e. diluted water/lithium bromide solution. Heat is required to remove the water from the solution. This heat is typically supplied by a gas furnace but could also be waste heat at appropriate temperature level. The energy efficiency of a gas fired absorption chiller is usually only 25% of that of a comparable compressor system. Based on the typical efficiency for converting fossil fuel into electricity (25-30%) and the energy mix of Europe, the CO_2 balance is about equal for both systems, i.e. vapor compression and gas fired absorption. Absorption systems could become more attractive where heat is supplied by solar collectors. On the other hand, if electricity production is mostly from renewable energy, as for example in Norway, electrically driven vapor compression systems will also have lower CO_2 emissions due to energy use.

Another possibility is the use of evaporative cooling, which is especially efficient in hot and dry climates. Warm and dry outside air is humidified by water spray. This humidification can reduce the air temperature several degrees, as one experiences when wearing a wet shirt in a dry summer breeze. This kind of evaporative cooling only works with dry air, which is the reason why it is often combined with sorptive systems. A water adsorping substance, e.g. silica gel, which attracts water molecules and incorporates them into its open pore structure, is used in order to remove moisture from the air. The air is heated by this process and has to be cooled prior to spraying water into the dry and chilled air. Both evaporative methods can make the use of conventional air-conditioning systems redundant. Systems working according to both principles are available on the market.

Another alternative is better insulation of the building, shading of roof areas as well as walls and especially windows and the introduction of large thermal masses which are preferably cooled by colder night outdoor air. Large thermal masses can be achieved with phase change materials such as encapsulated paraffin plaster. The phase change material absorbs heat during melting and rejects heat upon solidification – similar to the phase change of water and ice. Paraffin, which can be derived from vegetable oils, usually has an energy storage capacity of 60-70% of that of water/ice, but offers the advantage of a phase change temperature close to room temperature, i.e. 20 °C. A new building at the University of Washington in Seattle, USA reduces its energy use for office cooling by 98% by using phase change materials encapsulated within the walls and ceiling panels, which is solidified during the night with cold outdoor air entering through the automatically opened windows.[160]

All these measures reduce the total cooling load of the building and hence the capacity of the air conditioning system and could even make air conditioning systems – accounting for 10-40% of a buildings energy consumption[161] – obsolete. Although some cooling capacity may be needed for air dehumidification, especially in humid climate, dehumidification is also possible with sorptive systems again making conventional air conditioning systems redundant.

2.4.1.6 Heat Pumps (heating only)

Heating only heat pumps are used for heating spaces and/or drinking water. Ground water, soil or outdoor air are the most common heat sources of these heating devices. Typical coefficients of performance of such systems are around four, meaning that they produce four times more heating than the electricity used to drive the compressor. Depending on the energy mix of a country, i.e. the CO_2 emissions associated with the electricity production, heating with a heat pump system can substantially reduce CO_2 emissions compared to heating with fossil fuels. Approximately 98% of European heat pumps today use HFC as refrigerant[162] in charges of 1.5-15 kg for achieving 5 to 50 kW heating.[163]

Most heating only heat pumps are heating tap water or water which then heats the space to be heated. For these systems hydrocarbons are a technically feasible option with excellent energy efficiency. Heat pumps with HC-290 or HC-1270 were used in the 1990s and 2000s when CFCs were banned, however the majority of production was stopped due to the introduction of the Pressure Equipment Directive (PED) which imposed additional certification of the types of compressors normally used, incurring additional cost implications for manufacturers. As a result, the use of HFC blends R407C, R404A and R410A took over.[164] Today heat pumps with hydrocarbons (HC-290, HC-600a) are available for capacities <20 kW from at least 18 European manufacturers.[165] Unit prices are expected to be 5% higher due to safety requirements.[166]

CO_2 heat pumps are marketed especially in Japan. The thermodynamic characteristics of CO_2 with its even heat capacity during gas cooling in the transcritical process (see section 2.2.2) make it the ideal refrigerant and cycle for water heating heat pumps for high water temperature demands. In these cases, CO_2 emissions are cut by about 50% compared with conventional combustion type water heaters.[167] Over 2 million “eco cute” heat pumps had been sold by the end of October 2009.[168]

Figure 2.18 shows the maximum technically feasible phase-out of HFCs in heat pumps (heating only) in the EU provided additional measures are implemented (WAM), and the expected mix of alternative technologies with their estimated growth.[169] Fig. 2.18 also shows the equipment lifetime. Starting at the earliest end of use date, it visualizes when HFC consumption for existing equipment will end.

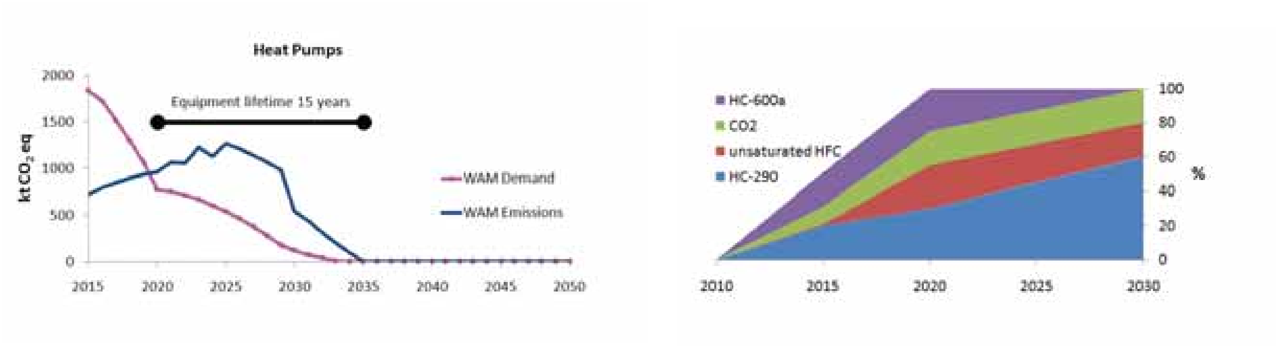


Figure 2.18
Estimated maximum technically feasible phase-out of HFCs in new heat pumps in the EU provided additional measures are implemented (WAM), and the expected mix of abatement options according to Schwarz et al. 2011.[170]

Industrial heat pumps are also available in the market as heating only. These heat pumps can be based on either HC-600a or ammonia. If temperatures are no higher than 55 °C, propane is also an option. These systems have been in the market for some time; one of these heat pumps is installed in Oslo Gardermoen airport to keep the parking place for the airplanes free of snow and ice.

2.4.2 Mobile Air Conditioning

Mobile air-conditioning (MAC) systems can be found in any kind of vehicle from passenger cars and light duty vehicles to trucks, buses, farming machines, trains, ships and airplanes. Other than passenger airplane air conditioning, where air is used in an air cycle, all vehicles use the vapor compression cycle – typically with HFC as refrigerant – in order to cool the cabin. HFC charges vary from 0.4 kg for small cars to 18 kg for articulated buses, up to 30 kg for trains and several tonnes for cruise ships. Passenger car air conditioning is the only sector where the current European legislation will result in a reduction of HFC demand and emissions (through the MAC Directive which will force all cars to use a refrigerant with GWP < 150 starting 2017). The truck and bus sector is expected to continue to use HFC-134a, reflected by a steady demand for HFCs even after 2030 (see Figure 2.19).

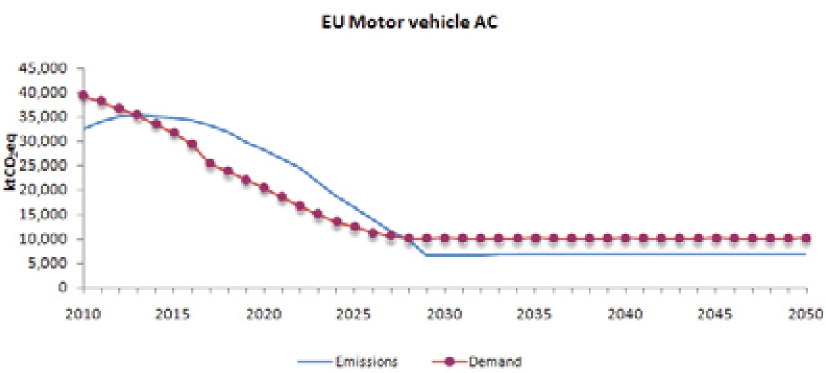


Figure 2.19
HFC-134a demand and emissions from the sector of mobile air conditioning of motor vehicles (passenger cars, trucks, buses) under the current F-Gas Legislation. The strong reduction trend until 2030 results from the HFC-134a phase-out under the MAC Directive. After 2030 the remaining emissions and demand is caused by truck and bus systems; while the demand also includes first fill for passenger cars which are exported to third countries where high-GWP HFCs are allowed.[171]

2.4.2.1 Car Air Conditioners

The typical car air conditioning system consists of a belt driven, open compressor which is connected by rubber hoses to the other components to allow for engine movement and vibrations. Car air conditioning systems worldwide are charged with 0.4-0.8 kg HFC-134a for single evaporator systems and approximately twice that amount for dual evaporator models. Leakage rates are in the order of 10% due to the compressor shaft seal and rubber hoses.

"Up to now, car manufacturers and suppliers have evaluated several refrigerant options for new car (and truck) air conditioning systems including R-744, HFC-152a and HFC-1234yf, all with GWPs below the EU threshold of 150. These options can achieve fuel efficiency comparable to the existing HFC-134a systems with appropriate hardware and control development. The use of hydrocarbons or blends of hydrocarbons has also been considered but so far has not received support from vehicle manufacturers due to safety concerns. The eventual decision which refrigerant to select for vehicle air conditioning will be made based on the GWPs of the above three options along with additional considerations including regulatory approval, costs, system reliability, safety, heat pump capability and servicing."[172]

Hydrocarbons or hydrocarbon blends, when correctly chosen, present suitable thermodynamic properties for the vapor compression cycle and permit high energy efficiency to be achieved with well-designed systems,[173] probably at limited additional cost. In several countries, including Australia, China and the USA, many existing car air conditioning systems are charged with hydrocarbon blends during service. Such retrofits are legal in some Australian states and illegal in others and in the USA. Official trials by vehicle manufacturers using hydrocarbons have so far been carried out only with indirect systems (due to safety concerns), introducing an unnecessary temperature difference and consequently lower efficiency. CO_2 car air conditioning systems have also been developed to a stage where they have demonstrated their technical feasibility and comparable energy consumption.[174]

2.4.2.2 Truck and Bus Air Conditioning

Truck air conditioning systems are very similar to car air conditioning systems, i.e. belt driven compressors with its inherent compressor shaft and rubber hose leakage rates of 10-15%.[175] Hence the same considerations regarding alternatives as outlined in section 2.3.2.1 will apply. The number of truck air conditioning systems is approximately 5% of passenger cars in the EU.

Bus air-conditioning systems are usually belt driven but have a higher refrigeration capacity and therefore also higher charge of refrigerant, around 6-14 kg, and up to 18 kg for articulated buses. For bus air conditioning, indirect hydrocarbon systems are a technically feasible option, but with 5-10% more energy consumption.[176] CO_2 technology has been developed including the required compact, lightweight, high pressure compressors. 22 buses with CO_2 air conditioning systems from three different bus manufacturers are operated in Germany by seven public transportation companies.[177] A further reduction of the energy consumption is expected by combining the air-conditioning system for cooling with a heat pump mode for the compartment heating in winter. A prototype of a CO_2 air-con /heat pump in a city bus saves 50% of the fuel for heating,[178] and there is potential for further improvement.

