Emission abatement options and cost effects for fluorinated green-house gases

Emission projections for fluorinated greenhouse gases up to 2050

Finnish Environment Institute (SYKE)
Tuuli Alaja
7.12.2009

Contents

1 Introduction

1.1 Background to F-gas emissions

The emissions of fluorinated greenhouse gases (F-gases) account for approximately 1% of the total greenhouse gas emissions in Finland. In 2007 the emissions of hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6) were at the level of 0.9 Tg CO_2 eq. The main sources of F-gas emissions in Finland are refrigeration and air conditioning equipment, foam blowing and foam products, technical aerosols, metered dose inhalers, fire suppression systems, semiconductor manufacturing and electrical equipment of the power transmission and distribution network. F-gases are not produced in Finland and therefore fugitive emissions from manufacturing do not occur. (NIR 2009)

The emissions of F-gases have increased substantially from the mid 1990's mainly due to the substitution of ozone depleting substances (ODS). In Finland the use of CFC substances has been restricted since 1995 (Vnp 677/1993) and the use of HCFC substances since 2000 (Vnp 262/1998). The use and placing on the market of CFCs was prohibited by the EC Regulation on substances that deplete the ozone layer (2037/2000/EC) and the use and placing on the market of HCFC substances restricted as well. However, the use of virgin HCFC substances is allowed in the servicing of old refrigeration and air conditioning equipment to the end of 2009 and the use of recycled HCFC substances to the end of 2014. These restrictions have led to the rapid growth of HFC and PFC emissions especially from the refrigeration and air conditioning sector.

The use and handling of F-gases is controlled by the EC Regulation on certain fluorinated greenhouse gases (842/2006/EC) and the Directive relating to emissions from air conditioning systems in motor vehicles (2006/40/EC). The F-gases Regulation (842/2006/EC) places requirements on the containment, labeling and reporting of F-gases as well as the training and certification of personnel handling the gases. The EC F-gases Regulation also includes specific bans for certain F-gases containing applications. Reassessment of the EC F-gases Regulation is due in 2011 and further restrictions are possible. The Directive (2006/40/EC) relating to mobile air conditioning systems (MACs) is better known as the EC MAC Directive. The EC MAC Directive gradually bans the use of refrigerants with GWP over 150 in mobile air conditioning devices. However, the emissions of F-gases have been increasing in Finland so far and the possible emission reducing effects of the EC F-gases Regulation are hard to assess.

1.2 Aims, objectives and execution of the project

There is no official register on the use of F-gases in Finland. The emissions estimates for the National Greenhouse Gas Inventory under the UNFCCC and the Kyoto Protocol are based on annual surveys and expert judgment. The project on the emission abatement options and cost effects for F-gases aimed to compile extensive background information on the current technology and availability of alternative options on the different F-gas emission source sectors in Finland. The information was used to produce emission projections and emission abatement cost estimates for F-gases. The data of the national F-gas inventories under the UNFCCC and the Kyoto Protocol by the Finnish Environment Institute (SYKE) was also utilized in the projections.

In the project three F-gas emission projections up to 2050 were established. The with measures (WM) projection is a business as usual projection, that assesses the impacts of the effective regulations and ongoing trends assuming no relevant changes in the operational environment will take place. The two with additional measures (WAM) projections are based on the assumption that the reassessment of the EC F-gases Regulation in 2011 will lead to further restrictions. The presented WM projection and WAM 1 projection for F-gases are used in the 2009 Reporting of Policies and Measures under Article 3(2) of Decisions 280/2004/EC by Finland (Reg. No. 652/020/2009). The base year for the 2009 PM Report projections is 2006 and thus the projected emissions and emission reductions in this report are also presented with the base year 2006.

The project was carried out by SYKE and funded by the Ministry of the Environment. The background information was compiled and the emission projections formed by coordinators Tuuli Alaja and Päivi Lindh in SYKE. The Report was written by Tuuli Alaja and the project work supervised by Senior Adviser Else Peuranen from the Ministry of the Environment and Development Engineer Kristina Saarinen from SYKE.

The report is mainly structured by the F-gas emission sources. The main data sources are described in Section 2.1 and the calculation methods of the projections in Section 2.2 by emission source sectors. Chapter 3 presents the background information, abatement cost estimates and emission projections of refrigeration and air conditioning equipment. The Chapter is divided into sections by the refrigeration subsectors, which include sectors of commercial refrigeration, industrial refrigeration, transport refrigeration, mobile air conditioning, residential and commercial air conditioning and heating as well as domestic refrigeration and ice rinks. The total emission projections for the refrigeration and air conditioning sector are finally presented in Section 3.13. The following chapters discuss the backgrounds and projections of the other emission sources; foam blowing and foam products, aerosols and one-component foams, electrical equipment and grouped emission sources, respectively. Finally the source specific F-gas emission projections are summarized and the total WM and WAM projections discussed in comparison with previously made projections in Chapter 8.

2 Methodology and data sources

2.1 Data sources

2.1.1 Literature and statistical information

Background information for the emission projections was acquired from Finnish and international literature as well as from the statistics of different institutions. The projections are principally based on the F-gas emission scenario work of Oinonen and Soimakallio (2001) as well as the activity data and results of the national F-gas inventories by the Finnish Environment Institute. The activity data of F-gas inventories are obtained from annual surveys of the Finnish companies operating in the different sectors defined as F-gas emission sources. In this report the national F-gas inventories by the Finnish Environment Institute are referred to as F-gas inventory or F-gas inventories for given years of activity.

The main literature used in the comparison of emission factors and equipment lifetimes consisted of IPCC Good Practice Guidance (2000), IPCC Guidelines (2006) and the emission projection report of AEA Technology (2004) as well as Oinonen and Soimakallio (2001). Additional literature for emission source specific information on emission factors and equipment lifetimes was also available for some subsectors.

In addition, statistical data were obtained from different institutions as a basis for subsectoral scenario calculations. The information of Agrifood Research Finland's (MTT) register of yearly ATP (Agreement on the international carriage of perishable foodstuff and on the special equipment to be used for such carriage) equipment approvals is utilized in the scenarios of transport refrigeration. The statistics of The Finnish Vehicle Administration (AKE) forms the basis of the scenario calculation of mobile air conditioning devices. The scenario of electrical equipment relies partly on the summarized emission estimates and activity data of annual emission and gas bank evaluations by the Finnish Energy Industries. Statistics of equipment sales amounts was acquired from The Association of Electronics Wholesalers and The Finnish Heat Pump Association (SULPU). The register of Horeca services, such as the amount of professional kitchens and served meals, by A.C. Nielsen Oy and the information of Statistics Finland on the volume growth of new construction production of commercial and office buildings were also utilized in the scenario calculations.

2.1.2 Questionnaires and personal contacts

Additional information and expert views were obtained from the main industry actors of different emission source sectors by questionnaires and personal contacts. Three different questionnaires regarding transport refrigeration, other refrigeration and air conditioning equipment and foam blowing were send to selected actor groups. A number of personal contacts were employed to acquire information on the present state and potential trends of especially domestic refrigeration, medical and technical aerosols, one-component foams (OCF), semiconductor manufacturing and fire suppression systems.

The general refrigeration and air conditioning equipment questionnaire was directed to the main companies importing, manufacturing or installing refrigeration and air conditioning equipment or importing bulk refrigerants. In the questionnaire the respondents were asked to estimate the prevailing situation and future development of the Finnish refrigeration and air conditioning industry separately for the subsectors in their field of expertise. The questionnaire was send to 28 companies and eight responses of varying extent were received. A few of the targeted industry actors declined to answer, because they deemed the predictions of future development as irrelevant speculation or impossible to estimate.

The questionnaire responses were handled qualitatively and used as indicators of the present state and potential trends of the Finnish refrigeration and air conditioning industry together with the information compiled from other sources. The questionnaire responses were given more weight in the fields, where the responses were consistent with each other. Only one respondent gave an estimate of the costs of substituting HFCs in refrigeration systems with alternative refrigerants. Therefore additional cost information was obtained by a personal contact.

The questionnaire of transport refrigeration was send to eight companies three of which responded. However, the three respondents were the three companies approved by the Finnish Food Safety Authority (Evira) for performing periodical inspections of ATP applications. The respondents include the only Finnish manufacturer of transport refrigeration applications. On these grounds the respondents can be seen as the main experts of the Finnish transport refrigeration sector. The responses were quite consistent with each other as well. The questionnaire responses were used to estimate the main assumptions for transport refrigeration together with the data of MTT's ATP equipment register. In addition, personal contacts were used to acquire background information of the transport refrigeration sector.

The third questionnaire was directed to the foam blowing industry for the companies currently using HFCs as well as the companies using other blowing agents. The questionnaire was send to 16 companies. Four companies replied on the questionnaire form and one by phone. Only one company provided cost estimates of the substitution of HFCs in the production of foams. However, there are only a few companies still using HFCs in foam blowing in Finland. The questionnaire responses were mainly used as indicators of future trends together with the information of literature and F-gas inventories as well as an additional personal contact.

The questionnaire responses and personal contacts are treated confidentially. The information was compiled gradually in a period starting from summer 2008 to spring 2009. In this report the information obtained by questionnaires and personal contacts is for simplicity's sake referred to as information from the industry.

2.2 Methodology

2.2.1 Calculation methods for F-gas emission projections

The F-gas emission source sectors are categorized as refrigeration and air conditioning equipment, foam blowing and foam products, aerosols and OCFs, electrical equipment and other grouped emission sources. Separate emission projections are made for all of the source categories. Specific calculation methods are established for each source category, because of the differences in available data and background information. The total F-gas emission projections are sums of the subsector scenarios.

The emission projections are presented in CO_2 equivalent emissions (CO_2 eq). The results are given in full Gg CO_2 eq or at the precision of two significant figures. The global warming potential values of IPCC's second assessment report (1995) for a time horizon of 100 years (GWP_{100}) are used, when available. This practice provides consistency with the F-gas inventories, since the IPCC (1995) GWP_{100} values are employed in them as well. The IPCC (1995) GWP_{100} values are not available for HFC-245fa and HFC-365mfc and therefore the respective values of the third assessment report (IPCC 2001) are used for these two substances. The GWP values used for the HFC and PFC substances and SF_6 are presented in Appendix 1.

Only direct emissions of HFC, PFC and SF_6 are included in the projections. The emissions of alternative natural refrigerants such as carbon dioxide and hydrocarbons are not taken into account. The GWP_{100} value is one for carbon dioxide and twenty for the hydrocarbons commonly used as refrigerants (UNEP TEAP 2009).

2.2.2 Calculation model for refrigeration and air conditioning equipment

The refrigeration and air conditioning sector includes a wide variety of applications and the sector is divided further into eleven sub source sectors. Separate HFC emission scenarios are formed for each subsector based on specific assumptions. The total HFC emission projections for refrigeration and air conditioning equipment are sums of the subsector scenarios. In the F-gas inventories emissions of refrigeration and air conditioning equipment are reported as one figure and the information could only be compared with the total emission projections of the sector. The subsectoral approach and calculation method are similar to the ones used in Oinonen and Soimakallio (2001).

The calculation model is based on the estimation of yearly emissions from the different stages of the equipment life cycle. Emission factors are specified for each subsector for the initial emissions of manufacturing or installation, for the operation phase and for the end-of-life phase. The amounts of refrigerants in each phase are estimated and multiplied by the emission factors. The yearly emissions are a sum of the emissions from the three life cycle phases.

Emissions of a given year = initial emissions + operation emissions + end-of-life emissions

The emissions of a given year are calculated separately for each refrigerant. The refrigerant emission amounts are divided and added up to HFC emission amounts by the HFC compositions of the refrigerants in question. The yearly total CO_2 equivalent emissions are then calculated from the HFC emission amounts.

The refrigerant amounts in each life cycle phase are estimated based on the refrigerant charge amounts used in the manufacturing of new equipment or the installation of new equipment and average equipment lifetimes. The installation amounts include the modifying of old equipment for new refrigerants. During operation the equipment is assumed to be maintained and recharged so, that the initial charge amount is not significantly reduced by the operation emissions. The entire initial charge amount is assumed to be decommissioned in the end of the equipment lifetime.

Refrigerant amount banked in equipment in a given year = refrigerant amount banked in equipment in the previous year + initial refrigerant charge of the given year – decommissioned refrigerant charge of the given year

The initial refrigerant charge amount of a given year is calculated by multiplying the number of introduced equipment by the average charge amount of the equipment. However, sufficient data on the yearly equipment sales or installations is not available for all of the subcategories. In these cases the annual growth of the initial charge amount is estimated from the 1999 initial charge amount used by Oinonen and Soimakallio (2001). The growth estimates are based on the varying background information available for the subcategory in question.

2.2.3 Calculation model for foam blowing and foam products

The activity data of F-gas inventories is used in the emission projections of foam blowing and foam products. The calculation model is modified from the F-gas inventory model to better assess the future development of the gas banked in foam products. The model is based on the HFC amounts used in manufacturing, the amounts banked in foams and emission factors of manufacturing and product lifetime.

Emissions of a given year = manufacturing and first-year losses + emissions of the gas banked in foams

Manufacturing and first-year losses = initial emission factor of a given foam product and blowing agent x the amount of blowing agent used in manufacturing

Emissions of the gas banked in foams = operation emission factor of a given foam product and blowing agent x (the amount of gas banked in foams in the previous year – the amount of gas exported in foam products + the amount of gas imported in foam products)

The amount of gas banked in foams in a given year = the amount of gas left in manufactured foams after manufacturing and first-year losses + the amount of gas left in the foam gas bank after operation emissions of the given year

The emissions are calculated separately for different foam products and blowing agents and the total emission estimate is a sum of these figures. The emissions of decommissioning are not specifically estimated, because most of the foam products are land filled or reused as frost insulation, in which case the HFC emissions continue more or less at the same rate as during the original usage. Eventually all of the initial HFC charge is expected to be emitted to the atmosphere.

2.2.4 Calculation model for aerosols and OCFs

The HFC emission projection of aerosols and OCFs is calculated with the F-gas inventory model. The model is based on the potential emissions of a given year. The potential emissions reflect the consumption of aerosol and OCF products in Finland and the amount of HFC propellants confined in the products. The entire propellant amount is expected to be released in two years.

Potential emissions of a given year = the amount of gas imported for aerosol and OCF production + the amount of gas imported in aerosol or OCF products – the amount of gas exported in aerosol or OCF products

Actual emissions of a given year = 0.5 x potential emissions of the given year + 0.5 x potential emissions of the previous year

The emissions are calculated separately for different HFC substances. The yearly total CO_2 equivalent emissions are calculated from the HFC emission amounts.

2.2.5 Calculation model for electrical equipment

The calculation model for the projection of SF_6 emissions from electrical equipment is similar to the calculation model of refrigeration and air conditioning equipment. The emissions are calculated for different phases of the equipment lifetime based on assumed emission factors and gas amounts in the phase in question.