Figures 2.20 and 2.21 show the maximum technically feasible phase-outs of HFCs in truck and bus air conditioners respectively in the EU provided additional measures are implemented (WAM), and the expected mix of alternative technologies with their estimated growth.[179] Both sub-sectors are expected to follow the same development as the passenger car sector, which currently appears to be unsaturated HFCs. So even though CO_2 has the potential to be used in 50% of all bus air-conditioning and 100% of all truck air conditioning systems by 2030 (and would in the case of truck air-conditioning be significantly cheaper), this option was deemed unlikely by Schwarz et al.

Figs. 2.20 and 2.21 also show the equipment lifetime. Starting at the earliest end of use date, it visualises when HFC consumption for existing equipment will end. Demand exceeds emissions in the EU due to exports of HFC containing truck and bus air conditioning systems.

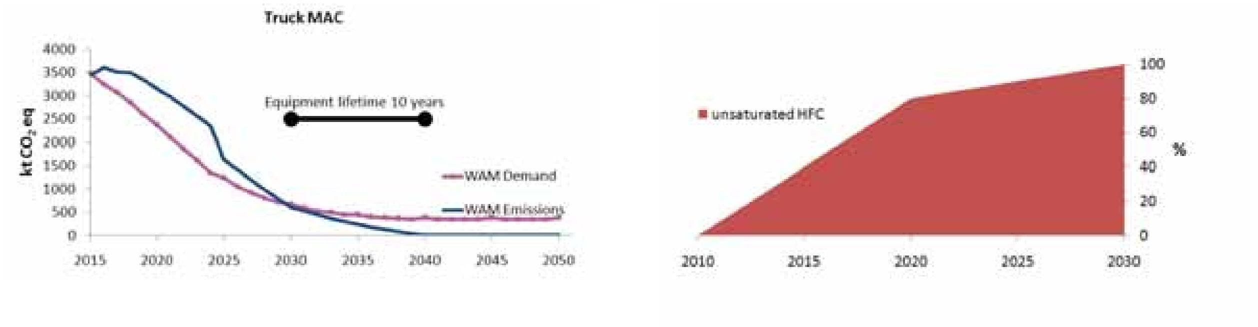


Figure 2.20
Estimated maximum technically feasible phase-out of HFCs in new truck air conditioners in the EU provided additional measures are implemented (WAM), and the expected mix of abatement options according to Schwarz et al. 2011.[180]

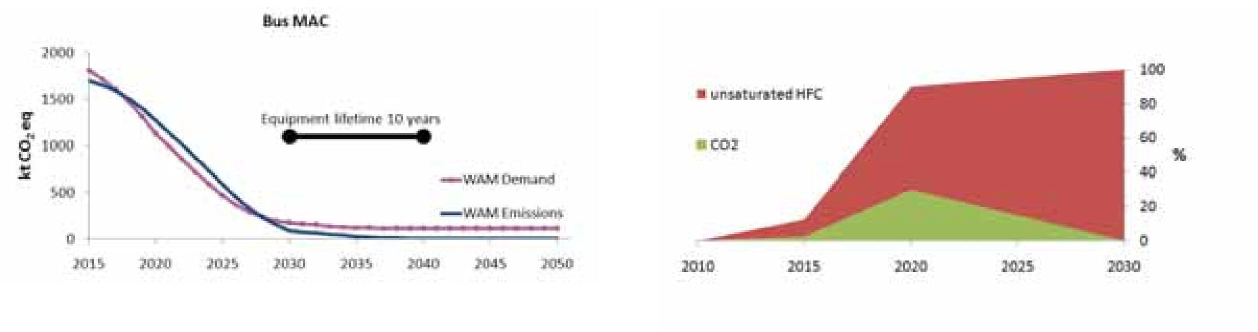


Figure 2.21
Estimated maximum technically feasible phase-out of HFCs in new bus air conditioners in the EU provided additional measures are implemented (WAM), and the expected mix of abatement options according to Schwarz et al. 2011.[181]

2.4.2.3 Rail Vehicle Air conditioning

Even though individual train air conditioning systems might be manufactured for a number of rail cars, there are seldom more than 500 identical systems produced making this sector different from the other mobile air-conditioning sectors. As a consequence a multitude of individual solutions has evolved. Typical refrigeration capacities vary from 20 to 40 kW with HFC refrigerant charges of 5-30 kg. For the air conditioning of the driver's cabin refrigeration capacities are 3 to 8 kW with refrigerant charges of 1.5 to 4 kg.[182] The number one refrigerant used in train air conditioning systems is HFC-134a (followed by R-407C in some countries), with the exception of one series of high speed trains in Germany which is air conditioned by air cycle machines. CO_2 is also an option for trains, with several tests carried out in the past. A diesel driven train has operated in Germany with a CO_2 MAC since 2011. Another project with an electric driven train is planned. Prototypes of compact electrically driven CO_2 air-conditioning systems for electric and diesel electric rail vehicles such as trams and local trains have undergone long-term tests (10,000 hours) in a climate test rig, which means that first vehicles could now be equipped for test operation.[183]

Figure 2.22 shows the maximum technically feasible phase-down of HFCs in rail vehicle air conditioning systems in the EU provided additional measures are implemented (WAM), and the expected mix of alternative technologies with their estimated growth.[184] Fig. 2.21 also shows the equipment lifetime. Starting at the earliest end of use date, it visualizes when HFC consumption for existing equipment will end.

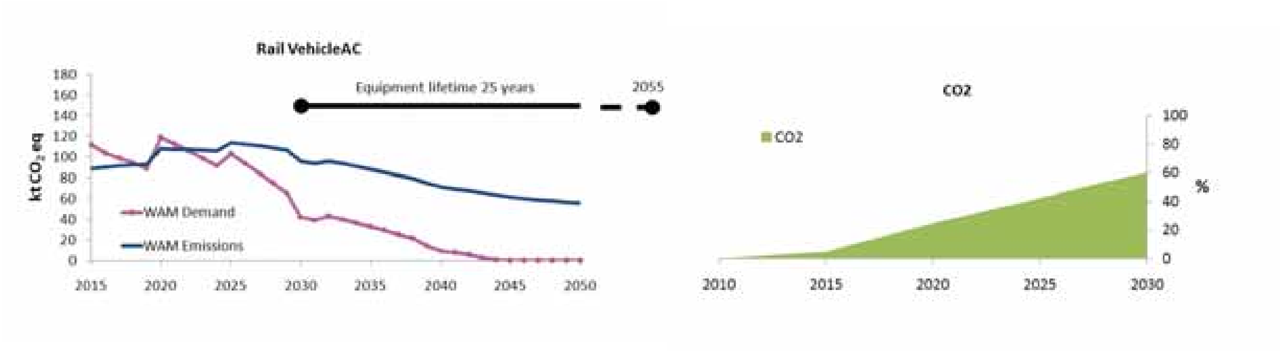


Figure 2.22
Estimated maximum technically feasible phase-down of HFCs in new rail vehicle air conditioning systems in the EU provided additional measures are implemented (WAM), and the expected mix of abatement options. Data from Schwarz et al. 2011.[185]

Case study Rail Vehicle Air Conditioning

Between 2003 and 2005, Liebherr-Transportation Systems supplied the air conditioning system for the latest generation ICE 3 high-speed train operated by German National Railways (Deutsche Bahn - DB). DB ordered 13 trains of the type. The ICE 3 is the first serial production train equipped with an air cycle air-conditioning system. The ICE 3 high speed trains have been in service for several years now and have demonstrated that this future-proof technology is superior to traditional vapor cycle air conditioning concepts in terms of eco-friendliness and life-cycle costs. The system for application in rail vehicles is compliant to UIC 553 and helps to reduce greenhouse gas emissions. As the system does not use any other refrigerant than clean air, there is no risk of leakage and compliance with any future legislation regarding HFC refrigerants in air-conditioning systems is absolute and unlimited. The air cycle air conditioning technology features significantly reduced life cycle-costs compared to common vapor cycle systems. The reliability of the air cycle air conditioning system helps to save direct maintenance costs and leads to considerably reduced vehicle downtimes. Maintenance does not require any additional trained and certified (EG 303/2008) refrigerant personal.[186] A total of 504 air cycle cooled systems for passenger cell air-conditioning are in service, i.e. 5% of all systems.[187]

2.4.2.4 Cargo and Passenger Ship Air Conditioning

Air conditioning aboard ships is usually performed by an HFC-134a system of appropriate capacity. For cargo vessels air conditioning systems have around 100 kW capacity with refrigerant charges of around 150 kg, passenger ships use around 500 kg HFC-134a in order to achieve around 1,000 kW capacity. Cruise ships, with often over 4,000 persons on board, have refrigeration capacities of up to 15 MW using 6,000 to 7,000 kg of HFC-134a. Except for cargo ships, where there are only trained personnel onboard, there are no HFC-free alternative technologies available. For cargo ships ammonia with a secondary loop system is a viable alternative.[188]

Since trains and ships are not covered by the current F-Gas Regulation, HFC demand and emissions are expected to remain constant at around 2,000 kt CO_2 eq. throughout the year 2050.[189]

Figure 2.23 and 2.24 show the maximum technically feasible phase-out of HFCs in cargo and and phase-down in passenger ship air conditioning systems respectively in the EU provided additional measures are implemented (WAM), with the expected mix of alternative technologies with their estimated growth.[190] Figs. 2.22 and 2.23 also show the equipment lifetime. Starting at the earliest end of use date, it visualizes when HFC consumption for existing equipment will end.

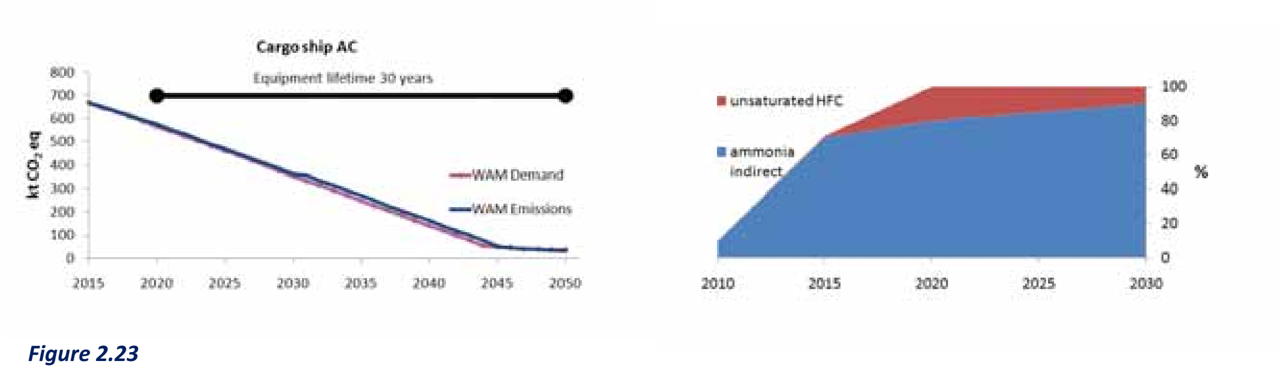


Figure 2.23

Estimated maximum technically feasible phase-out of HFCs in new cargo ship air conditioning systems in the EU provided additional measures are implemented (WAM), and the expected mix of abatement options. Data from Schwarz et al. 2011.[191]

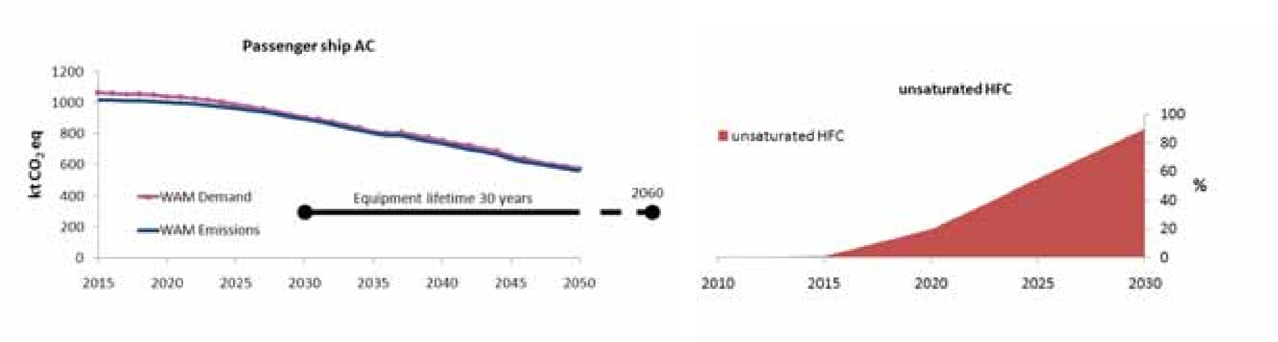


Figure 2.24

Estimated maximum technically feasible phase-down of HFCs in new passenger ship air conditioning systems in the EU provided additional measures are implemented (WAM), and the expected mix of abatement options. Data from Schwarz et al. 2011.[192]

2.5 Foam Blowing

"Growth in thermal insulation foams continues to be driven by increasing energy efficiency requirements in appliances, transport and buildings. Space constraints in the built environment (e.g. cavity dimensions) have driven dramatic shifts from fibrous products to foam products in some localised markets to meet the required thermal performance. However, fibre has largely maintained its share through growth in the residential refurbishment sector where cost is a prime issue."[193]

HFCs are used in foam blowing of polyurethane (PU) and extruded polystyrene (XPS) foam insulation and are the preferred choice for applications with very low thermal conductivity. Alternatives are hydrocarbons – widely used as blowing agent by the domestic refrigeration industry in Europe, Asia and South America and the building panel industry – and water and polymeric isocyanate reacting to generate CO_2 blowing agent in situ in the same plastics. Thermal conductivity properties are generally 1-2 mW m^{-1} K^{-1} to 4-6 mW m^{-1} K^{-1} higher for hydrocarbons and CO_2 (water) respectively as compared to the same foam blown with HFC,[194] which corresponds to approximately 5-20% thicker foam insulation needed for the same insulating properties depending on the foam product.

For foam insulation with a high thermal performance, primarily in the appliance sector but also in some construction and transport applications with space restrictions, it might – with current technology – be necessary to keep using HFCs.[195] These might be substituted by unsaturated HFCs and methyl formate which are being assessed at this time. Early work on unsaturated HFCs suggests that they deliver better thermal performance than their saturated counterparts, although toxicological work remains to be completed for those substances yet to be commercialized.[196] In all other applications, i.e. where the thickness of the insulation does not matter, hydrocarbons or CO_2 (water) can perfectly substitute HFC foams.[197] It would also be possible to shift to fibre insulation (mainly rock or glass), although typically they require greater thicknesses. A new kind of insulation system for internal insulation of external walls offers a possible alternative. This consists of a combination of rock wool and aerogel.[198] An alternative with much better insulation characteristics is vacuum insulation, which is already used in some extra low energy consuming appliances.

Without any additional measures the HFC demand and emissions from PU and XPS foam, under the current F-Gas Regulation, is expected to remain fairly constant throughout 2050, fig. 2.25. Manufacturing emissions are very high, with 5-15% in PU foam applications, and 25-35% in XPS production with HFC-134a (100% in XPS production with HFC-152a). While in the PU sector use-phase emissions exceed manufacturing emissions from 2020 onwards, in the XPS sector, manufacturing emissions are higher than use-emissions even in 2050. It should be noted that, unlike refrigerants, blowing agent emissions in the use-phase are not refilled and do not trigger demand.

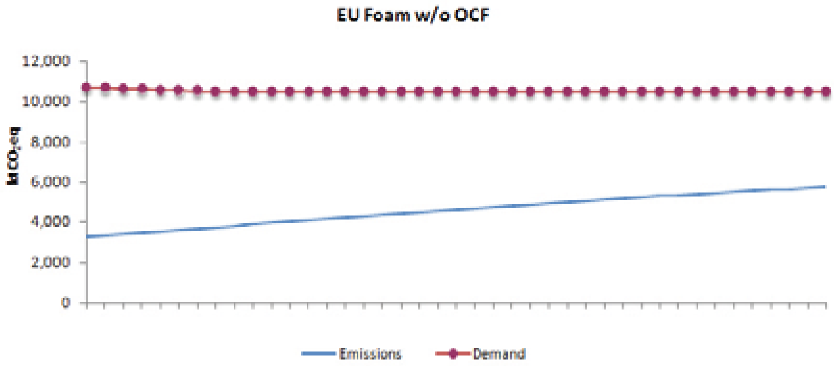


Figure 2.25
HFC demand and emissions in the PU and XPS foam sectors in EU-27 under the current F-Gas Regulation. While the annual application is assumed to remain unchanged, emissions from use continue increasing as the bank grows. Disposal emissions do not occur until 2050 because of the 50-years lifetime of the foam.[199] Curves are without one component foam (OCF).[200]

Figure 2.26 shows the maximum technically feasible phase-out of HFCs in foam blowing in the EU provided additional measures are implemented (WAM), and the expected mix of alternative technologies with their estimated growth according to Schwarz et al. (2011).[201] The market penetration for HC/CO_2 in XPS HFC-134a could be as high as 90% according to Schwarz et al.[202] as opposed to 85% as shown in Figure 2.26. According to maximum penetration rates (Schwarz et al. 2011), CO_2 (water) blown technologies could meet 100% of PU-spray foam requirements (at a lower cost the unsaturated HFC alternative), rather than 50% as outlined in the penetration mix[203] and in figure 2.26. Figure 2.26 also shows the estimated foam lifetime. Starting at the earliest end of use date, it visualizes when HFC demand for existing equipment will end.

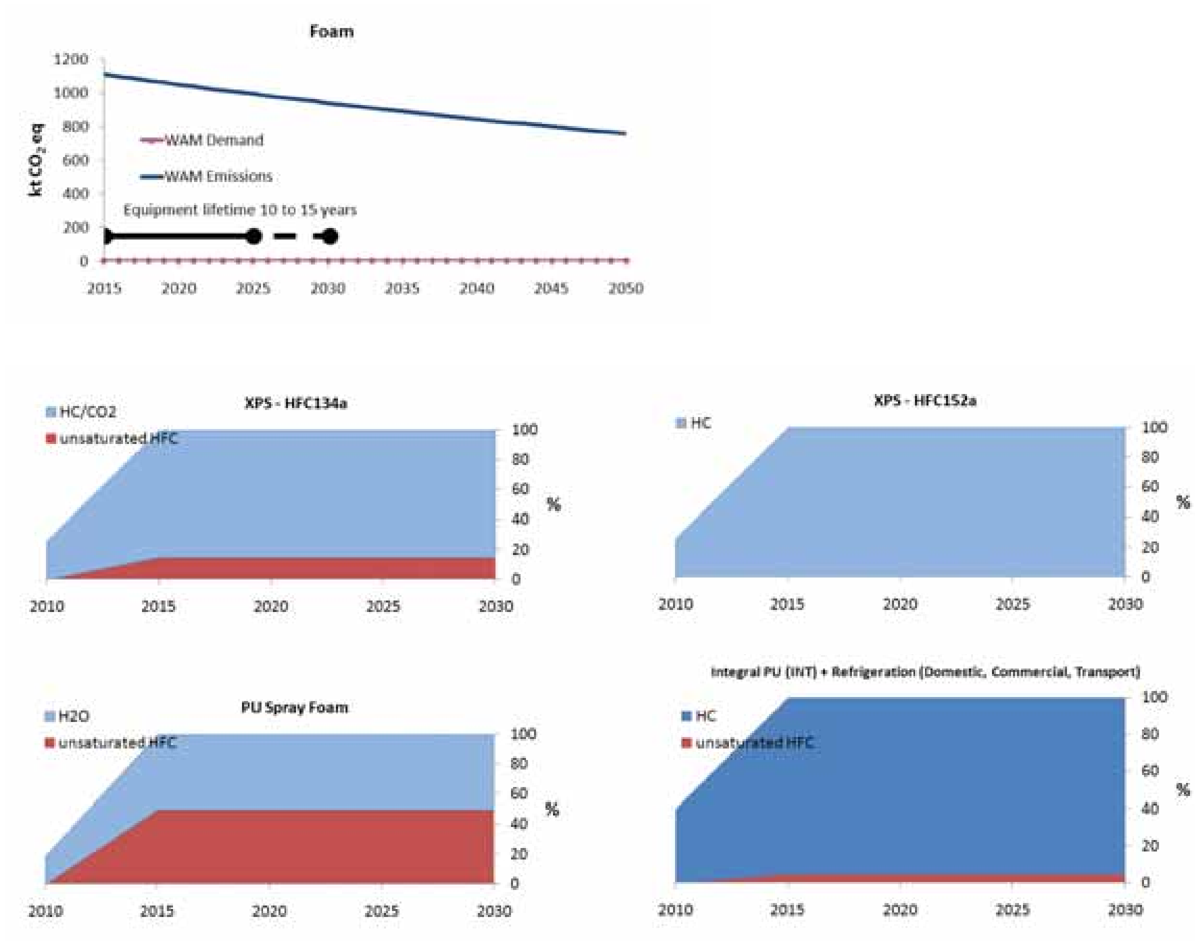


Figure 2.26

Estimated maximum technically feasible phase-out of HFCs in new foam in the EU provided additional measures are implemented (WAM), and the expected mix of abatement options for the various kinds of foams according to Schwarz 2011.[204]

2.6 Aerosols

More than half of all HFC-aerosols are for medical dose inhalers (MDI) for treatment of asthma and chronic obstructive pulmonary disease (COPD). In many EU countries, more than 98% of all non-medical sprays (the majority of which are cosmetic and household products) already use low-GWP propellants like hydrocarbons or dimethylether.[205] The remainder includes technical aerosols like freezer or precision cleaning sprays, which rely on the non-flammabilty and non-toxicity of HFCs. An alternative option for these applications is HFC-1234ze, which is already used by one manufacturer for service aerosols for the electronics industry. In so-called novelty aerosols (for noise making or similar frivolous purposes), propellant gas mixtures with GWP > 150 are prohibited by the F-gas Regulation. HFCs in these mixtures continue contributing to global warming emissions in a small amount.