Emissions of a given year = emissions of equipment manufacturing + operation emissions + end-of-life emissions

The amount of gas banked in equipment and the annual growth of the gas bank is estimated based on the annual gas bank evaluations of the Finnish Energy Industries. The operation emissions include emissions of maintenance as well as initial installations. The retiring gas amounts of decommissioned equipment are estimated in relation to the gas bank growth and average equipment lifetime. The amount of gas used in manufacturing and its future development is estimated separately on the basis of the F-gas inventory activity data. The bulk of the manufactured equipment is exported and the amount of gas used in manufacturing is not strictly related to the growth of gas banked in equipment in Finland.

2.2.6 Calculation model for grouped emission sources

Other grouped emission sources include semiconductor manufacturing, fire suppression systems, magnesium die casting, training shoes, research and HFC-23 emissions from refrigeration and air conditioning equipment. These emission sources are reported together in the F-gas inventories due to confidentiality. The emission projection of grouped emission sources is based on the activity data of the F-gas inventories. The development of different sources is estimated directly by defining annual emission growth rates for different time periods. The emissions of grouped sources include HFC, PFC and SF_6 emissions. The emissions of different sources are added up by substance and the yearly total CO_2 equivalent emissions are calculated from these emission amounts.

2.2.7 Calculation methods for emission abatement costs

Calculated emission abatement costs are in 2009 Euros per saved ton of CO_2 equivalent emissions. Future costs are discounted with a 4% discount rate. Present values are given by the equation below.

Present value = future cost / $(1 + r)^t$ Where r = discount rate
t = the number of years between the cost period and present year

Emission abatement costs are calculated separately for each year of equipment lifetime. The emission reductions of a given year are compared with the costs of the same year. Investment costs are allocated to annual costs for the entire lifetime of the abatement option in question. The allocation of investment costs is performed by multiplying total investment costs with the annuity factor.

Annuity factor = $r / (1 – (1 + r)^{-t})$ Where *r = discount rate*
t = lifetime of abatement option

This method is also used by Oinonen and Soimakallio (2001). When known, the operation and maintenance costs of the year are added to the investment costs. The total costs of the year are then divided by the CO_2 equivalent emission reduction of the year. The presented abatement costs are means of the discounted yearly abatement cost of the lifetime period of the abatement option in question. The cost estimates are rounded to full Euros.

3 Refrigeration and air conditioning equipment

3.1 Emissions, current technology and abatement options for refrigeration and air conditioning equipment

3.1.1 Emissions and general abatement options for refrigeration and air conditioning equipment

Refrigerants are the main source of F-gas emissions in Finland and account for almost ninety per cent of the total F-gas emissions (F-gas inventory 2007). Emissions occur in all stages of refrigeration and air conditioning equipment life cycles and there are several options for reducing them. General options for reducing direct F-gas emissions are specified in the IPCC/TEAP Technical Summary (2005) as improved containment, recovery, recycling and destruction of refrigerants, reduced charges, use of alternative refrigerants with lower GWP values and not-in-kind technologies. Refrigerant charges can be reduced either by applications with lower refrigerant charge per cooling capacity or by reducing refrigeration capacity demand (IPCC/TEAP 2005).

Refrigeration and air conditioning equipment also cause indirect greenhouse gas emissions due to their energy consumption. The energy-related indirect emissions have been estimated to account for approximately 80% the total greenhouse gas emissions of refrigeration and air conditioning equipment, which leaves only 20% for the direct emissions from refrigerants (IIR 2000 ref. Oinonen and Soimakallio 2001). There is a great variety of factors affecting the energy efficiency of refrigeration systems and extensive planning is needed for the most efficient overall solutions. In addition to the refrigerants' thermodynamic characteristics, required cooling capacity and technical details of the equipment, factors like heating, lighting and covering have to be considered. (Hakala and Kaappola 2005.) In Finland condensing heat of the refrigeration systems is often utilized in ambient heating (Information from the industry).

3.1.2 Conventional refrigeration technology and refrigerants

The conventional refrigeration technology in use is vapour compression cycle. It is used in a wide variety of applications from small stand-alone equipment to full supermarket and industrial systems. There are three main implementations of the vapour compression cycle, direct systems, indirect systems and cascade systems. Direct vapour-cycles have only one primary loop and the evaporator is placed directly in the refrigerated space. Indirect systems have a secondary loop with an intermediary heat transfer fluid for distributing the cooling effect in addition to the primary loop. Common heat transfer fluids are water and different water solutions. The secondary loop enables greatly reduced charges of the main refrigerant in the primary loop. Condensing of the vapour compression cycle is also possible to implement either directly or indirectly with an additional loop for a heat transfer substance. Indirect systems are less efficient than the comparable direct systems. This is due to higher condensing temperature or lower evaporation temperature and an additional pump for the circulation of the heat transfer fluid. Cascade systems have two vapour compression cycles joined by a heat exchanger, which is working as an evaporator for one cycle and as a compressor for the other cycle. (See Oinonen and Soimakallio 2001.)

Different refrigeration equipment applications and processes with varying refrigeration capacities require different characteristics from the refrigerants. The working temperatures and pressures of the vapour cycle, for example, differ between applications. In addition to compatible thermodynamic characteristics and efficiency an ideal refrigerant would be non toxic, non flammable, non corrosive and economical. From the environmental point of view refrigerants should also have a low or negligible GWP-value and ozone depleting effect. (See Oinonen and Soimakallio 2001.)

The most commonly used HFC refrigerants in new equipment in Finland are R-404A, R-134a, R-407C and R-410A (F-gas inventory 2007). R-404A is the main refrigerant in supermarket refrigeration systems and transport refrigeration. R-134a is mainly used in mobile air conditioning equipment and stand-alone equipment. R-407C and R-410A are common refrigerants for stationary air conditioning and heat pumps. The use of HFC refrigerants has been growing rapidly since the mid 1990's due to substitution of ozone depleting substances (ODS) (F-gas inventories). The use of CFCs in new refrigeration equipment has been banned since 1995 (Vnp 677/1993) and the use of HCFCs since 2000 (Vnp 262/1998). Stockpiled HCFC substances can be used in the servicing of old equipment to the end of 2009 and recycled HCFC substances to the end of 2014 (Regulation 2037/2000/EC). In addition, there are several so called service refrigerants consisting of HFCs and PFCs designed for replacing ODSs in old equipment. (Oinonen and Soimakallio 2001.)

3.1.3 Alternative refrigerants and technology

The alternative refrigerants are so called natural refrigerants, ammonia (NH_3/R-717), carbon dioxide (CO_2/R-744) and hydrocarbons (HC). Ammonia has good thermodynamic characteristics for use as a refrigerant, but toxicity restricts its use to applications where safety issues can be managed. Ammonia's corrosive characteristics and flammability in certain concentrations place additional requirements for the technology used. (See Oinonen and Soimakallio 2001, IPCC/TEAP 2005.) In Finland ammonia is the main refrigerant used in food processing and other industrial refrigeration and it is also used in ice rinks to some extent.

Hydrocarbons have similar thermodynamic and material compatibility features with halogenated refrigerants, but they are highly flammable. Flammability restricts the use of HCs to applications with small charges such as domestic refrigeration. (See Oinonen and Soimakallio 2001, IPCC/TEAP 2005.) Isobutene (R-600a) has already replaced R-134a in most domestic refrigerators in the Finnish market.

Carbon dioxide is an old refrigerant, which is starting to gain new applications. First new commercial CO_2 refrigeration systems in Finland have been introduced in recent years and it is expected to become the main refrigerant for full supermarket refrigeration systems (Huurre Group Oy 2009). Carbon dioxide is also applicable to heat pumps, small stand-alone equipment and transport refrigeration as well as to stationary and mobile air conditioning. Carbon dioxide is compatible with most materials, it is not flammable and is toxic only in high concentrations. When recaptured carbon dioxide is used, there is no direct greenhouse gas effect. The negative characteristics as a refrigerant are high working pressure and low critical temperature. Besides full CO_2 systems, carbon dioxide can be used in cascade systems at the low temperature side and as a heat transfer fluid in indirect systems. (See Aittomäki 2005.)

New carbon dioxide systems are very energy efficient. Indirect vapour compression cycle systems with glycol and CO_2 achieve a 10–15% reduction (Aittomäki 2005) and new direct full CO_2 systems a 15–20% reduction in energy consumption (Huurre Group Oy 2009) compared with conventional direct HFC systems.

Carbon dioxide compression systems for transport refrigeration are still under development (Information from the industry, Aittomäki 2005). Commercialized alternative technologies for transport refrigeration are cryogenic applications using liquid CO_2 and eutectic plates. Cryogenic refrigeration equipment is quiet and well suited for distribution services. Eutectic plates are mostly used for relatively small cold compartments and short hauls. The plates are refrigerated beforehand with separate equipment and their transport refrigerating capacity is usually limited to about five hours. (Luoto et al 2007).

There is an ongoing pursuit for a new refrigerant mainly to meet the requirements of the EC MAC Directive (2006/40/EC), but there are expectations for a substance with other applications as well. One new candidate for mobile air conditioning is R-1234yf, which has similar thermo physical properties as R-134a and has met the criteria for stability and compatibility as well as toxicity tests so far (Honeywell 2009a). It has a low GWP of four and an atmospheric lifetime of eleven days (Honeywell 2009a).

There are also a number of alternative refrigeration technologies, such as Stirling cycle, absorption cycle, thermoelectric systems, thermionic systems, thermo acoustic systems and magnetic refrigeration, in various stages of development. Absorption cycle technology is already commercially available in industrial refrigeration and efficient, when there is enough waste heat available as primary energy for the process (Oinonen and Soimakallio 2001).

3.2 Abatement costs for refrigeration and air conditioning equipment

3.2.1 Assumptions and abatement cost estimations

There is a great deal of variation in the cost estimations presented for greenhouse gas emission abatement options in the refrigeration sector. Compatibility of different applications varies between subsectors and there is a general lack of publicly available cost information. Some of the new solutions are still in an early state of development or have just recently entered the market.

The estimation of abatement costs depends on the chosen reference system and calculation parameters such as the system lifetime and refrigerant loss rates as well as discount rates and the emission factor used for electricity consumption, when indirect emissions are taken into account. New abatement cost estimates were calculated for commercial and industrial refrigeration based on the cost information from the Finnish refrigeration industry. However, the low response activity of the questionnaire resulted in only one answer with rough investment cost estimates and the uncertainty of the calculations is high. Additional cost information for a comparative and more precise abatement cost calculation for supermarket refrigeration systems was acquired from the industry by a personal contact.

The yearly reduced direct HFC emissions are calculated with the method used in the emission projections. Since the HFC reference systems are assumed to be state of the art systems, the lowest emission factors, for 2011 and onwards, for the subsector in question were used. The emission factors are presented in the chapters describing the subsector scenarios. Higher emission factors would have resulted in lower abatement cost estimates.

The calculated abatement cost estimates and their main assumptions are presented in Table 1 together with cost estimates compiled from international literature and converted to 2009 Euros. The presented abatement cost estimates for the different subsectors of refrigeration and air conditioning equipment vary between 247 €/t CO_2 eq costs and 66 €/t CO_2 eq savings.

Table 1. Abatement cost estimates for the refrigeration and air conditioning sector.

Refrigeration emission source sector	Abatement cost estimate (+/-) €/t CO_2 eq	Alternative refrigerant/ system	Reference refrigerant/ charge/ vapour compression system type	Other assumptions	Reference
Full supermarket systems	57 24	Non specified natural refrigerant	R-404A/150 kg/direct R-404A/900 kg/direct	Only additional investment costs taken into account. Costs for direct emission reductions only, 7 year lifetime, 4 % interest rate	Calculated based on information from the industry
Full supermarket systems	22 -19	Full CO_2, direct system	R-404A/400 kg/direct	Investment and leakage costs taken into account. Costs for direct emission reductions only, 10 year lifetime, 4 % interest rate. Including indirect emission reductions of improved energy efficiency, 10 year lifetime, 4 % interest rate, emission rate for electricity consumption 0,2 kg CO_2 eq/kWh[3]	Calculated based on information from the industry
Full supermarket systems	18 – 247	Different abatement options	Installed systems, state of the art energy usage	Costs for direct emission reductions only, 10 year lifetime, 10% interest rate Energy efficiency improvements may result negative costs (=savings).	IPCC/TEAP 2005, original amounts in US dollars in 2002 [1 2]
Professional kitchens	32 69	Non specified natural refrigerant	R-404A/250 kg/direct R-407C/250 kg/direct	Only additional investment costs taken into account. Costs for direct emission reductions only, 10 year lifetime, 4 % interest rate	Calculated based on information from the industry
Food processing industry	68	Non specified natural refrigerant	R-404A/300 kg/direct	Only additional investment costs taken into account. Costs for direct emission reductions only, 15 year lifetime, 4 % interest rate	Calculated based on information from the industry
Other processing industry	146	Non specified natural refrigerant	R-407C/300 kg/direct	Only additional investment costs taken into account. Costs for direct emission reductions only, 15 year lifetime, 4 % interest rate	Calculated based on information from the industry
Industrial refrigeration	24 – 33	Different abatement options	Installed systems	Costs for direct emission reductions only, 8% interest rate	IPCC/TEAP 2005, original amounts in US dollars in 2002 [1 2]
Residential and commercial air conditioning and heating	-3 – 150 -66	Different abatement options	Installed systems, state of the art energy usage	Costs for direct emission reductions only Including indirect emission reductions of improved energy efficiency	IPCC/TEAP 2005, original amounts in US dollars in 2002 [1 2]
MAC	11 – 37 7 - 33 24 - 158	HC R-152a CO_2	R-134a R-134a R-134a	Costs in EU-15 assuming there is no energy penalty from the use of alternative refrigerant and technology	European Commission 2003 [2]

[1] Exchange rate used EUR/USD 1,3050 (Suomen Pankki 23.4.2009)

[2] Present value **(2009)** calculated with 2 % interest rate

[3] Fortum 2009

3.2.2 Abatement costs for commercial refrigeration

According to Swedish and Danish experiences CO_2 supermarket refrigeration systems have had 6–10% higher investment costs than the conventional R-404A systems, but their lower energy consumption compensates the difference (Aittomäki 2005). As an example for a ten year period the investment costs are about ten per cent and the yearly maintenance costs about 90% of the total costs of a supermarket refrigeration system (Ekholm 2007). According to Girotto's (2007) total cost comparisons for a supermarket refrigeration system's life cycle HFC/CO_2 cascade systems have higher costs and direct CO_2 systems roughly the same costs as direct HFC systems with HFC leakage of 15%/year and HFC cost of 25 €/kg. When HFC leakage rate of 30%/year and HFC cost of 50 €/kg are used, the direct CO_2 system has clearly the lowest total costs (Girotto 2007).

In Finland the calculated emission abatement cost estimates of direct emissions from full supermarket systems range between 22–57 €/t CO_2 eq. The reference systems are direct vapour compression cycles of different sizes with R-404A as a refrigerant. The estimated abatement costs are higher for systems with smaller refrigerant charges, because of the lower emission abatement capacity. The lengthening of system lifetime, on the other hand, decreases the cost estimates. The calculated abatement costs for emissions of full supermarket systems are within the estimated cost range of IPCC/TEAP (2005), but moderate compared to the highest cost estimation presented there.