Not-in-kind substitutes include pump sprays or solid and roll-on deodorants. For pipe freezing in particular, transportable CO_2 systems and refrigeration systems are available as alternative to freeze sprays.[206]
In 2011, Roche announced that they prohibited the use of HFCs in aerosol products manufactured by Roche or its affiliates.[207]

2.7 Fire Protection

Fire-extinguishing applications can be divided into two categories: portable fire extinguishers and fixed flooding equipment. Overall, portable applications represent a much smaller share of total fire-extinguishing sector greenhouse gas emissions than total flooding applications.[208] In-kind (gaseous) alternatives are CO_2, inert gases (nitrogen or argon) or fluoro-ketone, whereas not-in-kind alternatives include water, water mist, dry chemical, foam and aerosols.[209]

The Fluorine-containing fire extinguishing fluid FK 5-1-12 with a very low GWP of one is available where HFC fire extinguishing agents have to be used.[210] About 20% more FK 5-1-12 is required for the same room size as HFC and the supply pressure must exceed 10 bar due to the fact that FK 5-1-12 is in liquid form under ambient conditions, whereas HFC fire extinguishing substances are in vapor form.[211]

Decomposition of FK 5-1-12 during firefighting and subsequent recombination can, like other HFCs, create decomposition products, e.g. HF, which are toxic to humans and corrosive to electronic equipment.[212] FK 5-1-12 should therefore not be used for existing systems which is designed for other than halogenated extinguishing agents.[213]

Since FK 5-1-12 has a very short atmospheric lifetime of under 14 days[214] there will be local decomposition products. The primary products were found to be COF_2 and $CF_3C(O)F$ with minor amounts of CF_3OH and $CF_3O_3CF_3$ also identified. From a practical experimental standpoint, the formation of CF_3OH in the presence of water vapor is of particular concern, since this can spontaneously decompose into COF_2 and HF.[215] FK 5-1-12 should therefore not be used for applications where halogen-free extinguishing agents have proved successful.[216]

3. PLACING ON THE MARKET PROHIBITIONS

Placing on the market (POM) limitations and ultimately prohibitions are very effective ways of reducing HFC emissions, see also *5.3.1 Danish Experience*. In order to ensure alternative technologies are sustainable, POM prohibitions should only be enforced when energy efficient alternative technologies exist for which the production capacity, safety standards, knowledge for manufacturing and handling as well as the availability of materials and components can be assured. At the same time, POM prohibitions also influence the availability of such alternatives/standards/knowledge and can thereby accelerate the transition. As described in Section 2, Schwarz et al. (2011)[217] estimate the maximum penetration rate or earliest feasible complete transition to alternatives in new units for the individual sectors and sub-sectors. "Maximum technically feasible transition to alternatives" therefore takes the above mentioned constraints into account, i. e. a faster transition – with current knowledge, technology and legislation – is assumed to be unlikely. A change in legislation may advance a technology change: safety belts in passenger cars (required by law since 1 January 1974 in Germany); catalytic converters (1975 in the USA and 1983 in Germany); and the prohibition of higher wattage light bulbs in the EU in recent years are examples of that.

For each alternative described in the data input sheets (DIS) (Schwarz et al 2011, Annex IV), the maximum potential of the particular alternative technology (abatement option - AO) was estimated separately by Schwarz et al. (2011) for the years 2015, 2020 and 2030 without considering the other AOs. Therefore the sum of all abatement options exceeds 100% in many sub-sectors, particularly in later years.[218] Favoring the AO with the highest possible emission or demand reduction potential (e.g. CO_2 to be preferred over HFC-1234yf in multi-split air conditioners), followed by the cost of the particular AO, individual penetration rates of AOs were added up until they reach 100% market penetration – for some sub-sectors this also included reductions of individual penetration rates when the total exceeded 100%.[219] The results were framed in the context of potential emission reductions by 2030 in the Schwarz et al. report. This report looks at what can be done through maximum feasible transition to alternatives in the context of the earlier timeframes of 2015 and 2020, since the DIS showed that many sectors and sub-sectors could effect early phase-outs.

A detailed analysis of all EU sector sheets was made and the earliest feasible dates for 100% penetration rate (i.e. when the transition to alternatives could be complete) of all AOs combined was calculated. For some (sub-) sectors these AOs had to include unsaturated HFCs (e.g. HFC-1234yf or HFC-1234ze) in order to facilitate a faster phase-out. Respective sub-sectors are marked in Table 3.1 if the use of unsaturated HFC continues after 2030.

Table 3.1 summarizes the potential HFC demand and emission reductions achievable in the year 2020 and 2030 (kt CO_2 eq. in the respective year) through transition to alternatives in new equipment at the maximum technically feasible rate for all sub-sectors – provided that appropriate EU HFC-legislation is issued and enforced. Numbers given represent the HFC demand and emission in the respective year.[220] When looking at the numbers one can clearly see that some sectors have very high HFC demand and emissions, e.g. centralized supermarket refrigeration systems and single split air conditioners, and will therefore give the greatest climate benefit if sector-specific legislation is issued.

In addition Table 3.1 shows the average life time of the equipment in the respective sector giving an indication of how long HFC equipment will be in use after production of new equipment is stopped. The year when the abatement option mix reaches 100%, i.e. the transition to alternatives can be completed, is the earliest time that HFCs could be phased out entirely in that particular (sub-) sector without exception – this year is also explicitly given in Table 3.1 and the sub-sectors are grouped according to their earliest HFC prohibition date. For many (sub-) sectors 100% market penetration, i.e. a total substitution of HFC technology, is reached long before the 2030 time frame requested by the EU for the preparation of the preparatory study.[221] In other subsectors, the prohibition date can be advanced if clearly defined exemptions can be crafted for certain outlier applications.

As road vehicle air conditioning systems are produced for a global market, alternative solutions for bus and truck air conditioning are solely based on unsaturated HFCs, even though CO_2 would be a technically feasible solution for both sub-sectors.

Considering the Danish experience (see chapter 5.3.1), it is clear that an accelerated phase out, even exceeding the rates shown in the respective figures of Chapter 2 or given in Table 3.1, could be feasible; although probably at increased cost.

In order to also see the cost of each tonne of CO_2-eq. "saved" (i.e. not used or not emitted) in the individual (sub-) sectors, one can apply marginal emission abatement cost (AC). Marginal emission ACs are the costs associated with incremental reductions in units of emissions.[222] For every subsector shown in Table 3.1, the aggregated mix of abatement options was used (retrieved from the DIS and the EU Sector sheets[223]) in order to establish average (sub-) sector AC for all abatement options combined. The abatement costs given in Schwarz et al. and shown in Table 3.1 reflect an average value over the years 2015 to 2030. Abatement costs are likely to be somewhat higher in the early years whereas they are expected to be lower in later years due to falling prices with increased production numbers – i.e. economies of scale. Positive AC figures mean that the abatement options are more expensive than HFC solutions, whereas negative AC figures mean that the abatement options are cheaper.

Demand (consumption) abatement costs vary widely, from -15.5 €/t CO_2 eq (for large industrial refrigeration) to 74.7 and 414.2 €/t CO_2 eq (for heating only heat pumps and rail car air conditioning respectively). Abatement cost figures given are well within those published by other sources. For example, EPA (2006, p. IV-53) lists 4.84 to 20.21 €/t CO_2-eq. (6.33 to 26.40 US$) for ammonia secondary loop centralized supermarket systems and -21.12 to 13.91 €/t CO_2-eq. (-27.59 to 18.18 US$) for HFC-152a passenger car air conditioning in 2020. For comparison, Enviros calculates 168 €/t CO_2 for energy efficient lighting, 82 €/t CO_2 for energy efficient washing machines in the domestic sector and 100 €/t CO_2 for insulating a flat roof of a commercial building with 100 mm insulation (in 2020).[224]

The CO_2 weighted average for all refrigeration and air conditioning applications considered in this comparison, i.e. excluding mobile air conditioning and household refrigerators (two applications which in the EU will largely be HFC-free in 2020 due to voluntary action by the appliance manufacturers and the EU MAC-directive for passenger car AC), is approximately 10 €/t CO_2 eq.

The Stern Review[225] suggests that the social cost of carbon today, if we remain on a BAU trajectory, is of the order of 85 $/t CO_2 (currently €64.50). Stern states that this is higher than typical numbers in the literature, largely because they treated risk explicitly and incorporated recent evidence on the risks. But nevertheless, as the Stern Review states, $85 per tonne is well within the range of published estimates and – even more important – this number is well above abatement costs in any sector and subsector shown in Table 3.1 (except for two small sub-sectors of heat pumps and rail vehicle MAC). Therefore, any of the aggregated abatement option mixes is cheaper for society than not replacing HFCs.

For society in general, mitigation costs of around 1% of GDP are small relative to the costs and risks of climate change that will be avoided.[226]

Table 3.1

Sector and subsector specific potential HFC demand and emission reduction in 2020 and 2030 in kt CO_2-eq. for the respective year[227] and demand and emission abatement cost (AC). These reductions are measured against an assumption of full implementation of the current F-Gas Regulation. The sub-sectors are grouped according to their earliest end of use in new production (i.e. potential POM prohibition date).