When energy efficiency improvements of a direct CO_2 system are taken into account, abatement costs for a full supermarket system are negative. Estimated savings for a middle sized supermarket system are 19 €/t CO_2 eq. There are two influencing factors here, the increase in emission reductions from lower electricity consumption and the cost savings of lower electricity consumption. The IPCC/TEAP (2005) also states that the increases in energy efficiency of new systems may result in negative abatement costs.

The abatement cost estimates for direct HFC emissions of refrigeration and cold-storage in professional kitchens are conducted with direct 250 kg charge HFC applications as reference systems. These systems can be considered large in the subsector. The estimations are solely based on additional investment costs, because no information on the maintenance costs was available. The estimated abatement costs are 32 €/t CO_2 eq for R-404A and 69 €/t CO_2 eq for the lower GWP R-407C as the reference refrigerant. The inclusion of HFC leakage costs and possible energy efficiency improvements would have a decreasing effect on the abatement cost estimates.

In Finland commercial refrigeration, especially supermarket refrigeration systems, which account for almost half of the refrigeration sectors HFC emissions, also has the highest potential for emission reductions. The emission abatement cost estimation, where CO_2 systems energy efficiency improvements are accounted for, indicates considerable savings. CO_2 systems are still in an early state of entering the market and their investment costs are expected to decline in the future. Further improvements in efficiency are also likely, when the technology matures.

3.2.3 Abatement costs for industrial refrigeration

Ammonia is already extensively employed in industrial refrigeration and has to be considered cost effective compared to HFC systems in most applications. One cost comparison of industrial refrigeration systems also indicates that the costs of CO_2/NH_3 cascade systems are 15% lower than R-410A reference systems (Aittomäki 2005).

However, industrial refrigeration includes a wide range of cooling and freezing systems in food and other processing industry and for some applications conventional HFC systems have evidently been the most efficient choice. For these applications the direct HFC emission abatement costs are estimated as 68 €/t CO_2 eq for food processing industry and 146 €/t CO_2 eq for other processing industry, when only additional investment cost estimates where available. The only difference between the calculations was the reference refrigerant used. Replacing a lower GWP refrigerant R-407C system is substantially less cost effective than replacing a R-404A system.

The estimated abatement costs seem high compared to the cost estimates in IPCC/TEAP (2005). However, a wider choice of abatement options, such as improved efficiency, refrigerant containment and refrigerant recovery, were taken into account in the IPCC/TEAP (2005) cost estimates for industrial refrigeration. Therefore the calculated emission abatement cost estimates are not really comparable with those of IPCC/TEAP (2005).

3.2.4 Abatement costs for transport refrigeration

The commercialized alternative techniques for transport refrigeration, cryogenic refrigeration and eutectic plates, are mainly suitable for distribution services and short hauls (Luoto et al 2007). These are not seen as viable abatement options for the transport refrigeration sector in general and cost estimates were not established. In addition, the greenhouse gas emissions of eutectic plates depend on the varying means of their refrigeration. Cryogenic applications also produce vast amounts of direct CO_2 emissions.

Closed CO_2 compression systems for transport refrigeration are still under development and there was no cost information available for the systems. The Finnish transport refrigeration industry expects there to be other new refrigerants in use in the subsector by 2020 as well. (Information from the industry.)

3.2.5 Abatement costs for mobile air conditioning

The EC MAC Directive restricts the use of HFC refrigerants of GWP over 150 and thus phases out the use of R-134a in MACs. European Commission (2003) estimated the emission abatement cost to be 11–37 €/t CO_2 eq for HC systems, 7–33 €/t CO_2 eq for R-152a systems and 24–158 €/t CO_2 eq for CO_2 systems. The new refrigerant R-1234yf is expected to be substantially more expensive than R-134a at least in the beginning of commercial production (Calm 2008), but the additional design changes required for adaption are minimal (Honeywell 2009b).

The costs of new refrigerants and systems for mobile air conditioning will be distributed to car buyers and owners and are not likely to be critical considering the prices of cars in Finland. The varying cost estimates per functional unit compiled from literature are presented here in 2009 Euros consistent with the figures of Table 1. The estimated additional production cost by European Commission (2003) are 17–45 € for HFC-152a systems, 77–242 € for CO_2 systems and 34–56 € for HC systems, but it is also stated, that these figures are most likely to be overestimations (European Commission 2003). Later on IPCC/TEAP (2005) estimated the additional investment costs per functional unit to be 41 € for HFC-152a systems and in the range of 41–155 € for CO_2 systems.

In a more recent assessment by General Motors the additional component costs of CO_2 systems for a typical small sized vehicle are estimated as 274 € and there are other additional costs said to be expected from production and assembly plant retooling as well as the new service equipment needed (Eustice 2008). In the comparisons of MAC refrigerant options by

Huyndai Kia Motors R-1234yf is found to be the most economical choice (Bang et al 2008). R-1234yf is expected to increase the costs of MACs by 3.5% compared to the R-134a systems, while CO_2 systems are expected to respectively increase the costs by 50% (Bang at al 2008).

3.2.6 Abatement costs for residential and commercial air conditioning and heating, domestic refrigeration and ice rinks

No abatement cost estimations were made for the other subcategories of refrigeration and air conditioning, since cost information was not available from the refrigeration industry. The cost estimates presented in IPCC/TEAP (2005) for residential and commercial air conditioning and heating imply that alternative refrigerants are very cost effective when indirect emissions are taken into account. CO_2 system applications have already been commercialized for both heat pumps and stationary air conditioning.

In Finland domestic refrigeration is mainly conducted with isobutene. HFC-applications on the Finnish market are rare and the abatement costs for substituting these applications are assumed to be close to zero. Ice rink construction has also generally transferred to natural refrigerants, typically indirect ammonia systems, and the costs are expected to be competitive with HFC-systems.

3.3 Main assumptions for HFC emission projections of refrigeration and air conditioning equipment

3.3.1 Definitions of the scenarios

Three main HFC emission scenarios were established for the refrigeration and air conditioning sector. With measures (WM) scenario is a business as usual projection, which relates the ongoing trends in the sector without further changes in the operational environment. The other two scenarios are with additional measures (WAM) scenarios, where future regulatory changes are taken into account.

Only direct emissions of HFC refrigerants are accounted for in the scenarios. The substituting refrigeration applications are expected to be realized at least as efficiently as the conventional HFC applications. On the other hand, possible improvements in energy efficiency are not taken into account either.

The scenarios are calculated with the dominant HFC refrigerants R-404A, R-407C, R-410A and R-134a used in initial installations and equipment manufacturing. The other so called service refrigerants are used in retrofitting old applications, but even their joint share of the yearly total HFC refrigerant charge amount is only about 3.5% (F-gas inventory 2007).

Some of the service refrigerants contain PFC-218. These emissions are not included in the refrigeration sectors sub scenarios, because of their negligible share, less than 1% in the 2007 inventory, of the refrigeration and air conditioning sectors total emissions. However, PFC emissions from the refrigeration sector were added to the total F-gas emission projections. No WAM scenario was conducted for these emissions and they were calculated as if they would stay at the 2007 inventory level.

3.3.2 Main assumptions for the with measures scenarios

The WM scenario for the refrigeration and air conditioning sector assesses the impacts of the EC regulation on F-gases (842/2006) and the EC Directive on emissions from air conditioning systems in motor vehicles (2006/40/EC). Emission factors for the subsectors were taken from Oinonen and Soimakallio (2001) as a starting point for the calculation of actualized emissions. These factors are used up to 2002 after which they are assumed to start decreasing. The refrigeration industry is expected to have started reacting to upcoming measures in preparation. The EC F-gases Regulation is principally estimated to reduce the emission factors 50% by 2011. The change is calculated linearly between years 2003 and 2011, except for domestic refrigeration and MACs, where the emission factors are projected to change by the equipment manufacturing year.

The yearly proportions of refrigerants charged into new equipment were assessed based on literature and estimates acquired from the Finnish refrigeration industry. The refrigerant agent proportions of Oinonen and Soimakallio (2001) are used up to the year 1999. The assumed or predicted changes in refrigerant proportions are calculated linearly between given years. The added up HFC substance emission proportions for 2007 from the refrigeration subsectors of the WM scenario were compared to the F-gas inventory of 2007. The highest difference in the 2007 HFC emission proportions is four percentage units. In the scenarios the amount of HFC-143, which is a component of R-404A, is slightly over estimated and other HFC substances respectively under estimated compared to the emission estimates of the 2007 inventory. The differences can be explained by the use of service refrigerants, which are not separately accounted for in the scenario calculations.

The annual total refrigerant charges of 1990's are mainly estimated based on Oinonen and Soimakallio (2001). The yearly total charge amounts are expected to have increased linearly from a given starting year to the total charge amount of 1999 in Oinonen and Soimakallio (2001). If there are no specific information on or known indicators of the volume of growth of the initial refrigerant charge after 1999 for a subsector, normal growth rates are used. The normal growth is assumed to be 2.0 %/ year until 2020 and 1.8% for the years 2021–2051. These are consistent with the growth rates of the Finnish economy assumed in the Long-term Climate and Energy Strategy of Finland (2008).

3.3.3 Main assumptions for the with additional measures scenarios

The WAM projections for refrigerant emissions are based on the assumption that the Commission's reassessment of the EC F-gases Regulation in 2011 will lead to additional regulatory measures. In the first WAM scenario (WAM 1) the use of HFC substances is assumed to be forbidden in new equipment from the beginning of year 2015 in all of the refrigeration subsectors. The second WAM scenario (WAM 2) presupposes, that the use of HFC substances of GWP higher than 150 is respectively forbidden in new equipment from the beginning of year 2015. In both WAM scenarios the use of HFCs is assumed to be permitted in old equipment to the end of their lifetimes. The refrigeration industry is projected to act on the restrictions in advance and the effect is calculated linearly between years 2011 and 2015.

The WAM 2 scenario is calculated with an imaginary refrigerant of GWP 150 and thus gives maximum emissions for the prevailing assumptions. The WAM 2 scenario was not separately calculated for MACs, since similar restrictions are included in the EC MAC Directive already assessed in the WM scenario. The WAM 2 scenario leaves an option for the new low GWP refrigerants under development and for applications where considerable efficiency gains are reached with HFC solutions.

3.4 Supermarket refrigeration systems

3.4.1 Present state of the supermarket refrigeration systems

Supermarket refrigeration systems are a major HFC emission source in the refrigeration and air conditioning sector. In Finland emissions from supermarket systems are estimated to account for about half of the total emissions from the refrigeration and air conditioning sector. Supermarket refrigeration applications include centralized or distributed full supermarket systems, condensing units and small stand-alone equipment (IPCC/TEAP 2005, Oinonen and Soimakallio 2001). Full supermarket systems are typically direct or indirect vapour compression systems using R-404A as a refrigerant agent (Information from the industry, Oinonen and Soimakallio 2001). In addition to R-404A a common refrigerant for stand-alone equipment, such as cold display cabinets for drinks and small ice-cream freezers, as well as condensing units with small refrigeration capacity is R-134a (UNEP TEAP 2009).

The Finnish supermarket refrigeration sector seems to be in transition to indirect vapour compression applications, which enable reduced refrigerant charges (Information from the industry). The Finnish refrigeration industry actors estimated refrigerant charges of indirect systems to be 30–75% smaller than in corresponding direct systems, while in UNEP (2007) the potential reduction was given as 75–80%. Earlier on Oinonen and Soimakallio (2001) considered the potential reduction of charge amounts with indirect systems to be as high as 90%. The other Nordic Countries have been forerunners in indirect refrigeration technologies, mainly because of the financial and regulatory measures in place (Aalto 2008).

The first CO_2 supermarket freezing system was introduced in Finland in 2007 (Huurre Group Oy 2009). Sweden, Norway and Denmark have had CO_2 based freezing systems in supermarkets since the 1990's (Ekholm 2007). The use of liquid CO_2 evaporators in freezers can decrease freezing compartment's energy costs 35–45%, and these systems have spread rapidly in the other Nordic Countries (Oy AGA Ab 2006). CO_2 applications are becoming common in small stand-alone equipment as well (Aittomäki 2005, UNEP TEAP 2009). The development of CO_2 supermarket systems in Finland has accelerated and new applications have been installed. The most recent development is a new full supermarket system using solely CO_2 as a refrigerant (Huurre Group Oy 2009).

3.4.2 Key assumptions of the supermarket refrigeration systems emission scenarios

The sales of supermarket refrigeration systems are expected to keep growing normally with economic growth at approximately 2% annual growth rate. The yearly amount of HFC refrigerants installed into new equipment, however, is expected to start declining. The estimates from the refrigeration industry ranged from zero growth to 2% annual decrease for the period 2008–2020, after which the decent of the yearly initial charge was predicted to accelerate (Information from the industry).

The main parameters for the HFC emission scenarios of supermarket refrigeration systems are presented in Table 2. The WM scenario for supermarket systems is based on the amount of refrigerants installed in new equipment in 1999 according to Oinonen and Soimakallio (2001). HFC usage is expected to have started from 1993 (0%) and increased linearly until 1999 due to the substitution of ozone depleting substances. From 2000 to 2007 the amount of installed refrigerants is assumed to have grown annually by 2%. After this the transition to indirect systems is expected to have started to undermine the annual growth of total refrigerant charge to 1% in 2008 and zero growth in 2009. Between years 2010–2020 the total refrigerant charge is expected to decrease annually by 0.5%. From 2020 onwards the decreasing effect is assumed to weaken and the initial refrigerant charge growth is set at zero. The estimated average equipment lifetime for supermarket systems is seven years.

In 2005 92% of the initial refrigerant charge is assumed to have been R-404a and 8% R-134a mainly used in small condensing units and stand-alone equipment. By 2010 the use of R-134a is assumed to rise to 10%. The assumed proportion of R-134a was increased based on the comparison of total HFC-substance emissions projected for the refrigeration and air conditioning sector with those of F-gas inventory 2007, in order to decrease the projected total proportion of HFC-143 emissions. The assumed R-134a consumption of supermarket refrigeration systems seems overestimated in light of the information from the industry, which indicated that the current R-404A proportion is over 95% of the initial consumption. However, the overestimation of R-134a proportion compensates for the use of service refrigerants in refitting old supermarket refrigeration systems, which is not separately taken into account in the scenarios. The overestimation of R-134a proportion also improves the reliability of the emission scenarios for the whole refrigeration and air conditioning sector.

In addition, the use of CO_2 applications is expected to substitute a 5% share of the HFC charge amount by 2010, after which the refrigerant proportions are expected to stay constant in the WM scenario. This is a cautious presumption, since the CO_2 consumption estimates for 2020 from the industry ranged between 10–40%.

The WAM 1 and WAM 2 scenarios are calculated based on the main assumptions described above The WAM 1 and WAM 2 scenarios are based on the main assumptions described above in Section 3.3.3. In addition to these two WAM scenarios a third one (WAM 3) was established for the supermarket refrigeration systems sector. In the WAM 3 scenario a restriction of charge amounts is expected to reduce the annual initial charge by 50% by 2015. The reducing effect is calculated linearly between years 2011 and 2015.

Table 2. Main parameters for the scenarios of supermarket refrigeration systems.

Supermarket refrigeration systems	
Initial refrigerant charge amount 1999	100 283 kg
Change of initial charge amount 2000–2007	+2.0% /year
Change of initial charge amount 2008	+1.0%
Change of initial charge amount 2009	0.0 %
Change of initial charge amount 2010–2020	–0.5 % /year
Change of initial charge amount 2021–2050	0.0 %
Refrigerant proportions of initial charge amount 1999	
R-404A	98.2%
R-134a	1.3%
R-22	0.3%
R-409A	0.2%
Refrigerant proportions of initial charge amount 2005	
R-404A	92.0%
R-134a	8.0%
Refrigerant proportions of initial charge amount 2010	
R-404A	85.0%
R-134a	10.0%
R-744 (CO_2)	5.0%
Emission factors 2002	
Initial emission factor	0.02
Annual emission factor	0.20
End-of-life emission factor	0.15
Emission factors 2011	
Initial emission factor	0.01
Annual emission factor	0.10
End-of-life emission factor	0.075
Equipment lifetime	7 years

3.4.3 WM and WAM emission scenarios for supermarket refrigeration systems

The HFC emission scenarios for supermarket refrigeration systems are presented in Figure 1. The emissions curb down after the peak in 2004 as a result of the decreasing of emission factors due to the EC F-gases Regulation. The downward trend is accelerated by the increase in retiring refrigerant charge amounts and the assumed increase in the use of R-134a and CO_2. From the annual emissions of approximately 439 Gg CO_2 eq in 2004 the emission decrease to the level of 274 Gg CO_2 eq by 2011. After 2011 the WM scenario emissions keep decreasing slightly, because of the reducing annual initial charge amount. The lowest emission point of about 256 Gg CO_2 eq is reached in 2027, after which the annual emissions are projected to stay constant, because of the assumed zero growth of the yearly refrigerant charge. In the WM scenario the average refrigerant charge would decrease approximately 60% between 2007 and

2050 as an effect of the transition to indirect equipment, if the supermarket refrigeration equipment sales are assumed to grow annually by 2%.

The total HFC refrigerant ban of WAM 1 scenario cuts the emissions down to zero by 2022. The WAM 2 scenario of GWP 150 refrigerant reduces the yearly emission to about 13 Gg CO_2 eq and the WAM 3 scenario, where charge amounts are restricted, reduces the yearly emission by half compared to the WM scenario, respectively by 2022.

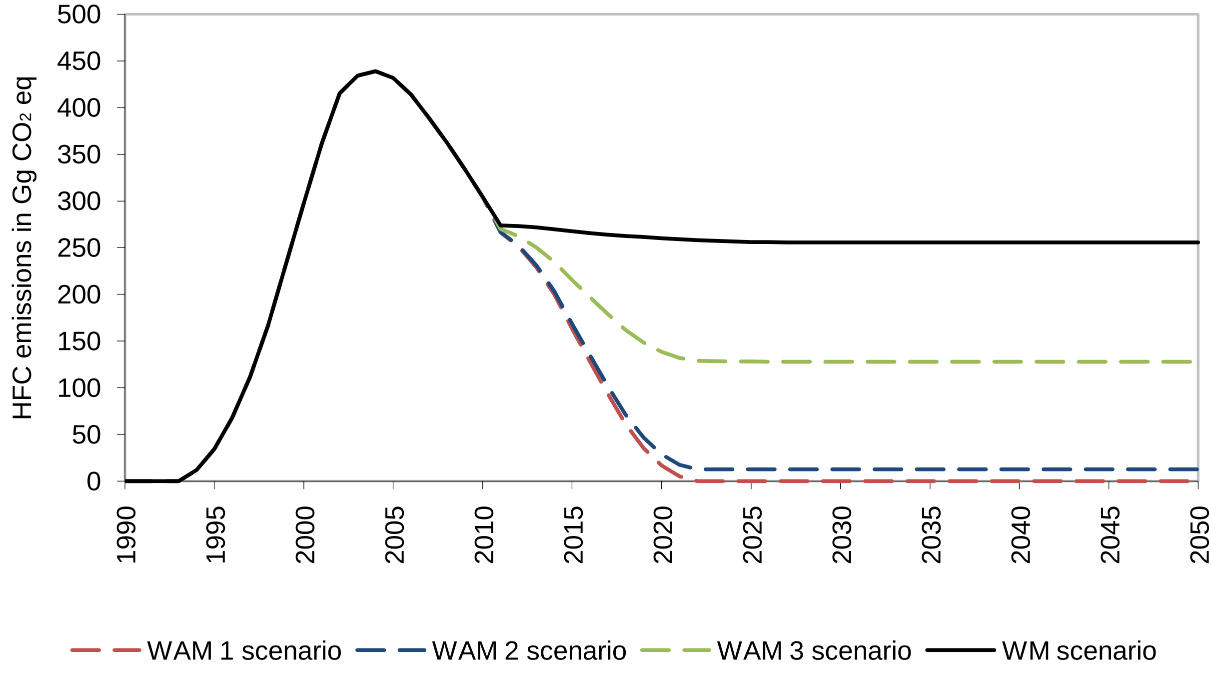

Figure 1. WM and WAM scenarios for HFC emissions from supermarket refrigeration systems in Gg CO_2 eq.

3.5 Professional kitchens and stand-alone commercial applications

3.5.1 Present state of the professional kitchens and stand-alone commercial applications sector

In addition to supermarket refrigeration systems commercial refrigeration includes professional kitchens and stand-alone equipment from other commercial uses like service stations and kiosks. The professional kitchens and stand-alone commercial applications subsector is estimated to account for only about 1% of the refrigeration and air conditioning sectors HFC emissions in Finland.

Professional kitchens typically have several separate cold storage applications for different storage temperatures. The applications vary from different centralized or distributed systems to stand-alone equipment. The systems are usually based on direct vapour compression, because the different temperature level requirements complicate the use of indirect systems (Oinonen and Soimakallio 2001). The main refrigerants in use are R-404A, R-134a and R-407C. The use of CO_2 in small stand-alone applications has also been growing (Aittomäki 2005, UNEP TEAP 2009). For example Coca-Cola has changed into CO_2 based sales cabinets and basins (Aittomäki 2005).

In Finland a register of Horeca (hotel, restaurant and catering) services is kept by A.C. Nielsen Oy. In 2007 there were 21 993 professional kitchens in the Horeca register (A. C. Nielsen 2007). The number of professional kitchens has been slightly declining in the recent years and has risen only about 3% from 1997 to 2007. However, the number of meals served by these kitchens has been increasing (A. C. Nielsen 2007).

3.5.2 Key assumptions of the professional kitchens emission scenarios

The HFC emission scenarios were made separately for refrigeration applications of professional kitchens and for other stand-alone equipment. The scenarios are based on the amount of refrigerants installed in new equipment in 1999 according to Oinonen and Soimakallio (2001). HFC usage is expected to have started from 1993 (0%) and increased linearly until 1999. On the grounds of the Horeca register's information, the annual initial charge of refrigerants is estimated to stay constant from 1999 onwards. The predictions of refrigeration industry actors support the zero growth assumption for the initial refrigerant charge (Information from the industry). The estimated average equipment lifetime for both sub scenarios is ten years.

The main parameters for the HFC emission scenarios of professional kitchens are given in Table 3. The refrigeration industry questionnaire respondents gave conflicting information on the predominant refrigerant of professional kitchens, the options being R-404A and R-407C. The assumed initial refrigerant proportions of 2007, where R-407C accounts for 80% of the total charge, were set based on the overall contemplation of projected HFC substance proportions for the refrigeration and air conditioning sector compared with those of the 2007 inventory. Since the comparison indicated over estimation of the R-404A proportion, the highest R-407C proportion estimate from the industry is used in the scenario calculation. This might not be the most descriptive estimation for the subsector, but it improves the reliability of the total projections for refrigeration and air conditioning equipment. In the WM scenario the annual initial refrigerant proportions are expected to stay steady from 2007 onwards. The WAM 1 and WAM 2 scenarios are based on the main assumptions described above in Section 3.3.3.

Table 3. Main parameters for the scenarios of professional kitchens.

Professional kitchens	
Initial refrigerant charge amount 1999	3 067 kg
Change of initial charge amount 2000–2050	0.0% /year
Refrigerant proportions of initial charge amount 1999	
R-404A	80.9%
R-134a	19.1%
Refrigerant proportions of initial charge amount 2007	
R-404A	10.0%
R-134a	10.0%
R-407C	80.0%
Emission factors 2002	
Initial emission factor	0.02
Annual emission factor	0.15
End-of-life emission factor	0.15
Emission factors 2011	
Initial emission factor	0.01
Annual emission factor	0.075
End-of-life emission factor	0.075
Equipment lifetime	10 years

3.5.3 WM and WAM emission scenarios for professional kitchens

The HFC emission scenarios for professional kitchens are presented in Figure 2. The emissions start descending after the peak of 9.2 Gg CO_2 eq in 2004, because of the decreasing emission factors due to the EC F-gases Regulation and increasing retiring refrigerant amounts. The assumed transition from R-404A to R-407C has a decreasing effect on the emission level as well, even though the decrease of R-134a proportion has a slight opposite effect. Finally the WM scenario emissions steady to the level of 4.3 Gg CO_2 eq by 2017, due to the expected zero growth of the annual initial refrigerant charge. The WAM 1 scenario of total HFC refrigerant ban reduces the emissions to zero and the WAM 2 scenario of GWP 150 refrigerant to 0.38 Gg CO_2 eq by 2025.

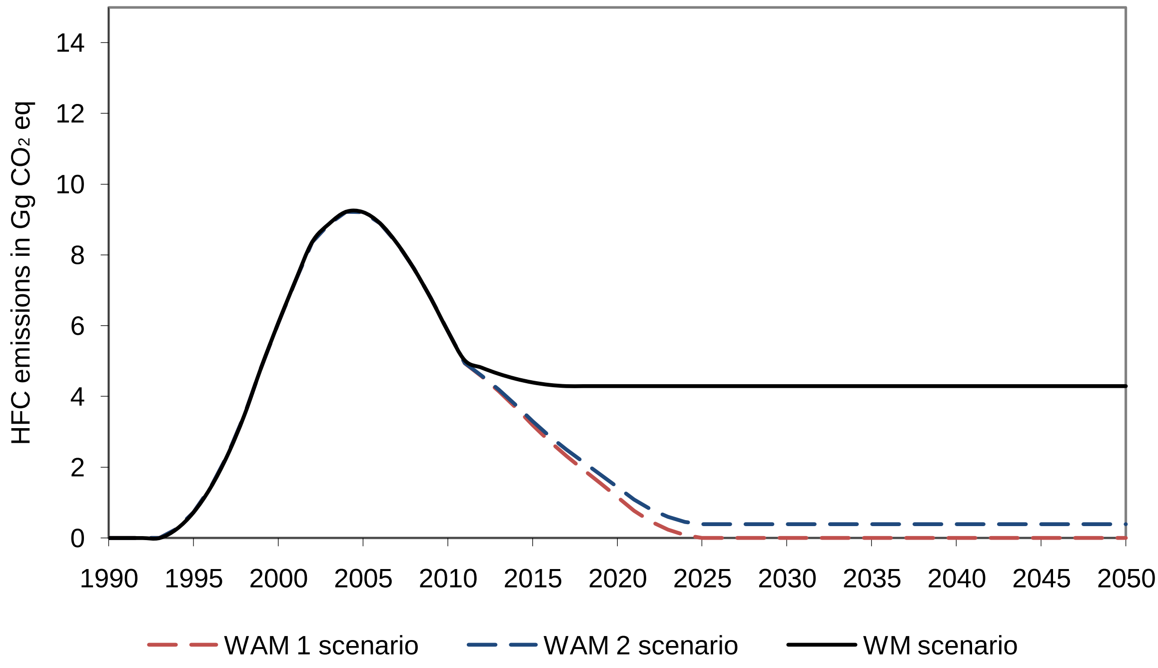

Figure 2. WM and WAM scenarios for HFC emissions from professional kitchens in Gg CO_2 eq.

3.5.4 Key assumptions of the stand-alone commercial applications emission scenarios

The HFC emission scenarios of other stand-alone commercial applications are based on the initial charge amount of 1999 from Oinonen and Soimakallio (2001). The annual initial charge amounts of before and after 1999 are calculated with the same assumptions as in the scenarios of professional kitchens.

The main parameters for the HFC emission scenarios of stand-alone equipment are presented in Table 4. As an exception of the refrigeration and air conditioning sectors main assumptions the EC F-gas Regulation is not expected to affect the annual emission factor of stand-alone equipment. The average equipment refrigerant charge in 1999 was only 0.3 kg (Oinonen and Soimakallio 2001) and for example the regulatory leak inspections only apply to equipment with charges of 3 kg or more. In addition, the estimated loss rate is low to begin with, since there are a lot less pipes and junctures in stand-alone equipment than in the other commercial refrigeration systems.

The main refrigerants used in stand-alone equipment are R-134a and R-404A, but the Finnish refrigeration industry actors gave conflicting views of the proportions of these two refrigerants. In addition to the two candidates for the predominant refrigerant CO_2, HCs and R-407C are used to some extent (Information from the industry). In the WM scenario the use of natural refrigerants is expected to substitute 10% of the HFC refrigerant usage by 2010. The dominant refrigerant is assumed to be R-134a as in 1999 (Oinonen and Soimakallio 2001). The HFC refrigerant proportions are set at 80% R-134a and 10% R-404A in 2010, after which the refrigerant proportions are expected to stay constant. The WAM 1 and WAM 2 scenarios are based on the main assumptions described above in Section 3.3.3.

Table 4. Main parameters for the scenarios of stand-alone commercial applications.

Stand-alone commercial applications	
Initial refrigerant charge amount 1999	2 500 kg
Change of initial charge amount 2000–2050	0.0% /year
Refrigerant proportions of initial charge amount 1999	
R-404A	18.0%
R-134a	82.0%
Refrigerant proportions of initial charge amount 2010	
R-404A	10.0%
R-134a	80.0%
CO_2 or other natural refrigerant	10.0%
Emission factors 2002	
Initial emission factor	0.02
Annual emission factor	0.03
End-of-life emission factor	0.20
Emission factors 2011	
Initial emission factor	0.01
Annual emission factor	0.03
End-of-life emission factor	0.10
Equipment lifetime	10 years

3.5.5 WM and WAM emission scenarios for stand-alone commercial applications

The HFC emission scenarios for stand-alone equipment are illustrated in Figure 3. The emissions increase until 2009 and decline only slightly due to the reduced loss rates of manufacturing and decommissioning as well as the increased use of natural refrigerants. In the WM scenario the annual emissions steady to 1.4 Gg CO_2 eq by 2020. The WAM 1 scenario reduces the emissions to zero by 2025 and the WAM 2 to 0.14 Gg CO_2 eq respectively. All in all the amount of emissions from commercial stand-alone applications are negligible compared to the other subsectors of refrigeration and air conditioning equipment.