	Sector / Sub sector	Potential reduction from current F-Gas Reg. baseline (kt CO_2 eq in that year): demand reduction 2020	demand reduction 2030	emmission reduction 2020	emmission reduction 2030	Demand AC (€/t CO_2 eq)	Emission AC (€/t CO_2 eq)	Earliest end of use in new production	Equipment lifetime
2015	**Domestic Refrigeration**								
	Refrigerators + Freezers	0.0	0.0	6.5	11.9	**0.4**	**1.0**	2015	15
	Foam								
	XPS Foam HFC-134a	3,636.7	4,092.4	1,354.2	1,552.8	**0.3**	**1.0**	2015	10
	XPS Foam HFC-152a	460.2	460.2	460.2	460.2	**-1.6**	**-1.6**	2015	
	Spray Foam	4,801.5	4,801.5	915.7	1,368.8	**10.0**	**61.6**	2015	10
	Other PU foam	2,057.8	2,057.8	392.4	586.6	**0.2**	**3.5**	2015	15
	Fire Protection								
	Fire protection HFC-23	4,637.8	2,945.8	346.4	961.3	**1.0**	**3.1**	2015	20
2020	**Commercial Refrigeration**								
	Centralized systems	15,724.8	25,214.0	4,444.8	14,741.1	**14.6**	**23.7**	2020	12
	Condensing units	6,385.2	8,948.9	1,045.7	3,927.2	**0.7**	**1.2**	2020	15
	Stand-alone equipment	223.2	218.8	17.1	149.3	**-0.3**	**-0.8**	2020	10
	Transport Refrigeration								
	Vans	213.8	516.3	104.4	421.2	**37.2**	**45.1**	2020	10
	Stationary A/C								
	Moveable type	3,972.0	5,368.8	500.0	2,781.1	**4.4**	**8.9**	2020	10
	Single Split type	31,896.6	45,428.5	5,573.3	22,970.5	**10.8**	**19.0**	2020	10
	Multi-spilt [1)]	3,669.3	6,425.6	574.2	2,826.7	**7.0**	**13.1**	2020 [1)]	13
	Ducted rooftop	1,281.8	1,489.3	136.2	572.8	**3.1**	**8.2**	2020	10
	Displacement Chillers	5,718.5	6,850.9	623.2	2,512.0	**2.2**	**5.9**	2020	12
	Heat pumps (heating only)	3,089.5	6,146.8	361.3	2,281.7	**74.7**	**130.2**	2020	15
	Mobile A/C								
	Cargo ship	140.4	352.9	109.4	320.4	**15.8**	**16.7**	2020	30
	Bus [1)]	738.8	1,694.0	437.7	1,615.7	**42.7**	**48.5**	2020 [1)]	10
	Truck [1)]	1,916.1	4,017.3	983.8	4,169.6	**37.2**	**43.1**	2020 [1)]	10
	Aerosols								
	Aerosols [1)]	3,636.7	3,636.7	3,636.7	3,636.7	**10.0**	**10.0**	2020 [1)]	-
	TOTAL IN 2020	***94,200.4***		***22,023.2***					
2030	**Industrial Refrigeration**								
	Small industrial refrigeration [1)]	1,143.3	2,185.5	265.5	870.5	**-0.6**	**-0.9**	2030 [1)]	30
	Large industrial refrigeration [1)]	3,429.8	6,556.6	796.5	2,611.6	**-15.5**	**-21.6**	2030 [1)]	30
	Transport Refrigeration								
	Trucks and trailers	1,686.1	4,324.9	798.7	2,990.0	**2.0**	**2.6**	2030	10
	Fishing vessels [1)]	312.3	538.7	185.9	405.2	**3.2**	**3.4**	2030 [1)]	30
	Reefer Containers	2,536.5	4,165.3	unknown	unknown	**9.0**	unknown	2030	14
	Stationary A/C								
	Centrifugal Chillers	183.9	460.1	13.8	82.1	**5.5**	**11.1**	2030	25
	Mobile A/C								
	Passenger ships [1)]	19.9	159.9	12.1	124.8	**33.1**	**35.0**	2030 [1)]	30
	Rail vehicles [1)]	45.0	128.8	492.4	26.0	**414.2**	**555.6**	2030 [1)]	25
	Fire Protection								
	Fire protection HFC-227ea [1)]	1,951.3	2,578.1	146.0	440.5	**7.4**	**22.3**	2030 [1)]	20
	TOTAL IN 2030		***21,098.0***		***7,550.6***	Includes only sub-sectors reaching end of use in new production in 2030; in case all other uses have been phased out by 2020			
		Potential reduction from current F-Gas Reg. baseline (kt CO_2 eq in that year): demand reduction 2020	demand reduction 2030	emmission reduction 2020	emmission reduction 2030				
	TOTAL	**105,509**	**151,764**	**24,734**	**75,418**	Total of all sub-sectors in the respective year			

[1)] A ban of HFCs is feasible by the date given if the remaining HFC use (typically 5% or 10%) can be clearly identified as exemptions

The left-hand graph in Figure 3.1 shows the development of HFC demand (consumption) and emissions in the EU with the current F-Gas Regulation together with the gradual reduction achieved by the sum of the maximum technically feasible transition to alternatives in all sub-sectors as indicated in chapter 2. The right-hand graph shows the accumulated CO_2-eq. tonnes which will be avoided if the maximum technically feasible transitions are followed. By 2030 this amounts to approximately 1,600 Mega tonnes CO_2-eq. in HFC demand (consumption) and 600 Mega tonnes CO_2-eq. in HFC emissions. As most HFCs have long atmospheric lifetimes, most of the HFC used in e.g. 2015 and emitted in subsequent years will still be in the atmosphere by 2030.

A transition closely following the maximum technically feasible replacement schedule as presented in the various figures of chapter 2 will result in more HFC-emissions abated than only POM prohibitions upon the year of 100% market penetration. This makes sense since POM prohibitions constitute only one measure – albeit a necessary one – in the package of policies that will be needed to address HFC emissions in the European Union. But it is also the product of conservative assumptions. For example, 100% market penetration is only considered for 2015, 2020, and 2030 – not any intervening years where 100% market penetration might first occur. In addition, it assumes no market transformation or technological innovation in these subsectors, an unlikely scenario since the abatement options have yet to reach the most advantageous part of the innovation curve and the industry can be expected to achieve significant gains as the technologies mature. It also assumes no emission reductions result from a POM prohibition until the day it takes effect, thereby excluding all reductions that occur during the transition made in anticipation of the POM prohibition entering into force.

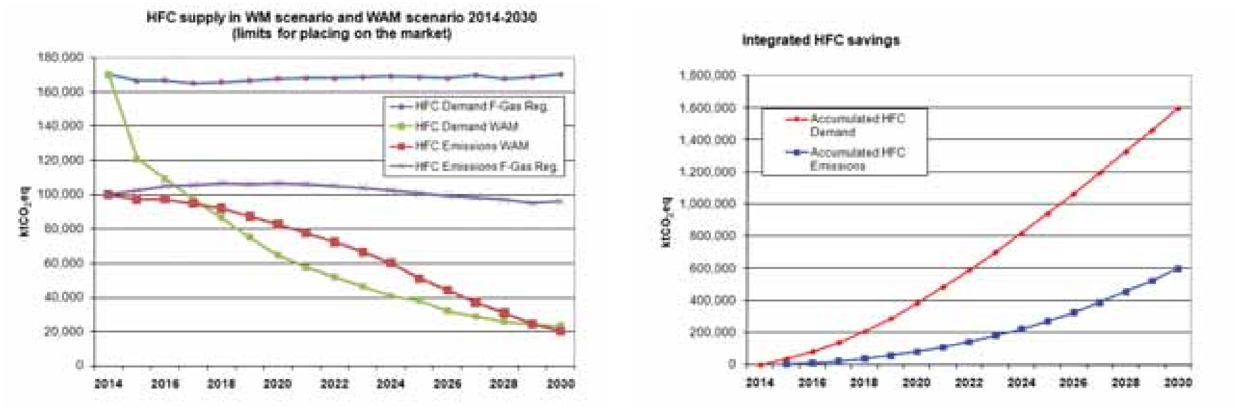


Figure 3.1
HFC demand (consumption) in kt CO_2 eq. with current F-Gas Regulation (F-Gas Reg.) and the maximum technically feasible which could be achieved with additional measures (WAM) (left) and the resulting accumulated amount of HFC consumption and emission which could be avoided by these measures (right). Figures are produced with data kindly provided by Öko-Recherche.

Basically the triangular shaped "gap" between the demand (consumption) with current F-Gas Regulation (F-Gas Reg. scenario in Figure 3.1) and the maximum technically feasible transition to alternatives (WAM lines in Figure 3.1) could be avoided if legislation follows the maximum technically feasible line (WAM). Adopting POM prohibitions with measures (e.g. quantitative limits of placing on the market of HFCs) that capture the maximum technically feasible transition to alternatives (WAM lines in fig. 3.1) up to the POM prohibition dates in Table 3.1 will abate a total of 1.6 Gt CO_2-eq. of HFC demand and 600 Mt CO_2-eq. emissions by 2030.

3.1 Experiences from selected sectors and countries

A good example of placement on the market (POM) prohibitions is the EU MAC Directive for air conditioning systems in passenger cars. Figure 3.2 shows its expected effect on the European HFC-emissions from this sector.

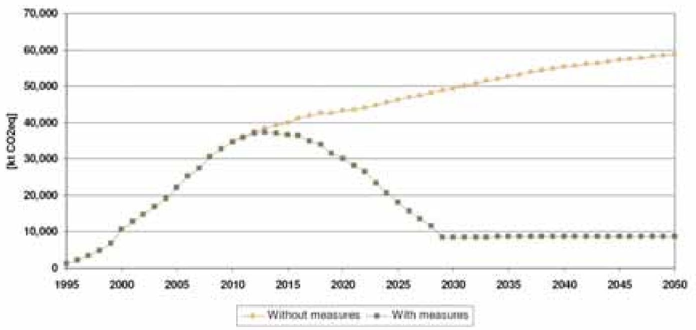


Figure 3.2

EU-27 emissions from mobile air conditioning in the without measures (WOM) and with measures (MAC Directive) scenarios. The effect of the MAC Directive for passenger cars can clearly be seen in the curve split from 2011 onwards. From 2030 HFC emissions are only released from MAC systems in trucks, buses, ships and railcars.[228]

In Denmark larger stationary refrigeration and air conditioning equipment with refrigerant charges over 10 kg must be built without HFCs. The Danish HFC-prohibition, in force since 1st January 2007, has spurred the application of refrigeration and air conditioning systems without HFCs.

It is worth noting that Canada, Denmark, Norway, Sweden, and the USA banned the use of CFCs in spray cans in 1978 – with a few essential use exemptions – long before replacements were developed.[229] It should be possible to place the same ban on aerosols relying on HFCs.

Halogen-free solvents and processes or manufacturing techniques without cleaning processes are already accepted and in use in Germany. Although the use of HFEs and in exceptional cases also HFCs is still allowed, these exemptions are not used (with one exception), leading to the conclusion that the use of fluorinated solvents is not strictly necessary.[230]

4. IMPACTS OF POM PROHIBITIONS AND QUANTITATIVE LIMITS FOR POM

Placing on the market (POM) prohibitions and quantitative limits for POM are addressed in Schwarz et al. for various open and closed HFC applications in the EU.[231] Open applications include aerosols and foam blowing agents, whereas closed applications include all refrigeration and air conditioning as well as fire protection equipment. Two different scenarios are analyzed: POM prohibitions upon the year when the technically feasible penetration mix in the respective sub-sector reaches 100% (scenario D4 and D5 in Schwarz et al., 2011); and quantitative limits for the POM of HFCs following the maximum market penetration of alternative technologies ('phase-down' scenario D6). The latter scenario achieves greater avoided HFC emissions in 2030; 71,740 kt CO_2eq. compared to 52,279 kt CO_2-eq. for POM prohibitions in open and closed applications. The difference is in part due to the fact that the POM prohibitions (D4 and D5) include fewer sub-sectors than the quantitative limits scenario (D6). The only sub-sectors not included in the D6 scenario are heat pumps, rail air conditioning and spray foam due to high abatement cost (over 50 €/t CO_2-eq, see Table 3.1) and reefer containers due to the fact that they are operated worldwide.

This study demonstrates that with POM prohibitions at the earliest possible date, alongside measures to capture the maximum technically feasible transition to alternatives up to the POM prohibition date for each sub-sector, annual avoided emissions by 2030 will be 75,418 kt CO_2-eq. per year. This represents cumulative avoided HFC emissions of 600 Mt CO_2-eq. between 2010 and 2030 (see Table and Figure 3.1).

Table 3.1 contains all necessary data needed for defining (sub-) sectors where a POM prohibition will have a high efficiency (low abatement cost) and high effectiveness (total amount of CO_2-eq. abated by that sub-sector), or in other words result in most kt CO_2-eq. abated at the least cost per kt CO_2-eq. Good candidates are centralized commercial refrigeration systems, industrial refrigeration systems (these actually have negative ACs), moveable air conditioners, split and multi-split air conditioners and large displacement chillers for closed applications and technical aerosols and HFC-134a XPS foam for open applications. Other sectors, like domestic refrigeration and commercial hermetic systems or HFC-152a XPS foam, have a high efficiency (i.e. low ACs), but only a limited impact as CO_2-eq. consumptions and emissions are already quite low in these sectors. Nonetheless, this should not exclude those sectors from future legislation.