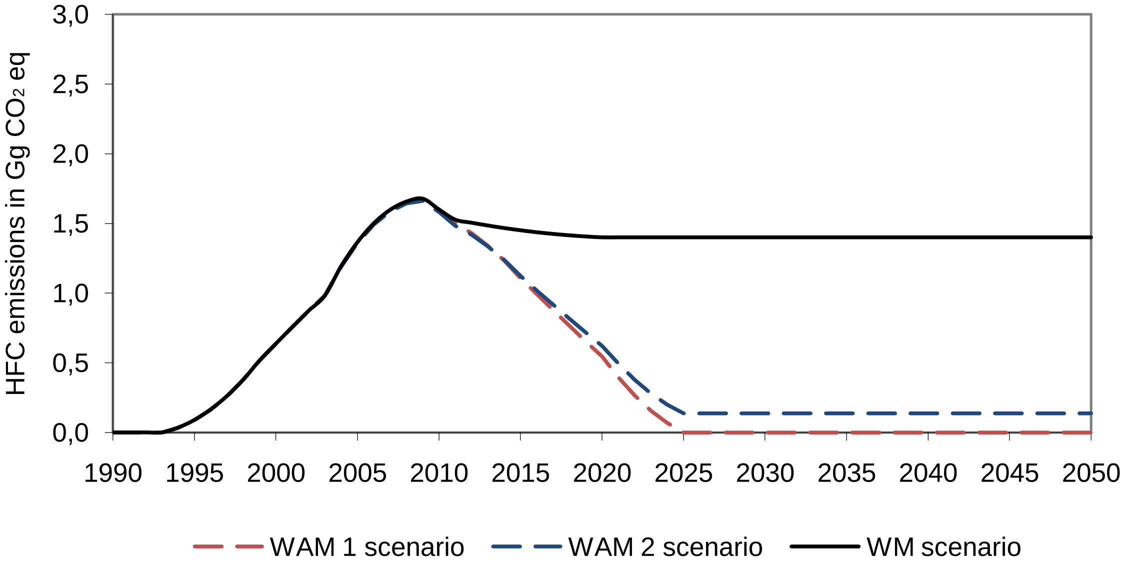

Figure 3. WM and WAM scenarios for HFC emissions from stand-alone commercial applications in Gg CO_2 eq.

3.6 Industrial refrigeration

3.6.1 Present state of the industrial refrigeration sector

Industrial refrigeration is needed in food processing and cold storage and a wide variety of other cooling and freezing applications for the processing industry. Industrial refrigeration is estimated to account for approximately 12% of the refrigeration and air conditioning sectors HFC emissions in Finland. Industrial refrigeration applications are mainly indirect vapour compressions systems (Information from the industry). However, the refrigeration capacities of industrial systems vary greatly and there are a lot of different applications and technologies customized for the process in question (IPCC/TEAP 2005). Natural refrigerants, especially ammonia, are widely used (Information from the industry, IPCC/TEAP 2005).

3.6.2 Key assumptions of the food processing industry emission scenarios

Separate projections were made for the food processing industry and the other processing industries. The scenarios are based on the amount of refrigerants installed in new equipment in 1999 according to Oinonen and Soimakallio 2001. HFC usage is expected to have started from 1993 (0%) and increased linearly until 1999 (100%). Both sectors of industrial refrigeration are expected to grow normally with economic growth. Further transition to indirect systems, resulting in smaller average charges, is expected to slow down the growth of the annual initial refrigerant charge until 2020. The growth rate of the annual refrigerant charge to industrial refrigeration systems is set at 0.5% between 2000–2020 and 1.8% between 2021–2050. The average equipment lifetime for industrial refrigeration systems is assumed to be fifteen years.

The main parameters for the HFC emission scenarios of food processing industry are presented in Table 5. The use of natural refrigerants was estimated to account for 80% of the total usage in 2007 and the remaining 20% to be R-404A and R-134a by half-and-half. Information from the industry indicated, that the current use of natural refrigerants is in the magnitude of 75–90% and that the rest of the initial use consists mainly of R-404A. The proportion of R-134a was again increased based on the overall contemplation of the projected HFC substance proportions in comparison with the 2007 inventory. The assumed probably somewhat overestimated proportion of R-134a compensates for the use of service refrigerants and improves the reliability of the total HFC emission projections for the refrigeration and air conditioning sector. In the WM scenario the initial refrigerant charge proportions are expected to stay constant from 2007 onwards. The WAM 1 and WAM 2 scenarios are calculated based on the main assumptions described above in Section 3.3.3.

Table 5. Main parameters for the scenarios of food processing industry.

Food processing industry	
Initial refrigerant charge amount 1999	56 791 kg
Change of initial charge amount 2000–2020	+0.5% /year
Change of initial charge amount 2021–2050	+1.8% /year
Refrigerant proportions of initial charge amount 1999	
R-717 (NH_3)	73.3%
R-404A	24.3%
R-134a	1.4%
R-22	0.8%
R-409A	0.2%
Refrigerant proportions of initial charge amount 2000	
R-717 (NH_3)	73.3%
R-404A	25.3%
R-134a	1.4%
Refrigerant proportions of initial charge amount 2007	
R-717 (NH_3) or other natural refrigerant	80.0%
R-404A	10.0%
R-134a	10.0%
Emission factors 2002	
Initial emission factor	0.02
Annual emission factor	0.15
End-of-life emission factor	0.15
Emission factors 2011	
Initial emission factor	0.01
Annual emission factor	0.075
End-of-life emission factor	0.075
Equipment lifetime	15 years

3.6.3 WM and WAM emission scenarios for food processing industry

The HFC emission scenarios for food processing industry are represented in Figure 4. The emissions curve down from 2006 to 2011, mainly because of the declining emission factors assumed due to the EC F-gases Regulation. When the emission factors have become stable there is a small increase in the annual emissions of the WM scenario. After the slight rise in the emission level, the emissions decline further as an effect of the increase in retiring R-404A refrigerant amounts. The trend is overturned by the growth of the annual initial refrigerant charge in 2023. In the WM scenario the emissions increase to 52 Gg CO_2 eq by 2050 which is slightly higher than the estimated peak of 51 Gg CO_2 eq in 2006. The WAM 1 scenario of total HFC refrigerant ban reduces the emissions to zero by 2030. The WAM 2 scenario of GWP 150 refrigerant reaches the lowest emission level of 2.4 Gg CO_2 eq respectively by 2030, after which the emissions start increasing again reaching 3.4 Gg CO_2 eq by 2050.

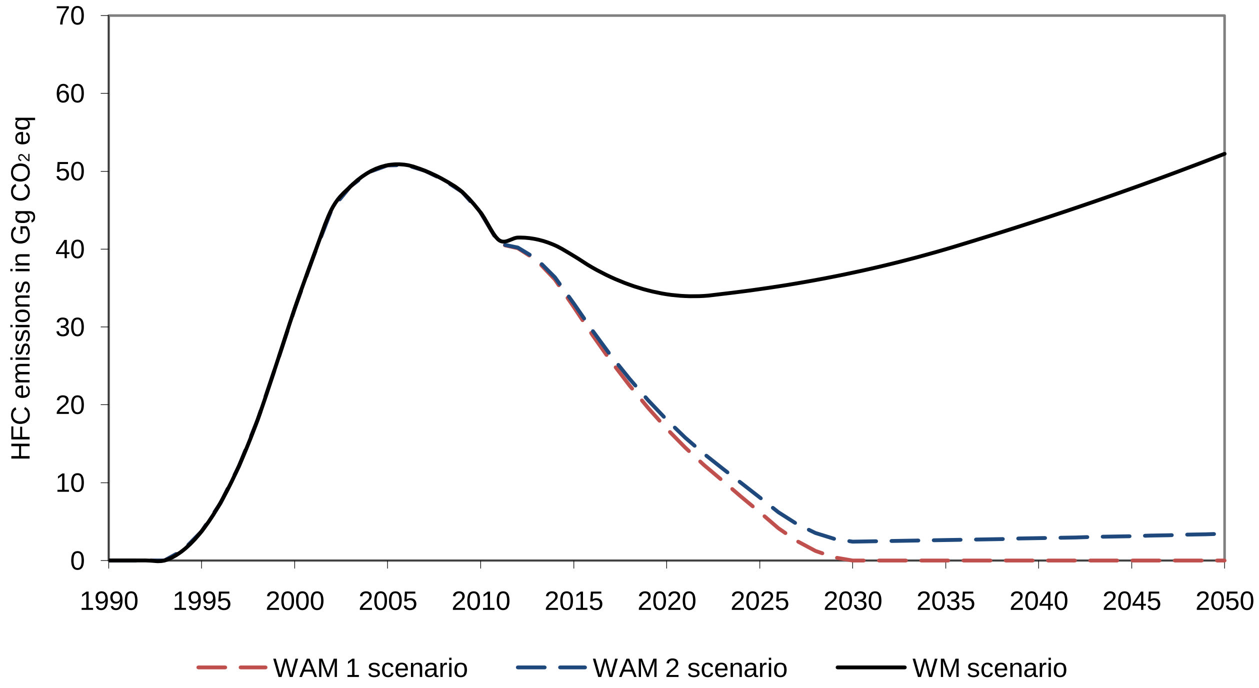

Figure 4. WM and WAM scenarios for HFC emissions from food processing industry in Gg CO_2 eq.

3.6.4 Key assumptions of the processing industry emission scenarios

The HFC emission scenarios of the other processing industries are based on the initial charge amount of 1999 from Oinonen and Soimakallio (2001). The annual initial charge amounts of before and after 1999 are calculated with the same assumptions as in the scenarios of food processing industry. The average equipment lifetime is also assumed to be the same, fifteen years.

The main parameters for the HFC emission scenarios of processing industry are presented in Table 6. The proportions of different refrigerants charged into new equipment in 2007 are assumed to be the same as in food processing industry except for R-407C, which accounts for 10% of the refrigerant charge in stead of R-404A. The refrigeration industry actors gave conflicting views of the refrigerant proportions of the current annual initial charge. The estimated proportion of ammonia ranged from 30% to 90% and the other suggested refrigerants were R-134a and R-407C (Information from the industry). The assumed proportions are mainly based on the information of Oinonen and Soimakallio (2001) and the contemplation of the total HFC substance projections in comparison with the 2007 inventory. In the WM scenario the assumed proportions are expected to stay constant from 2007 onwards. The WAM 1 and WAM 2 scenarios are again based on the main assumptions described above in Section 3.3.3.

Table 6. Main parameters for the scenarios of processing industry.

Processing industry	
Initial refrigerant charge amount 1999	64 363 kg
Change of initial charge amount 2000–2020	+0.5% /year
Change of initial charge amount 2021–2050	+1.8% /year
Refrigerant proportions of initial charge amount 1999	
R-717 (NH_3)	72.1%
R-404A	16.6%
R-134a	8.4%
R-407C	2.9%
Refrigerant proportions of initial charge amount 2007	
R-717 (NH_3) or other natural refrigerant R-717 (NH_3)	80.0%
R-134a	10.0%
R-407C	10.0%
Emission factors 2002	
Initial emission factor	0.02
Annual emission factor	0.15
End-of-life emission factor	0.15
Emission factors 2011	
Initial emission factor	0.01
Annual emission factor	0.075
End-of-life emission factor	0.075
Equipment lifetime	15 years

3.6.5 WM and WAM emission scenarios for processing industry

The HFC emission scenarios of processing industry are presented in Figure 5. The same factors are at work here as in the scenarios of food processing industry. The downward emission trend starting from the peak of 46 Gg CO_2 eq in 2005 is first caused by the assumed reduction of emission factors due to the EC F-gases Regulation. The decline is followed by temporary leveling, after which the emissions keep decreasing due to the diminishing share of R-404A emissions. In the WM scenario the annual growth of the initial refrigerant charge turns the trend upwards in 2023 leading to emissions of 37 Gg CO_2 eq by 2050. The WAM 1 scenario reduces the emissions to zero by 2030. The WAM 2 scenario reduces the emissions close to zero by 2030 after which the emissions increase to 0.31 Gg CO_2 eq by 2050.

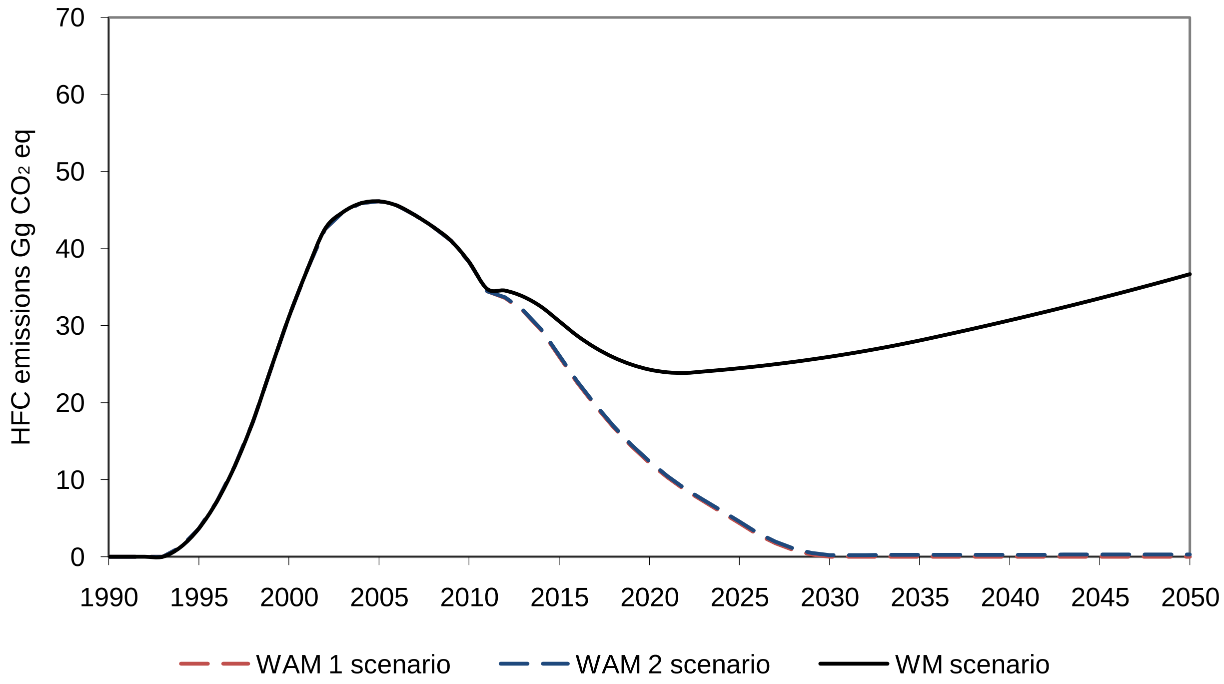

Figure 5. WM and WAM scenarios for HFC emissions from processing industry in Gg CO_2 eq.

3.7 Transport refrigeration

3.7.1 Present state of the transport refrigeration sector

Transport refrigeration consists of road, rail, air and sea transport of refrigerated or frozen goods. Thermo controlled transportation is required especially for perishable foodstuffs. In Europe 90% of the import and export of foodstuffs is conducted by road or by combined sea and road transport (Luoto et al 2007). The international transportation and transportation equipment of perishable foodstuffs is regulated by the ATP-agreement. In Finland the ATP-agreement is enforced by Evira (Finnish Food Safety Authority). The ATP approved transportation equipment is certified by MTT (Agrifood Research Finland), which keeps a register of these applications. In addition, there are three transport refrigeration companies approved by Evira for performing periodical inspections of ATP applications.