Different abatement options exist for the different sectors and subsectors of HFC use as outlined in Chapter 2. The various options can have investment costs which might be equal, higher or lower than the HFC product they are replacing. While most of the technologies achieve similar energy efficiencies, some of them result in energy savings. Therefore annual costs of energy consumption are taken into account when comparing the different options. Also annual service cost for all refrigeration and air conditioning applications have to be taken into account, which especially for larger HFC systems in the EU have become more expensive due to the increased number of service checks required by the F-Gas Regulation. Since most air conditioning and refrigeration systems lose refrigerant, i.e. are not tight, the annual cost of the refrigerant also has to be considered. Using the investment cost and annual running cost (Article 3+4 plus additional service plus refrigerant refill plus energy cost) data presented in the EU sector sheets of Schwarz et al.,[232] one can calculate the cost over the lifetime of the equipment from an end-user perspective (see Tables 4.1-4.3).

Table 4.1

Investment and annual running cost for replacing HFCs in specific refrigeration applications based on data presented in the EU sector sheets of Schwarz et al. (2011). The table also shows the payback time for an individual owner together with expected savings (negative number means higher cost). Lifetime costs of equipment and payback times in Tables 4.1-4.3 were calculated without interest rate.

	Investment Costs (€)	Annual Running Costs (€)	Payback (years)	End-User Savings (€)	Lifetime Costs of Equipment (€)
DOMESTIC REFRIGERATION					
HFC-134a	401.20	35.38	---	---	932
R-600a	408.30	34.75	11.27	2	930
COMMERCIAL REFRIGERATION					
Stand-Alone Systems					
HFC-134a	1,004.00	254.50	---	---	3,549
R-600a/R-290 direct	1,101.00	240.66	7.01	41	3,508
R-744	1,201.60	240.66	14.28	-59	3,608
Condensing Units					
HFC-134a	8,120.00	3,233.20	---	---	56,618
HFO-1234yf + sec. liquid	12,544.00	3,080.40	28.95	-2,132	58,750
R-290 direct	9,620.00	2,976.02	5.83	2,358	54,260
R-744	10,292.00	3,027.22	10.54	918	55,700
R-290 + sec. liquid	12,008.00	3,066.80	23.37	-1,392	58,010
Centralized Systems					
HFC-404A direct	323,450.00	25,440.17	---	---	628,732
HFO-1234yf + R-744 casc	372,600.00	24,482.16	51.30	-37,654	666,386
HC + sec liquid + R-744	371,315.00	24,545.25	53.49	-37,126	665,858
HC + CO_2 + R-744 cascade	368,288.00	22,731.53	16.55	-12,334	641,066
R-744 transcritical	384,920.00	23,326.40	29.08	-36,105	664,837
INDUSTRIAL REFRIGERATION					
Small Industrial Equipment					
HFC-404A direct	434,750.00	70,983.33	---	---	2,564,250
R-717	621,418.00	60,035.00	17.05	141,782	2,422,468
Large Industrial Equipment					
HFC-404A direct	6,060,000.00	1,264,843.33	---	---	44,005,300
R-717	8,972,000.00	1,073,800.00	15.24	2,819,300	41,186,000
TRANSPORT REFRIGERATION					
Refrigerated Vans					
HFC-134a	3,015.00	463.00	---	---	9,960
HFO-1234yf	3,240.00	477.00	N/A	-435	10,395
R-744	3,375.00	428.00	10.29	165	9,795
Refrigerated Trucks / Trailers					
HFC-404A	20,098.00	6,524.62	---	---	85,344
R-290	22,016.00	6,147.25	5.08	1,856	83,489
R-744	22,626.00	6,326.80	12.78	-550	85,894
Fishing Vessels					
HFC-404A / R-744	2,015,000.00	190,230.00	---	---	7,721,900
NH3 / R-744	2,301,500.00	178,700.00	24.85	59,400	7,662,500

Table 4.2

Investment and annual running cost for replacing HFC in specific stationary air conditioning applications based on data presented in the EU sector sheets of Schwarz et al. (2011). The table also shows the payback time for an individual owner together with expected savings (negative number means higher cost). Lifetime costs of equipment and payback times in Tables 4.1-4.3 were calculated without interest rate.

	Investment Costs (€)	Annual Running Costs (€)	Payback (years)	End-User Savings (€)	Lifetime Costs of Equipment (€)
STATIONARY AIR CONDITIONING					
Moveable Systems					
HFC-410A direct	311.00	142.20	---	---	1,733
HFC-32	316.00	142.20	N/A	N/A	1,738
HFO-1234yf	365.00	139.70	21.60	-29	1,762
R-290	301.00	139.70	0	35	1,698
R-744	365.00	139.70	21.60	-29	1,762
Split Systems					
HFC-410A direct	773.00	216.10	---	---	2,934
HFO-1234yf	904.00	214.50	81.88	-115	3,049
R-290 (direct)	743.00	210.20	0	89	2,845
R-744	947.00	210.30	30.00	-116	3,050
Multi-Split / VRF Systems					
HFC-410A direct	9,703	3,556.60	---	---	55,939
HFO-1234yf	11,545	3,424.80	13.98	-129	56,067
R-290 + secondary	11,980	3,360.80	11.63	88	55,670
R-744	10,884	3,430.92	9.40	-253	55,486
R-290 evap secondary	12,930	3,360.80	16.48	-244	56,620
Rooftop Systems					
HFC-410A direct	10,158.00	6,471.39	---	---	74,872
HFO-1234yf	11,930.00	6,331.50	12.67	-373	75,245
R-290 + secondary	11,608.00	6,300.38	8.48	260	74,612
R-744	11,342.00	6,339.10	8.95	139	74,733
R-290 evap secondary	12,108.00	6,300.38	11.40	-240	75,112
Chillers Displacement					
HFC-407C direct	22,750.00	10,023.50	---	---	143,032
HFO-1234yf	26,100.00	9,920.00	32.37	-2,108	145,140
R-290 direct	23,225.00	9,805.00	2.17	2,147	140,885
R-717	30,482.00	9,119.15	8.55	3,120	139,912
R-744	28,580.00	9,858.00	35.23	-3,844	146,876
Centrifugal Chillers					
HFC-134a	146,300.00	141,735.13	---	---	3,689,678
HFO-1234ze	172,200.00	140,800.80	27.72	-2,542	3,692,220
R-290	148,575.00	140,763.00	2.34	22,028	3,667,650
R-718	166,602.00	140,840.40	22.69	2,066	3,687,612
Heat Pumps					
HFC-410A direct	7,036.00	1,844.19	---	---	34,699
HFC-32	7,445.00	1,843.81	N/A	-453	35,102
HFO-1234yf	7,564.00	1,844.64	N/A	-535	35,234
R-290	7,356.00	1,839.81	73.06	-254	34,953
R-744	7,850.00	1,839.94	191.53	-750	35,449
R-600a	7,496.00	1,839.81	105.02	-394	35,093

Table 4.3
Investment and annual running cost for replacing HFC in specific mobile air conditioning applications and fire protection based on data presented in the EU sector sheets of Schwarz et al. (2011). The table also shows the payback time for an individual owner together with expected savings (negative number means higher cost). Lifetime costs of equipment and payback times in Tables 4.1-4.3 were calculated without interest rate.

	Investment Costs (€)	Annual Running Costs (€)	Payback (years)	End-User Savings (€)	Lifetime Costs of Equipment (€)
MOBILE AIR CONDITIONING					
Cargo Ship A/C					
HFC-134a	39,600.00	12,647.00	---	---	419,010
XP10	44,700.00	13,533.00	N/A	-31,680	450,690
R-717 / Brine	60,107.00	12,563.00	244.13	-17,987	436,997
Passenger Ship A/C					
HFC-134a	128,700.00	40,915.00	---	---	1,356,150
XP10	163,800.00	44,040.00	N/A	-128,850	1,485,000
Bus A/C					
HFC-134a	13,000.00	6,690.07	---	---	79,901
HFO-1234yf	13,195.00	6,760.27	N/A	-897	80,798
R-744	15,080.00	6,722.91	N/A	-2,408	82,309
Truck A/C					
HFC-134a	300.00	481.80	---	---	5,118
HFO-1234yf	300.90	487.20	N/A	-55	5,173
R-744	361.80	480.48	46.82	-49	5,167
Rail Vehicle A/C					
HFC-134a	25,080.00	4,278.39	---	---	132,040
R-744	32,532.00	4,252.24	284.97	-6,798	138,838
FIRE PROTECTION					
Fire Protection HFC-227ea					
HFC-227ea	11,626.00	123.34	---	---	14,093
FK-5-1-12	15,131.00	90.78	107.64742	-2,854	16,947
Fire Protection HFC-23					
HFC-23	12,964.00	120.11	---	---	15,366
FK-5-1-12	15,131.00	90.78	73.8833958	-1,580	16,947

As Tables 4.1, 4.2 and 4.3 show, while investment costs are often higher for alternatives to HFCs, these costs are often absorbed by lower running costs over the lifetime of the equipment. In addition these energy savings increase the amount of the total CO_2 eq. savings by 2%.[233]

Table 4.4 shows the economic and social impact of setting quantitative limits for placing on the market of HFCs according to Schwarz et al. (2011). The average abatement cost for all technologies shown in Table 4.4 is 16.2 € / t CO_2-eq. The economic impact for equipment operators is estimated to be €1,500 million per year, whereas the total cost for the entire society is estimated to be €5,612.8 million.

Annualized net costs per individual user vary widely from negative costs of -€ 22,642 for large industrial refrigeration equipment in the EU (based on energy efficient ammonia in direct expansion mode), to positive annualized net cost of +€ 2,283 for commercial centralized systems in the EU (supermarkets). In the sectors of small air conditioning systems the net costs per operator (end-user in the EU) are comparably low with +0.55 €/year (moveable systems) and +5.1 €/year (single split systems). These moderate costs are important because the combined emission reduction potential of the two sectors accounts for 55% of the emission reduction potential in the EU of the twelve affected sectors and a similar high proportion of worldwide emissions. All sectors with higher end-user cost than 15 €/year have commercial entities as end users for which higher financial resources can be assumed than for private households.[234]

Sales of equipment suppliers are expected to increase considerable, most likely creating new jobs. For the EU the additional earnings are estimated to be in the range of €2,860 million/year.[235] Since the current F-Gas Regulation requires extensive servicing of HFC-systems, the service turnover is expected to fall by some €1,356 million/year, once regular leak checks (up to 4-times per year) are no longer necessary. This figure includes a gain of €114 million/year due to new CO_2 and ammonia systems.[236]

Table 4.4 also shows these losses/gains in servicing of HFC containing equipment and the possibility of new jobs created by the HFC phase-out. Other than the transport refrigeration sector, all sectors will have decreased service costs. Nonetheless, the increase in turnover at equipment suppliers due to the often higher price – at least in the early years – of alternative technology is expected to be bigger than the reduced service turnover. Since the same companies are often manufacturing, installing and servicing the equipment, the reduced demand for service is not expected to lead to an increase in unemployment. Employment may actually rise slightly due to additional hardware during the conversion of the manufacturing lines.[237]

Table 4.4

Overview of impact of quantitative limits for the POM of HFCs.[238]
(data courtesy of Öko Recherche)