The refrigerated transportation is mainly conducted with refrigerated trucks and trailers or containers, which can be transported by road, sea or rail. In Finland refrigerated rail transport is uncommon. The Finnish railway company VR does not have refrigerated railcars, but it is possible to connect electricity to refrigeration equipment if needed (Mälkiä 2008). Domestic distribution services especially in cities are often carried out with refrigerated vans or light trucks.

The transport refrigeration subsector is estimated to account for approximately 5% of the total HFC emissions of refrigeration and air conditioning equipment in Finland. Vapour compression cycle is the dominant technology for transport refrigeration equipment. The refrigeration equipment either uses the power of the car engine or has its own electric motor (Luoto et al 2007). The most commonly used refrigerant is R-404A. Approximately 3–4% of the refrigerated trucks have R-410A as a refrigerant and some non ATP approved trucks and vans have R-134a equipment (Information from the industry, Register of ATP equipment approvals).

Cryogenic refrigeration is based on liquid CO_2, which is vaporized in the process and led to outside air (Luoto et al 2007). There are a few cryogenic CO_2 applications even registered as ATP transportation devices, but based on the transport refrigeration questionnaire responses the number of cryogenic refrigeration equipment is still estimated to be less than 1% of the total quantity of refrigerated transport devices. The respondents expected cryogenic applications to increase their market share somewhat by 2020, but to be replaced by other applications afterwards. Cryogenic applications need considerable amounts of CO_2 leading to direct emissions and in the future, when the technology has improved, natural refrigerants are more likely to be used in closed refrigeration systems (Information from the industry). The transport refrigeration industry respondents also expected there to be a new refrigerant in use by 2020. This new refrigerant was predicted to dominate the markets later on (Information from the industry). The new refrigerant could be for example a fluorinated alkene such as HFC-1234yf.

3.7.2 Key assumptions of the transport refrigeration emission scenarios

The HFC emission scenarios for transport refrigeration are based on the estimated yearly quantities of new transport refrigeration equipment taken into use. The yearly quantities for 1990–2007 are calculated from MTT's register of yearly ATP approvals, which are estimated to amount for 40% of the total number of new transport refrigeration devices based on information from the industry. The questionnaire respondents gave quite consistent estimates of the share of ATP applications, ranging from 35% to 40%. The figures calculated from the ATP register information were smoothed with five-year running means. From 2008 onwards the annual number of equipment taken into use is expected to grow normally with economic growth.

The estimated quantities include HFC refrigerated trucks, full trailers, half trailers, exchangeable truck bodies, containers and vans. The number of vans, which have considerably smaller refrigerant charges in their equipment, is estimated as 3% of the annually introduced transport refrigeration applications. The average charge amounts are based on the ATP register information and the questionnaire responses, which supported each other. The average charge for equipment in vans is set at 2.0 kg and for the other applications at 6.3 kg. The average equipment lifetime is presumed to be eight years for all of the transport refrigeration equipment applications. The main parameters for the HFC emission scenarios of transport refrigeration are presented in Table 7.

In the scenarios HFC transport refrigeration is assumed to have been conducted with R-404A until 2002. The use of R-410A in refrigerated transport equipment is expected to have started in 2003 and to rise to 15% of the yearly total refrigerant charge by 2010. All of the questionnaire respondents expected the share of R-410A to increase in the future. The small amount of R-134a used in transport refrigeration is not taken into account in the scenarios, since the information from the industry indicates that the usage is likely to end. In the WM scenario the refrigerant proportions are expected to stay constant from 2010 onwards.

The WAM 1 and WAM 2 scenarios are based on the main assumptions described above in Section 3.3.3, but in addition to them a third WAM scenario was made. In the WAM 3 scenario the additional measures are assumed to restrict the use of HFC substances with highest GWP values and the use of R-404A in transport refrigeration equipment to be replaced by R-410A. The transition is again assumed to take place linearly between years 2011 and 2015

Table 7. Main parameters for the scenarios of transport refrigeration.

Transport refrigeration	
Average charge amount in the refrigeration equipment of vans	2.0 kg
Average charge amount in the other applications	6.3 kg
Proportion of vans	3.0%
Change of initial charge amount 2008–2020	+2.0% /year
Change of initial charge amount 2020–2050	+1.8% /year
Refrigerant proportions of initial charge amount 2002	
R-404A	100%
Refrigerant proportions of initial charge amount 2010	
R-404A	85.0%
R-410A	15.0%
Emission factors 2002	
Initial emission factor	0.006
Annual emission factor	0.325
End-of-life emission factor	0.25
Emission factors 2011	
Initial emission factor	0.003
Annual emission factor	0.1625
End-of-life emission factor	0.125
Equipment lifetime	8 years

3.7.3 WM and WAM emission scenarios for transport refrigeration

The HFC emission scenarios for transport refrigeration are illustrated in Figure 6. The emissions begin in 1994 and increase quite consistently to 37 Gg CO_2 eq by 2006. The following downward trend is caused by the declining emission factors assumed due to the EC F-gases Regulation and the increasing share of R-410A. This effect ends in 2011, after which the WM scenario emissions start increasing steadily with the growth of the yearly installed equipment volume. In the WM scenario the annual emissions rise to 67 Gg CO_2 eq by 2050, which is an 80% increase from the peak of 2006.

The WAM 1 scenario of HFC refrigerant ban reduces the emission to zero by 2023. The WAM 2 scenario of GWP 150 refrigerant reduces the emissions to 1.9 Gg CO_2 eq at their lowest and increases to the level of 3.3 Gg CO_2 eq by 2050. In the WAM 3 scenario the yearly emissions increase slightly from 2011 to 2013, after which the further transition to R-410A overcomes the equipment volume growth and turns the emission trend down. The emissions start to increase again from 2023 onwards, when all the remaining R-404A applications have retired, and reach 38 Gg CO_2 eq by 2050.

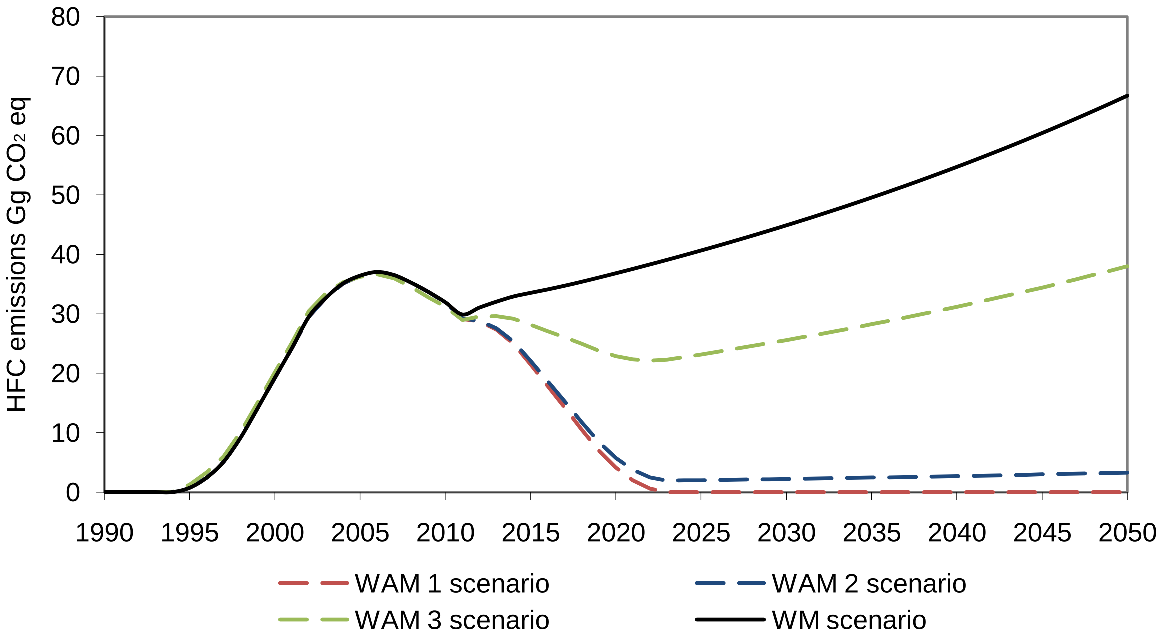

Figure 6. WM and WAM scenarios for HFC emissions from transport refrigeration in Gg CO_2 eq.

3.8 Mobile air conditioning

3.8.1 Present state of the mobile air conditioning sector

Mobile air conditioning devices (MACs) have increased rapidly in the European markets since the 1990's. In Finland the proportion of air conditioned vehicles from the yearly registered new passenger vehicles and vans has risen from 30% in 1999 (Oinonen and Soimakallio 2001) to approximately 98% in 2007 (F-gas inventory 2007). Greenhouse gas emissions from MACs have increased accordingly. Two thirds of the emissions have been estimated to be direct emissions from the refrigerant R-134a and one third due to indirect emissions of higher fuel consumption (European Commission 2003). In Finland MACs account for almost one third of the direct HFC emissions from refrigeration and air conditioning equipment.

The EC MAC Directive regulates the future use of refrigerants in MAC systems. Since the phase out of CFC-12 systems in the 1990's MACs have been using R-134a. The EC MAC Directive gradually bans the use of refrigerants with GWP over 150, including R-134a. The type-approval of new car models with a MAC system based on a refrigerant of GWP over 150 is banned from the beginning of 2011 and registering and sales of new vehicles with such systems is totally banned from 2017 onwards. In addition, the EC MAC Directive includes respective restrictions for the installation and maintenance of MACs. The leakage rates of R-134a systems in new vehicles are also regulated during the transition period, the allowed rates being 40 g/HFC/year for one evaporator systems and 60 g/HFC/year for systems with two evaporators. Recharging a MAC leaking abnormal amounts of HFC refrigerant before the required maintenance work is done is forbidden by the directive as well.

The most promising candidates for replacing R-134a in MACs are CO_2, R-152a and the new synthetic blend refrigerant R-1234yf (HFO-1234yf, $C_3H_2F_4$). The use of hydrocarbons has been ruled out by car manufacturers and suppliers due to safety concerns, mainly high flammability (IPCC/TEAP 2005, EPA 2007). The use of R-152a also has a flammability risk and is therefore mainly considered for secondary loop systems, where refrigerant charges are small and the refrigerant does not enter the passenger cabin air in the event of collision or equipment failure (EPA 2007). The conventional R-134a systems are direct vapour compression systems and R-1234yf is the only one of the new refrigerant candidates with characteristics similar enough to have potential for direct substitution of R-134a. CO_2 systems require new technical applications and the level of the gas in the passenger compartment must be controlled (Eustice 2008). The CO_2 systems working pressure and temperature are higher than R-134a systems and the systems predicted average service life has been estimated to be only 4–5 years, after which recharging will be needed due to high leakage rate (Eustice 2008).

The alternative technologies are expected to be possible without energy efficiency losses, since the design of the whole system, not the choice of refrigerant, dominates the energy consumption of a vehicle (European Commission 2003). EPA (2007) estimated a 21% reduction potential of MAC fuel consumption for R-152a secondary loop systems. The additional fuel consumption for CO_2 systems has been estimated to be 14–54% lower than for R-134a systems, the lowest reduction potential occurring in high temperatures (35 °C) (Graz 2009). Additional fuel consumption reductions of 10–20% are also expected for R-1234yf systems with internal heat exchangers (Rinne 2009). However, a life cycle impact assessment by Hyundai Kia Motors indicates, that R-1234yf systems have better fuel efficiency during MAC operation and smaller total CO_2 equivalent emissions for a system lifetime than CO_2 systems (Bang et al 2008).

The different technical options are still tested and developed by car manufacturers and all of the air conditioned new vehicles imported to Finland in 2008 still had conventional R-134a systems (F-gas inventory 2008). R-1234yf production is expected to start by the end of 2010 (Spatz and Minor 2008) if the registration process of the new chemical will be successful. Its good compatibility with R-134a systems should allow rapid global adoption (Spatz 2009).

3.8.2 Key assumptions of the mobile air conditioning emission scenarios

The scenarios for HFC emissions from MACs are based on the number of yearly vehicle registrations from the statistics of The Finnish Vehicle Administration (AKE) until 2007. From 2008 to 2050 the registration of new vehicles is expected to stay constant in accordance with the LIISA 2005 calculation model of Technical Research Center of Finland (VTT) by Mäkelä et al (2006). In a study of the future of Finnish vehicle stock 2006 – 2030 Pöllänen et al (2006) also assumed, that the sales of new cars would stay close to the 2005 figures. The proportions of air conditioned vehicles used in the calculation of scenarios are from the yearly F-gas inventories. After 2007 the proportions are expected to stay constant.

The import of used vehicles to Finland increased from 5 000 passenger vehicles in 2002 to approximately 32 000 passenger vehicles in 2003, due to changes of taxation (AKE 2008). Based on this information the import of used vehicles prior to 2001 is assumed to have been negligible and not taken into account in the scenario calculations. Between 2008–2030 the number of imported used vehicles is expected to decrease annually 3.2% as in Pöllänen et al (2006), after which the imported number is assumed to stay constant. The age of imported second hand vehicles varies, but in the calculations the proportions of air conditioned vehicles and refrigerant charges are assumed to be the same as in new vehicles.

The average charge of new MACs has been decreasing about 1% annually and this trend has been expected continue in the future as well (Schwarts 2005). In the scenarios the starting point of average MAC refrigerant charges is 1995, when the charges were 0.835 kg for passenger vehicles and vans, 10.46 kg for buses and 1.78 kg for trucks (Oinonen and Soimakallio 2001). The 1% annual reduction of the average charges is expected to take place from 1995 to 2020, after which the average charge amounts are assumed to stay constant.

There is one company that manufactures and exports passenger vehicles in Finland. The confidential F-gas inventory information on the annual imported quantities is used in the scenarios until 2007. The exported amount of air conditioned vehicles is estimated for 2008–2012 based on the company's internet news-sheets about future production. From 2012 onwards the exported amount is assumed to stay constant. The average refrigerant charge amount is used for the MACs of older car models from 1995 to 2003. For the currently manufactured model a specific confidential charge amount, reported by the company for the F-gas inventory in 2008, is used. This charge amount is expected to stay constant and is used also for the assumed future exports. In Finland the exported quantities of trucks and buses are small and these are not taken into account in the scenario calculations.

The main parameters for the HFC emission scenarios of MACs are presented in Table 8. The registered new vehicles are mainly imported with the air conditioning equipment already installed and thus emissions from manufacturing or installation of MACs for these vehicles are not included in the scenarios. As an exception to the main assumptions the annual emission factors are expected to change by the equipment's initial registration year in Finland, the factor decreasing linearly from 2004 to 2011. The MACs in vehicles initially registered from 2011 onwards are expected to have an annual emission factor of 0.05, which is in the level required by the EC MAC Directive. The end-of-life emission factor is expected to decrease based on the main assumptions, by 50% from 2002 to 2011. The initial emission factor for manufacturing and installation of MACs of exported vehicles is assumed to stay constant for different car types, 0.005 for the older Saab models manufactured until 2003 and 0.002 for the newer Porsche models manufactured in 1997 and after. The average equipment lifetime for all MACs is set at 12 years.