	Environmental impacts			Economic impacts			Social impacts		
Quantitative limits for the placing on the market of HFCs	Number of replaced units in 2030	Reduction of direct HFC emissions 2030 (kt CO_2 eq)	Reduction of indirect energy-rel. CO_2 emiss. kt CO_2	Marginal emiss. abatement cost €/t CO_2 eq	Direct net costs to sector M€/year	Direct net cost per operator € /year	Investment cost of equipment (=sales of equip. suppliers) w/o first fill M€/y	Loss (-) / Gains (+) from service Art 3+4 or new service for NH_3+CO_2 M€/y	Job creation (equipment + service)
Domestic Refrigeration	2,783,424	12	1.8	1.0	0.01	0.004	2.0	-0.3	+
Hermetic Commercial	5,737,309	149	79.0	-0.8	-0.12	-0.02	81.3	-14.3	++
Condensing units	3,020,046	3,927	201.6	1.2	105.0	2.9	752.7	-185.9	+++
Centralized systems	144,901	14,741	233.9	23.7	418.8	2,283	773.9	-86.3	+++
Industrial Ref small	5,968	871	75.3	-0.9	-0.92	-153	67.3	-6.5	++
Industrial Ref large	2,909	2,612	667.7	-21.6	-65.9	-22,642	498.7	-3.6	+++
Refrigerated Vans	601,764	421	7.1	45.1	20.9	31.8	17.8	+1.5	+
Refrigerated Trucks	532,335	2,990	100.5	2.6	16.8	15.2	141.7	+3.7	++
Fishing vessels	365	405	8.7	3.4	1.96	5,368	6.3	0	+
Cargo ship AC	3,715	320	0.7	16.7	5.60	1,504	4.1	+0.01	+
Passenger ship AC	469	125		35.0	2.90	6,190	0.7	0	0
Bus AC	609,411	1,616		48.5	107.1	158	1,011.4	-	+++
Truck AC	19,520,298	4,170		43.1	227.9	11.7	724.2	-	+++
Moveable AC systems	34,283,827	2,781		8.9	18.7	0.55	74.4	-85.7	+
Split AC systems	96,697,511	22,970		19.0	488.7	5.1	630.4	-483.5	+++
Multi split AC systems	1,570,583	2,827		13.1	53.5	26.4	316.6	-256.0	+++
Rooftop AC systems	522,524	573		8.2	11.8	9.0	99.2	-85.3	++
Chillers	771,866	2,512	207.0	5.9	36.3	25.2	357.0	-143.7	+++
Centrifugal chillers	3,799	82		11.1	1.51	318	3.0	-3.1	0
Fire protection 227ea	48,550	440		22.3	10.9	225	5.4	-4.4	+
Fire protection 23	24,455	961		3.1	3.18	130	0.0	-2.2	0
Aerosols	9,000,000 cans	3,637		10.0	36.3	4.0	0.0	-	+
XPS-152a	13 (prod. lines)	460		-1.6	-0.7	-56,400	2.5**	-	+
XPS-134a	13 (prod. lines)	1,553		1.0	1.2	98,000	2.5**	--	+
PU other	77 (prod. lines)	587		3.5	0.32	4,130	3.3**		+
Total	166,886,028*	71,740	1,583	16.2	1,500.0	-	5,612.8	-1,355.7	+++

* Without number of aerosol cans. ** Additional ann. cost of raw material and production line.

While some costs may appear high, they are low related to the estimated cost of climate change. Stern et al. state: *"Comparing the social costs of carbon on a BAU trajectory and on a path towards stabilization at 550 ppm CO_2 eq, we estimate the excess of benefits over costs, in net present value terms, from implementing strong mitigation policies this year [2006], shifting the world onto the better path: the net benefits would be of the order of $2.5 trillion. This figure will increase over time. This is not an estimate of net benefits occurring in this year, but a measure of the benefits that could flow from actions taken this year; many of the costs and benefits would be in the medium to long term."*[239]

Banning HFCs offers new opportunities across a wide range of industries. Markets for low-carbon energy products are likely to be worth at least $500bn per year by 2050.[240] According to Stern et al. individual companies and countries should position themselves to take advantage of these opportunities.

5. ADDITIONAL MEASURES TO REDUCE HFC EMISSIONS

Even after POM prohibitions come into effect, HFC technologies will remain in use in existing equipment. These systems will need to be refilled and contained during their lifetime and HFCs recovered at end of life. Equipment lifetimes vary from 10-30 years, depending on the sector (see Table 3.1). This section gives an overview of technologies and measures available in order to reduce HFC emissions from existing equipment. Additional measures to reduce HFC emissions from equipment already placed on the market depend on the nature of the product. Options include improved reporting system, recovery during servicing and at end of life, the use of extremely tight systems, the use of drop-in substitutes, increasing the cost of HFCs and offering incentives for reducing HFC emissions. Consumer pressure can effect swift changes in behaviour and support the above measures.

Improving definitions and clarifying provisions under the current F-Gas Regulation as follows could help reduce HFC emissions:[241]

Clarifying terms like owner, operator and hermetically sealed systems – which should not only be used to refer to factory sealed systems, as most larger refrigeration systems are built on-site but should be as tight as factory sealed systems.

Extending liability from operators to installation, maintenance and service personnel and companies. The F-Gas Regulation should be streamlined with other EU legislation such as the Pressure Equipment Directive, the Energy Performance of Buildings Directive and the Renewable Energy Directive.

5.1 Improve HFC Reporting System

The current F-Gas reporting scheme can be improved through the following measures:[242]

- Extend provisions to HFCs contained in factory sealed systems such as mobile air conditioning systems, moveable and split room air conditioners, one component spray foam or metered dose inhalers;
- Extend provisions to imported and exported pre-charged equipment;
- Extend provisions to quantities of reclaimed and destroyed F-Gases;
- Report leakage rates of certain applications in order to establish a statistical basis for system tightness;
- Amend Annex I of the F-Gas Regulation so that it is phrased in a way such that new substances are automatically covered under reporting;
- Include unsaturated HFCs in reporting measures;
- Continuously update GWP values given by the IPCC.

5.2 Recovery

Recovery, recycling and reclamation requirements have been successfully implemented for some years in a number of countries.[243] Refrigerant recovery and recycling from small equipment represents a cost-effective option for reducing emissions from stationary equipment worldwide.[244]

Since there are few drop-in substitutes for HFC refrigeration and air conditioning systems, recovered and recycled refrigerant can be used for servicing existing equipment, thereby reducing the need to manufacture new HFC after a POM ban. While it is not possible to replace the HFCs in insulation already on the market, HFCs can be recovered at end of life of the foam products.

Recovery can be improved through improved enforcement and providing more clarity to key terms. The current Regulation requires products and equipment "…to the extent that it is technical feasible an does not entail disproportionate costs, be recovered by appropriately qualified personnel, to ensure their recycling, reclamation or destruction." The terms "technically feasible" and "disproportionate cost" are not defined however.

Consideration should also be given to mandating producer responsibility schemes, e.g. take back schemes (in force in Germany since 2009) or deposit and refund schemes (e.g. in Denmark since 1992).

5.3 Containment

For HFC containing refrigeration and air conditioning systems already placed on the market, emissions stem from fugitive emissions, tightness degradation, component failures from poor construction or faulty assembly, losses due to excessive equipment vibration, losses due to refrigerant handling during maintenance and servicing, accidental losses and losses at equipment disposal that is due to venting, rather than recovering refrigerant at the end of the system's life.[245] Some of these emissions can be prevented by better maintenance and control (e.g. tightness degradation) others are more difficult to address (e.g. component failure). Increasing leak repair of large equipment represents a cost-effective option for reducing emissions from stationary equipment worldwide.[246] Typical German supermarket refrigeration systems have leakage rates between 5% and 10%, i.e. 5% to 10% of the total system charge is emitted to the atmosphere every year.

Typically, over 30% of all leaks stem from mechanical joints.[247] Leakage rates can therefore be reduced by avoiding mechanical joints as far as possible and using welding or brazing instead, especially in hidden or inaccessible pipes. Another major leak source is pipes that have been damaged by vibration. Decoupling of compressors from the rest of the plant is therefore very important. Such measures can be implemented during major service of an existing system.

The current Regulation requires stationary refrigeration and air conditioning systems to be checked regularly depending on the systems amount of refrigerant:[248]

- At least annually for applications with 3 kg or more of F-gases (unless the equipment is hermetically sealed, in which case this goes up to 6 kg)
- At least once every six months for applications with 30 kg or more of F-gases
- At least once every three months for applications with 300 kg or more of F-gases
- Leakage detection systems must be installed on applications with 300 kg or more of F-gases, and when these are in place, checking requirements are halved
- If a leak is detected and repaired, a further check must be carried out within one month to ensure that the repair has been effective

Current measures could be improved through clarifying provisions, e.g. the time period for leakage repair should be clearly stated, e.g. within 14 days.

The current leakage control scheme should also be extended to all closed F-Gas applications, i.e. transport refrigeration in road, rail and sea vessels and low charge (below 3 kg) units such as refrigerators, moveable and split room air conditioners and domestic heat pumps.

In addition, the F-Gas Regulation measures should be strengthened to state maximum leakage rates, the stringency of which should increase over time, similar to the energy efficiency label of consumer goods. EN378 could be used as a starting point and best practice demonstrated by statistics (see 5.1 above) could guide decisions on maximum allowable leakage rate at regular intervals.

5.4 Drop-in replacements

For some applications the climate impact of HFCs in existing equipment can be reduced by replacing HFCs with drop-in solutions, e.g. either lower charge or lower-GWP alternatives. Currently the possibilities are limited, however.[249] UBA states *"reductions in refrigerant emissions in existing systems are usually only possible by means of technical measures to improve leak prevention and by regular leakage checks of the kind now prescribed by law"*.[250] Even though this statement is given for centralized commercial refrigeration systems, it is true for most other refrigeration and air conditioning systems as well.

For some refrigeration and air conditioning systems lower-GWP HFCs and to a small extent HCs could be used as drop-in replacements. The options are limited due to the fact that the systems placed on the market were designed for the fluid (refrigerant) they are charged with (e.g. the electrical switches are not explosion proof as might be required when using HCs or flammable low-GWP HFCs). The compressor motor and pipe work is usually made of copper preventing the use of ammonia, while CO_2 has much higher operating pressures than the HFCs used today, prohibiting its application as a drop-in replacement.

HCs may be technically feasible drop-in replacements in small systems such as condensing units, heat pumps or unitary/moveable air conditioning systems, if all relevant safety standards and codes-of-practice are strictly followed and necessary precautions are taken. In addition, the compressor oil should be changed to a higher viscosity grade because HCs are more soluble. The GTZ Handbook "Guidelines for the safe use of hydrocarbon refrigerants" is one source of information on the utilisation of HC refrigerants.[251]

UK supermarket Tesco has retrofitted a number of stores in Poland with R407F. R407F has a GWP of 1,824, which is still high however less than half that of R404A (GWP 3,922). The supermarket also claims that the systems are more energy efficient.[252]

A HC-drop-in replacement is marketed in some places in Australia and the USA for passenger car air conditioning systems, where hydrocarbon blends have been introduced as drop-in refrigerants to replace CFC-12 and to a lesser extent for HFC-134a (see Section 2.4.2.1).

No drop-in replacement exists for foam insulation already placed on the market. For foam production lines in all applications, where the thickness of the insulation does not matter, hydrocarbons can substitute HFCs in foam production taking the necessary precautions for flammability.[253] For foam insulation with a high demand for thermal performance – primarily in the appliance sector, but also in some construction and transport applications – it might be possible to substitute HFCs by unsaturated HFCs and methyl formate, which are being assessed at this time. Early work on unsaturated HFCs suggests that they deliver better thermal performance than their saturated counterparts, although toxicological work remains to be completed for those substances yet to be commercialized.[254]

A Fluor-containing fire extinguishing fluid on Fluoroketone basis (FK 5-1-12) with a very low GWP of one is available as a drop-in replacement for certain HFC fire extinguishing systems[255] (see Section 2.7).

In the case of HFC-solvents HFEs could be used as drop-in replacement. For etching chambers conversion of existing systems is not technically feasible. Exhaust gas cleaning would be the option of choice for existing etching chambers.[256]

5.5 HFC taxes

Greenhouse gas taxes, if sufficiently high to influence user behaviour, can help reduce HFC emissions. These taxes have been imposed by Denmark and Norway on all refrigerants. In Denmark, the tax for R404A is approximately 75 €/kg while in Norway it is approximately 80 €/kg. These additional costs encourage many users to keep their system tight, especially if the charge is in the order of several hundred kg as for centralized systems in a larger supermarket. Nonetheless, analysing Norwegian data (see 5.5.2) suggests that the market gets used to these taxes after some time.

While the Danish tax has been adjusted over the years, the Norwegian has stayed pretty much on the same level. The latest revision of IPCC data together with an increase in the tax level in Denmark has resulted in approximately the same level as in Norway. Sweden intends to introduce a tax at around the same level[257] while Poland appears to be considering an HFC tax at a lower rate, 6.5 € per kg HFC-134a.[258]

The Australian government has passed a tax bill to enter into force July 1st, 2012 with AUD 23/ton CO_2eq. which corresponds to approximately 22 €/kg HFC-134a.The New Zealand government is expected to follow the Australian legislation.

5.5.1 Danish Experience

As of 1st March 2001, Denmark extended its CO_2-tax, introduced in 1996, to all other greenhouse gases. For R404A the tax used to be approximately 50 €/kg which was raised to approximately 75 €/kg from 1st January 2011. Consequently these high prices encouraged users to keep systems tight, which is reflected in a smaller annual increase of Danish HFC-emissions from 2001 onwards (Figure 5.1) despite an increase in the penetration rate of car air conditioning systems from approximately 30% to 80% of all new cars during the same time period. F-gas emissions have stabilized and begun to decline due to Danish legislation, which in 2007 banned new HFC-based refrigerant stationary systems.[259] Figure 5.1 shows that while taxes on HFCs did not reduce HFC emissions in Denmark, it slowed the increase in HFC emissions. However the HFC prohibition effective since 2007 caused a halt to the growth and eventually a reduction in HFC emissions.

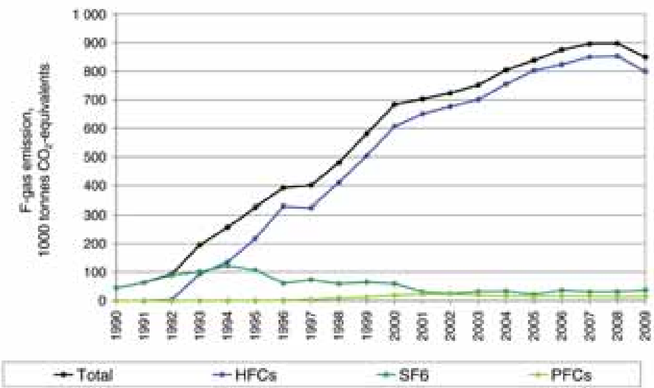


Figure 5.1
F-gas emissions. Time-series for 1990 to 2009.[260]

The Danish regulations have led to a decline in the consumption (demand) of F-gases of which HFCs are the most important group. Import of bulk HFC substances has been significantly reduced from around 1,000 tonnes per year in 2000 to around 350 tonnes per year in 2010.[261]

In order to promote the spread of natural refrigerants, the Danish Environmental Protection Agency has used funding from the HFC tax to set up a Knowledge Centre for HFC-free Refrigeration.[262] The center provides free advice and assistance when deciding what kind of refrigeration system to choose.

5.5.2 Norwegian Experience

In 2003, Norway introduced an import tax on all HFCs and PFCs, about twice as high as Denmark at that time. Figure 5.2 shows the annual emissions of HFCs and PFCs from 1990 to 2005 in blue bars. The yellow bars show the estimated additional amount of F-gases that would have been emitted if no import tax had been introduced in 2003, assuming the development followed the same trend as before 2002. The tax appears to have reduced growth in HFC emissions, but not reversed the increasing trend.[263] Recent HFC emission data from Norway[264] indicates a renewed rise in HFC emission growth rate (Figure 5.3), suggesting that the tax is less effective at that time, which coincides with the end of the HCFC phase-out. The comparison to the Danish experience – where HFC emissions also were rising even after the introduction of taxation – clearly demonstrates the need for bans on HFCs to effectively reduce HFC emissions.

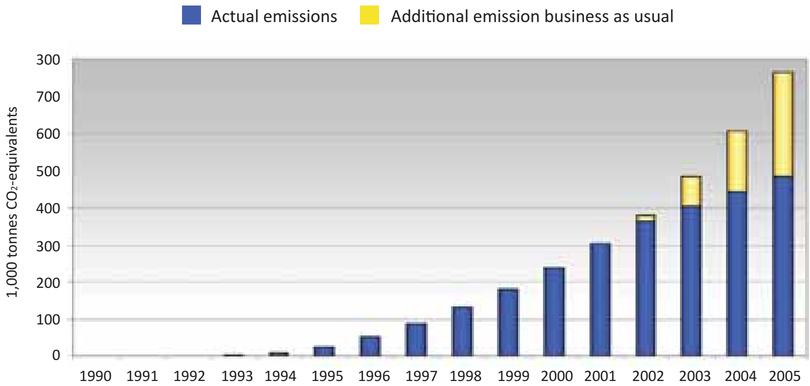


Figure 5.2
Actual emissions and emissions "business as usual" of HFCs and PFCs (not including emissions from metal production).[265]

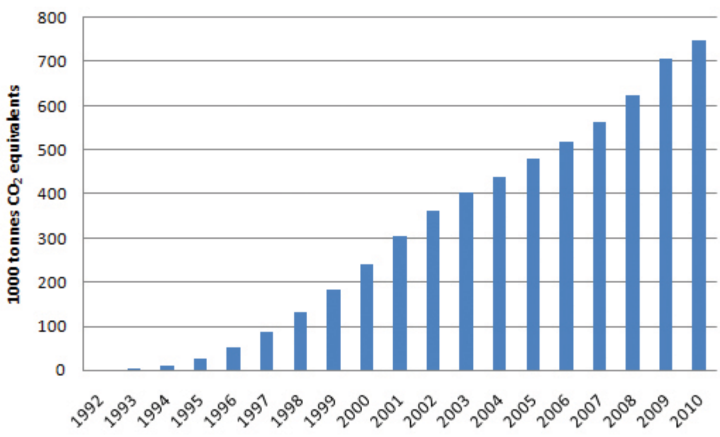


Figure 5.3
CO_2-weighted HFC emissions in Norway up to 2010

5.6 Incentives for environmentally benign technologies

Government incentives have been effective in funding environmental benign technologies such as low-GWP alternatives to HFCs. In Germany for example, supermarket companies can apply for subsidies for improving the energy efficiency of centralized commercial refrigeration systems. The usual subsidy for improving the energy efficiency of existing refrigeration systems is 15%, whereas it increases to 25% when natural refrigerants are applied and to 35% when heat recovery is installed. This funding scheme has increased the number of centralized supermarket systems operating with R-744 and hydrocarbons.

5.7 Consumer pressure

To date this is chiefly occurring in those countries where there is a high environmental awareness level of and appreciation by the consumers. International ice cream and soft drink manufacturers are placing HFC-free equipment on the market due to an initiative by Greenpeace for the 2000 Olympics in Sydney. More than 800,000 HC ice cream freezers and 420,000 bottle coolers have been installed in Europe, Asia and Latin America – often with better energy efficiency than the HFC equipment replaced.[266] Nonetheless, these are only spearheads and stronger international legislation is required in order to reduce and eventually eliminate the use of HFCs.

A way of increasing consumer awareness and subsequent market pressure is the issuance of an ecolabel for products without HFCs. Ecolabels are often voluntary, but Green Stickers showing energy efficiency and carbon emissions are mandated by law in the EU and North America for major household appliances and automobiles. Currently it is being discussed in Germany if the Blue Angel – the oldest ecolabel in the world – can be used for energy efficient HFC-free supermarkets.

Refrigerants, Naturally! is a global not-for-profit initiative of companies committed to combat climate change and ozone layer depletion by substituting harmful fluorinated gases with natural refrigerants. Refrigerants, Naturally! was launched in 2004 by The Coca-Cola Company, Unilever and McDonald's and currently has – in addition to the three founding members – PepsiCo, Red Bull and Unilever as members. It provides participants, among other things, with the following:

- A forum to collect intelligence and share information on HFC-free technologies and public policy trends.
- A practical tool and critical mass to collectively communicate with the supply chain and to take position in the public domain.

The Consumer Goods Forum (TCGF) is a newer and much larger initiative created in 2009 now consisting of more than 650 large companies with a combined sales of €2.5 trillion.[267] TCGF has committed to “mobilize resources within our respective businesses to begin phasing-out HFC refrigerants as of 2015 and replace them with non-HFC refrigerants (natural refrigerant alternatives) where these are legally allowed and available for new purchases of point-of-sale units and large refrigeration installations.”[268]

6. ACRONYMS

AC	*Abatement cost*
A/C	*Air conditioning*
AO	*Abatement option*
BAU	*Business as usual*
CFC	*Chlorofluorocarbon*
CO_2	*Carbon dioxide*
CTOC	*UNEP Chemicals Technical Options Committee*
DIS	*Data Input Sheet*
DX	*Direct evaporation*
FP	*Fire protection*
FTOC	*UNEP Foams Technical Options Committee*
GWP	*Global warming potential*
HC	*Hydrocarbon*
HC-290	*Propane*
HC-600a	*Isobutane*
HC-1270	*Propylene*
HCFC	*Hydrochlorofluorocarbon*
HF	*hydrofluoric acid*
HFC	*Hydrofluorocarbon*
HTF	*Heat Transfer Fluid*
HFO	*Hydrofluroolefin – unsaturated HFC*
HTOC	*UNEP Halons Technical Options Committee*
IPCC	*Intergovernmental Panel on Climate Change*
MAC	*Mobile air-conditioning*
MTF	*Maximum technical feasible*
MTOC	*UNEP Medical Technical Options Committee*
PNEC	*Predicted No Effect Concentration*
R134a	*an HFC*
R441A	*a HC-blend*
R717	*Ammonia*
R718	*Water*
R744	*Carbon dioxide*
RAC	*Refrigeration and air conditioning*
RTOC	*UNEP Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee*
UNEP	*United Nations Environment Programme*
TFA	*Trifluoroacetic acid*
WAM	*With additional measures*

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