The WM scenario is calculated with the assumption that R-152a would be the main refrigerant in 2017, with a share of 80% of the annual initial refrigerant charge of MACs. The remaining 20% is assumed to be CO_2. The exported equipment are assumed to be solely R-152a systems also by 2017. The transition from R-134a is calculated linearly between 2008–2017. With a GWP of 140 R-152a is close to the 150 GWP limit placed by the EC MAC Directive. If the main refrigerant would be the new refrigerant R-1234yf (GWP 4) or something similar, the projected direct emissions would decrease even more. The WAM 1 scenario is conducted based on the main assumptions described above in Section 3.3.3 and this also applies to a situation were CO_2 systems would become dominant in MACs. The WAM 2 scenario was not calculated since the EC MAC Directive already places similar restrictions, which are taken into account in the WM scenario.

Table 8. Main parameters for the scenarios of mobile air conditioning.

Mobile air conditioning	
Change of new vehicle registrations 2008–2050	0.0% /year
Change of used vehicle imports 2008–2030	–3.2% /year
Change of used vehicle imports 2031–2050	0.0% /year
Refrigerant proportions of initial charge amount 2007	
R-134a	100%
Refrigerant proportions of initial charge amount 2017	
R-152a	80.0%
R-744 (CO_2)	20.0%
Emission factors for equipment installed for export in vehicles	
Initial emission factor	0.002 or 0.005
Emission factor for equipment in vehicles registered in 2004 or before	
Annual emission factor	0.20
Emission factor for equipment in vehicles registered in 2011 or after	
Annual emission factor	0.05
End-of-life emission factor 2002	0.20
End-of-life emission factor 2011	0.10
Equipment lifetime	12 years

3.8.3 WM and WAM emission scenarios for mobile air conditioning

The HFC emission scenarios for MACs are presented in Figure 7. The emissions increase sharply to the peak of 215 Gg CO_2 eq in 2008 with the growing share of vehicles equiped with MACs. From there on the emission trend turns downwards as an effect of the decreasing emission factors and the transition to lower GWP refrigerants required by the EC MAC Directive. The tightest downward slope ends aroun 2011, when the emision factors steady. The next change in the WM scenario emission trend is caused by the end of refrigerant agent transition in 2017. The decreasing trend continues, while the R-134a equipment are retiring. All of the remaining R-134a equipment retire by 2028, but a slight decrease is maintained by the assumed decrease in the import of used passanger vehicles. In the WM scenario the emissions steady to the level of 9.0 Gg CO_2 eq in 2042. In the WAM 1 scenario of total HFC refrigerant ban the emissions decrease to zero by 2027.

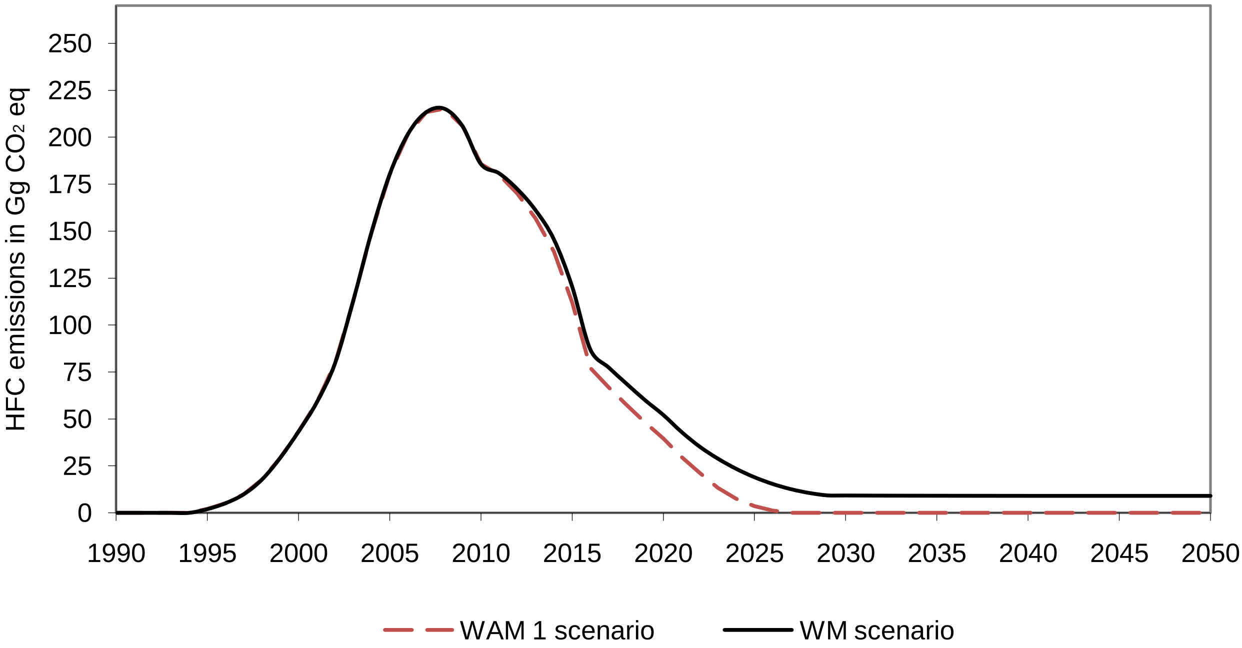

Figure 7. WM and WAM scenarios for HFC emissions from mobile air conditioning in Gg CO_2 eq.

3.9 Stationary air conditioning

3.9.1 Present state of the stationary air conditioning sector

In Finland stationary air conditioning (AC) is used mainly in commercial and office buildings. Stationary air conditioning equipment include different centralized and distributed systems, with direct or indirect vapour compression technology. The cooling capacities range from only a few kilowatts to thousands of kilowatts. The high performance systems are mainly centralized water chillers, where water is used as a heat transfer fluid in a secondary loop. Small low capacity systems are typically industrially manufactured room air conditioners, which can be either direct or indirect applications. (See Oinonen and Soimakallio 2001.)

Most of the stationary air conditioning equipment in Finland are indirect applications, where the refrigerant charges are considerably smaller than in direct systems (Information from the industry, Aalto 2008). The main HFC refrigerants in use are R-407C, R-410A and R-134a (Information from the industry). HFC emissions from stationary air conditioning equipment are estimated to account for approximately 4% of the total emissions of refrigeration and air conditioning equipment in Finland.

In 2005 Kalliomäki et al estimated that the number of small AC devices of 12–70 kW, mostly used for computer suites and small office and commercial facilities, in Finland was 19 000 units. The number of middle sized 70–300 kW equipment was estimated as 10 000 units and the number of higher than 300 kW capacity equipment used in large office and commercial buildings as 3 500 units (Kalliomäki et al 2005). The Directive on the Energy Performance of Buildings (2002/91/EC) imposes periodical inspections of air conditioning equipment by capacity levels. The Directive has been implemented in the Finnish legislation from the beginning of 2008. The cooling capacity does not necessarily correlate with the refrigerant charge amount, since the choice of technology also affects it (Lavento 2008). In 2008 the number of small 3–30 kg charge equipment was estimated as about 30 000, middle sized under 300 kg charge equipment as 500 and larger than that as an additional 500 equipment (Lavento 2008).

In densely built areas an alternative option for building separate cooling systems is district cooling. District cooling is produced in a centralized production plant, where from refrigerated water is distributed by pipes to several buildings. District cooling can be produced with absorption technology, compression technology, heat pumps or naturally cold water or air. In Finland district cooling is available at least in Helsinki, Turku and Lahti. (Kalliomäki 2005.)

In Helsinki district cooling is provided by Helsingin Energia. In the summer it is produced by absorption technology using the surplus heat produced in a CHP plant. In the winter, when the CHP plant's heat is needed in district heating, cold seawater is used for district cooling. In addition, there is a heat pump plant utilizing the heat content of purified waste water and producing district cooling and heating in the same process. (Helen 2009a.) In 2006 the district cooling capacity in use in Helsinki was 60 MW and the capacity is expected to expand to 100 MW by 2010 and 250 MW by 2020 (Helen 2009b). The district cooling network of Turku is also expanding (Turku Energia 2009).

The development of passive and low-energy building is also evolving solutions for cooling without conventional AC compressor equipment. These include for example passive cooling with night ventilation and using ground as a heat sink by circulating water in bore holes and the buildings ceiling (Butler 2008). Krausse et al (2007) concluded that natural ventilation could maintain thermal comfort even in buildings with sealed facades in deep-plan urban areas in most UK locations. There are also different technologies, absorption, adsorption and dessicant cooling, available for solar heat driven air conditioning (Clausse et al 2008).

Ammonia and hydrocarbons are best applicable for indirect vapour compression systems, where safety issues can be managed for example by confining the refrigerant in a machine room with alarms and venting devices (IPCC/TEAP 2005). Carbon dioxide is used in both direct and indirect vapour compression systems. Carbon dioxide AC systems are already produced and marketed in the Nordic Countries (See Green and Cool 2009, Advansor 2009). Different low GWP (less than 60) mixtures of hydrocarbons, dimethylether (DME/RE 170) and HFC-152a have been tested for residential air conditioning and heat pumps as well (Park and Jung 2007).

The global and European sales of AC equipment has been growing strongly in the recent years (Fluorocarbons and Sulphur hexafluoride 2006). The growth has been expected to continue and for example Schwarz (2005) forecasted the number of water chillers to double and the number of room air conditioners to grow 40% by 2010 in Germany. Kalliomäki et al (2005) estimated the annual growth of the energy consumption of AC equipment as 5–10% in Finland.

3.9.2 Key assumptions of the stationary air conditioning emission scenarios

The HFC emission scenarios for air conditioning equipment are based on the initial refrigerant charge of 1999 in Oinonen and Soimakallio 2001. Oinonen and Soimakallio calculated the total refrigerant charge from the volume of refrigerated buildings, average cooling capacity and refrigerant charge for capacity. Since air conditioning equipment is mostly used in commercial and office buildings, the growth of annual new construction production volume of these buildings was presumed to indicate the growth of the annual refrigerant charge. The average annual volume growth for 1999–2007 was calculated from the information of Statistics Finland. This annual growth rate of 11.8 % is used in the scenarios from 2000 to 2007. Prior to 1999 the yearly HFC refrigerant charge is expected to have grown linearly starting from 1993. From 2008 onwards the yearly refrigerant charge is assumed to grow normally, because there are other trends like the expanding of district cooling, energy efficiency demands and low-energy and passive building methods curtailing the growth. The main parameters for the stationary AC equipment emission scenarios are presented in Table 9.

The prevailing trend in AC refrigerants has been the use of R-410A in new equipment and the use of R-407C in existing old systems (Park and Jung 2007). This seems to be the main trend in the Finnish AC sector as well (information from the industry). The questionnaire responses indicate that the share of R-410A is going to increase and natural refrigerants are also going to be gaining ground. The assumed growth of R-410A usage to a 70% share of the initial charge and the diminishing of R-404A usage by 2007 are backed up by the HFC substance proportions of the F-gas inventory 2007. In the WM scenario the R-410A proportion of the initial charge amount is expected to further increase to 80% and natural refrigerant proportion to 10% by 2020 and the proportion of R-407C to decline to 5%, respectively. The proportion of R-134a is estimated to have declined to 5% by 2007 and to stay constant afterwards. The WAM 1 and WAM 2 scenarios are based on the main assumptions described above in Section 3.3.3. For simplicity's sake the average equipment lifetime is set at 13 years, even though the AC sector includes a wide variety of equipment with different capacities and lifetimes.

Table 9. Main parameters for the scenarios of stationary air conditioning.

Stationary air conditioning	
Initial refrigerant charge amount 1999	14 694 kg
Change of initial charge amount 2000–2007	+11.8% /year
Change of initial charge amount 2008–2020	+2.0% /year
Change of initial charge amount 2021–2050	+1.8 % /year
Refrigerant proportions of initial charge amount 1999	
R-407C	51.8%
R-404A	22.9%
R-134a	20.5%
R-22	4.5%
R-410A	0.3%
Refrigerant proportions of initial charge amount 2000	
R-407C	56.3%
R-404A	22.9%
R-134a	20.5%
R-410A	0.3%
Refrigerant proportions of initial charge amount 2007	
R-407C	25.0%
R-134a	5.0%
R-410A	70.0%
Refrigerant proportions of initial charge amount 2020	
R-407C	5.0%
R-134a	5.0%
R-410A	80.0%
R-744 (CO_2) or other natural refrigerant	10.0%
Emission factors 2002	
Initial emission factor	0.007
Annual emission factor	0.10
End-of-life emission factor	0.15
Emission factors 2011	
Initial emission factor	0.0035
Annual emission factor	0.05
End-of-life emission factor	0.075
Equipment lifetime	13 years

3.9.3 WM and WAM emission scenarios for stationary air conditioning

The HFC emission scenarios for stationary AC equipment are illustrated in Figure 8. The WM scenario emissions keep increasing rather constantly. The decrease of emission factors due to the EC F-gases Regulation induces only a small and temporary tumble in the emission trend around 2011. In the WM scenario the annual emissions increase from about 30 Gg CO_2 eq in 2006 to 78 Gg CO_2 eq by 2050. Without the assumed changes in refrigerant proportions, the growth would be even stronger.The WAM 1 scenario of HFC refrigerant ban reduces the emissions to zero by 2028. The WAM 2 scenario of GWP 150 refrigerant reaches its lowest point of 4.7 Gg CO_2 eq also in 2028, but from then on the emissions increase slowly reaching 6.9 Gg CO_2 eq by 2050.

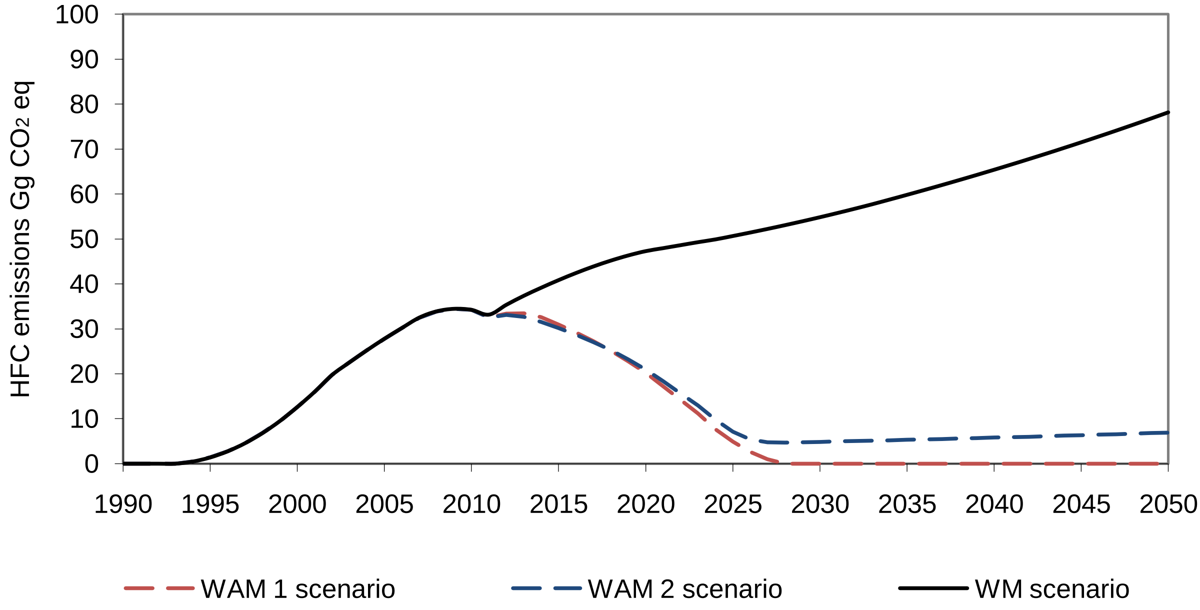

Figure 8. WM and WAM scenarios for HFC emissions from stationary air conditioning in Gg CO_2 eq.

3.10 Heat pumps

3.10.1 Present state of the heat pumps sector

Heat pumps utilize ambient heat, heat energy stored in air, soil, rock or water, in heating buildings or service water. Waste heat from industrial processes can be utilized by heat pumps as well. Heat pumps can be grouped by the source of heat and its distribution method. The common heat pumps are ground heat pumps, air-to-air heat pumps, air-to-water heat pumps and exhaust air heat pumps. In addition to one-family houses heat pumps are used for real estate heating and district heating. When the process is reversed heat pumps can be used in cooling also. Heat pumps often have the reversing capability, which enables their use in heating in the winter and in cooling in the summer. (See SULPU 2008a, Oinonen and Soimakallio 2001.) In Finland heat pumps account for approximately 1% of the HFC emissions from refrigeration and air conditioning equipment.

Heat pumps need electricity, but the consumption is considerably smaller than in direct electricity heating. Ground source heat pumps have been estimated to achieve 60–70 % reduction and exhaust air heat pumps 25–30 % reduction in the energy consumption of a one-family house (Lukkari 2008). According to Oinonen and Soimakallio (2001) direct emissions from HFC refrigerants in heat pumps discredit less than 5% of the emission reductions acquired with the conserved energy.

Heat pumps are typically indirect vapour compression systems using refrigerants R-410A, R-407C and R-134a. Ammonia and hydrocarbons are used to some extent as well. The dominant refrigerant at the moment is R-410a, but it is expected to be replaced by CO_2 in the future (Information from the industry). EcoCute CO_2 heat pump water heaters were commercialized in Japan in 2001 and by 2007 there were twenty different CO_2 heat pump brands under the name available on the market (r744.com 2008). There are both residential and commercial water heating models available and new applications for air conditioning and cooling also (r744.com 2008).

Passive and low-energy building technologies have been developed for two decades mainly in Europe. The research has resulted in passive house designs that require around 80–90% less primary energy than current European houses and need supplementary heating or cooling energy only on the coldest and hottest days. These designs use extreme insulation of the building envelope, which prevents energy leakage. Solar gains through glazing and waste heat from appliances and residents bodies are utilized in the heating. Incoming fresh air can be warmed by leading it through a grid of underground pipes and a heat exchanger where the energy of exhaust air is recovered. Passive houses are spreading fast in Europe as the competence in passive house designs spreads. (Butler 2008.) The energy consumption of passive houses is so low, that the energy consumption of heat pumps becomes relevant and for example investments in ground heat pumps are not likely to be economically feasible anymore.

3.10.2 Key assumptions of the heat pumps emission scenarios

The sales of heat pumps have been growing rapidly and the growth is expected to continue at least the next ten years (Information from the industry; SULPU 2008b). The HFC emission scenarios for heat pumps are based on the number of heat pumps in use according to the statistics of The Finnish Heat Pump Association (SULPU) and their forecast for the year 2020.

The transition to HFC refrigerants in new equipment is estimated to have begun in 1994 (0%) and to have been completed by 1999 (100%). The annual equipment installation numbers from 2000 to 2007 are based on the statistics of SULPU. The annual average equipment installation growth rates for different heat pumps in 2008–2019 are estimated from the forecasted numbers of heat pumps in use in 2020 by SULPU. As an exception the growth rate of ground heat pumps is estimated to be slower than the SULPU estimate suggests. The annual growth rate of ground heat pumps is tuned down to 10%, because of the expanding passive and low-energy building. The highest annual growth of 33% is estimated for air-to-water heat pumps, which have just entered the Finnish markets. The growth rates by heat pump types are presented in Table 10, among other main assumptions for the scenarios. From 2020 onwards the number of new installations is assumed to grow normally, except for ground heat pumps and exhaust air heat pumps, for which the annual installation numbers are expected to stay constant.

Refrigerants R-134a and R-407C are expected to be replaced by R-410A in new heat pumps by 2010, when all of the initial refrigerant charge is calculated as R-410A. The proportion of natural refrigerants is taken into account from 2010 onwards and in the WM scenario it is estimated to grow to 10% by 2020. The WAM 1 and WAM 2 scenarios are calculated on the grounds of the main assumptions described above in Section 3.3.3. Based on literature and the questionnaire responses the average refrigerant charge for heat pumps is estimated to be 2 kg except for real estate heat pumps and district heat pumps. Real estate heat pumps are defined as heat pumps with capacity higher than 50 kW (Information from the industry) and the average charge is estimated as 15 kg. District heat pumps have capacity higher than 1 MW (Information from the industry) and the average charge is estimated to be 100 kg.

The emission factors of Oinonen and Soimakallio (2001) for one-family houses and apartment buildings are used for all air pump types. Because these emission factors for initial and annual emissions are low to begin with, they are not assumed to decrease in compliance with the main assumptions, but to stay constant for the whole period under observation. The end-of-life emission factor, on the other hand, is expected to decrease the 50% set in the main assumptions. The average lifetime for all heat pump types is estimated to be 15 years.

Table 10. Main parameters for the scenarios of heat pumps.

Heat pumps		
Average charge amount district heat pumps	100 kg	
Average charge amount real estate heat pumps	15 kg	
Average charge amount other heat pumps	2 kg	
Change of annual equipment installations	**2008–2020**	**2021–2050**
District heat pumps	+8.0% /year	+1.8% /year
Real estate heat pumps	+23.0% /year	+1.8% /year
Ground heat pumps	+10.0% /year	0.0% /year
Air-to-air heat pumps	+2.0% /year	+1.8% /year
Exhaust air heat pumps	+4.0% /year	0.0% /year
Ait-to-water heat pumps	+33.0% /year	+1.8% /year
Refrigerant proportions of initial charge amount 1999		
R-407A	33.3%	
R-134a	33.3%	
R-410A	33.3%	
Refrigerant proportions of initial charge amount 2010		
R-410A	100.0%	
Refrigerant proportions of initial charge amount 2020		
R-410A	90.0%	
R-744 (CO_2) or other natural refrigerant	10.0%	
Initial emission factor	0.006	
Annual emission factor	0.03	
End-of-life emission factor 2002	0.20	
End-of-life emission factor 2011	0.10	
Equipment lifetime	15 years	

3.10.3 WM and WAM emission scenarios for heat pumps

The HFC emission scenarios for heat pumps are represented in Figure 9. In the WM scenario emissions keep climbing with the annual growth of equipment installation numbers. From the level of 4.9 Gg CO_2 eq in 2006 the annual emissions increase to 110 Gg CO_2 eq by 2050. The visible changes in the emission trend in 2022 and 2035 are caused by changes of the annual retiring refrigerant charge amount and reflect the preceding changes in the annual growth of equipment installations. The WAM 1 scenario af HFC refrigerant ban reduces the emissions to zero by 2030. The WAM 2 scenario of GWP 150 refrigerant reaches its lowest point of 6.8 Gg CO_2 eq respectively in 2030, after which the emissions increase reaching 9.6 Gg CO_2 eq by 2050.

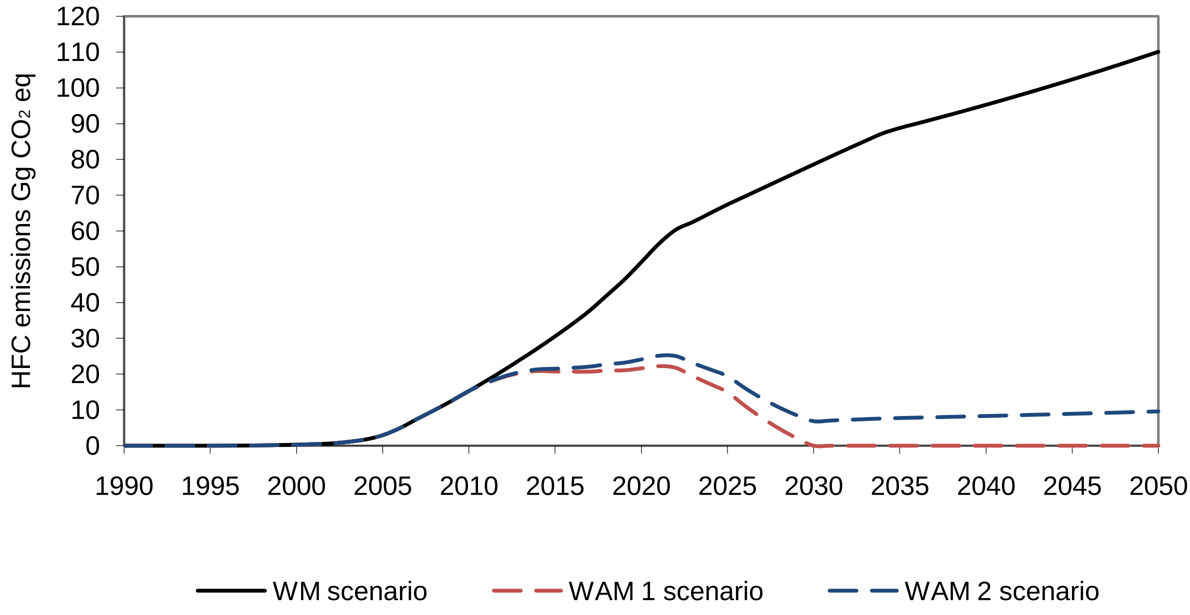

Figure 9. WM and WAM scenarios for HFC emissions from stationary air conditioning in Gg CO_2 eq.

3.11 Domestic refrigeration

3.11.1 Present state of the domestic refrigeration sector

Domestic refrigeration includes stand-alone refrigerators, freezers and coolers and their combinations typical in household use. Domestic refrigeration equipment are usually factory-sealed direct vapour compression systems (IPCC/TEAP 2005). The main HFC refrigerant in use is R-134a, but this has all but phased out in Finland (Information from the industry). The dominant refrigerant is isobutane (information from the industry), which can be used safely with the small charge amounts of most domestic refrigeration equipment. There are some wine cooler applications using absorption technology and ammonia mixture as a refrigerant on the markets as well (Lavento, 2007a). The HFC emissions from domestic refrigeration are almost negligible, about 0.2% of the total emissions from refrigeration and air conditioning equipment in Finland.

3.11.2 Key assumptions of the domestic refrigeration emission scenarios

The HFC emission scenarios of domestic refrigeration are calculated based on the annual sales of domestic refrigeration units. The unit sales figures for recent years were received from The Association of Electronics Wholesalers. The sales figures prior to 1999 are from Oinonen and Soimakallio (2001), originally compiled from The Association of Electronics Wholesalers and Home Electronics Association (Kodintekniikkaliitto ry) by Oinonen in 2000. These figures do not include wine coolers, but the wine cooler sales is assumed to be small compared to the other domestic refrigeration applications and the emissions to be within the limits of other uncertainties in the scenario. From 2007 to 2020 the unit sales is expected to grow annually the normal 2%, which is also the forecast of The Association of Electronics Wholesalers. From 2021 to 2050 the annual growth is estimated to be 1.8%.

The main parameters for the HFC emission scenarios of domestic refrigeration are presented in Table 11. The refrigerant charges of domestic refrigeration equipment range from about 60 g to 160 g (Information from the industry) and the average charge is estimated to be 100 g. In accordance with the information from the industry the average equipment lifetime is estimated as 10 years.

According to Oinonen and Soimakallio (2001) the import and production of R-134a units begun in 1993, while the proportion of R-134a was 40% of the total refrigerant charge of new domestic refrigeration equipment. Based on Oinonen and Soimakallio (2001) the R-134a proportion is expected to have stayed constant until 1999. The further transition to R-600a is expected to have started from 2000 and is calculated linearly between 2000 and 2010. Without additional measures R-134a is estimated to maintain a 5% share of the annual initial refrigerant charge from 2010 onwards. The WAM 1 and WAM 2 scenarios are calculated based on the main assumptions described above in Section 3.3.3, even though the WAM 2 scenario is not likely for domestic refrigeration, because of the current dominance of R-600a applications.

The refrigerant charges of domestic applications are usually handled only in the manufacturing and end-of-life states and as an exception from the main assumptions the annual emission factor is assumed to change by the equipment sales year. There are only a few companies manufacturing domestic refrigeration applications in Finland (F-gas inventory) and the bulk of the sold units are imported. Therefore the emissions from manufacturing in Finland are estimated to be negligible and are not taken into account in the scenario calculations. The end-of-life emission factor is expected to decrease more than the 50% stated as main assumption, because of substantial improvements in the refrigerant recovery assumed due to the Waste Electrical and Electronic Equipment (WEEE) Directive (2002/96/EC). The change from 20% to 3% end-of-life emissions is calculated linearly between years 2002 and 2011 in line with the main assumptions.

Table 11. Main parameters for the scenarios of domestic refrigeration.

Domestic refrigeration	
Average charge per unit	0.1 kg
Change of annual equipment sales 2007–2020	+2.0% /year
Change of annual equipment sales 2021–2050	+1.8 % /year
Refrigerant proportions of initial charge amount 1999	
R-134a	40.0%
R-600a (isobutane)	60.0%
Refrigerant proportions of initial charge amount 2010	
R-134a	5.0%
R-600a (isobutane)	95.0%
Annual emission factor for equipment sold in 1999 and before	0.01
Annual emission factor for equipment sold in 2002 and after	0.003
End-of-life emission factor 2002	0.2
End-of-life emission factor 2011	0.03
Equipment lifetime	10 years

3.11.3 WM and WAM emission scenarios for domestic refrigeration

The HFC emission scenarios for domestic refrigeration are represented in Figure 10. The sharp upturn of emissions in 2003 is caused by the beginning of end-of-life emissions. After this the decreasing emission factors and the further transition to refrigerant R-600a turn the emission trend downwards. The lowest point of the WM scenario is reached in 2020, after which the emissions start rising slowly with the growth of unit sales. The WAM 1 scenario of HFC refrigerant ban decreases the emissions to zero by 2025 and the WAM 2 scenario of GWP 150 refrigerant close to zero respectively. The emissions from domestic refrigeration are low throughout the scenarios, even the highest peak being only 2.7 Gg CO_2 eq.

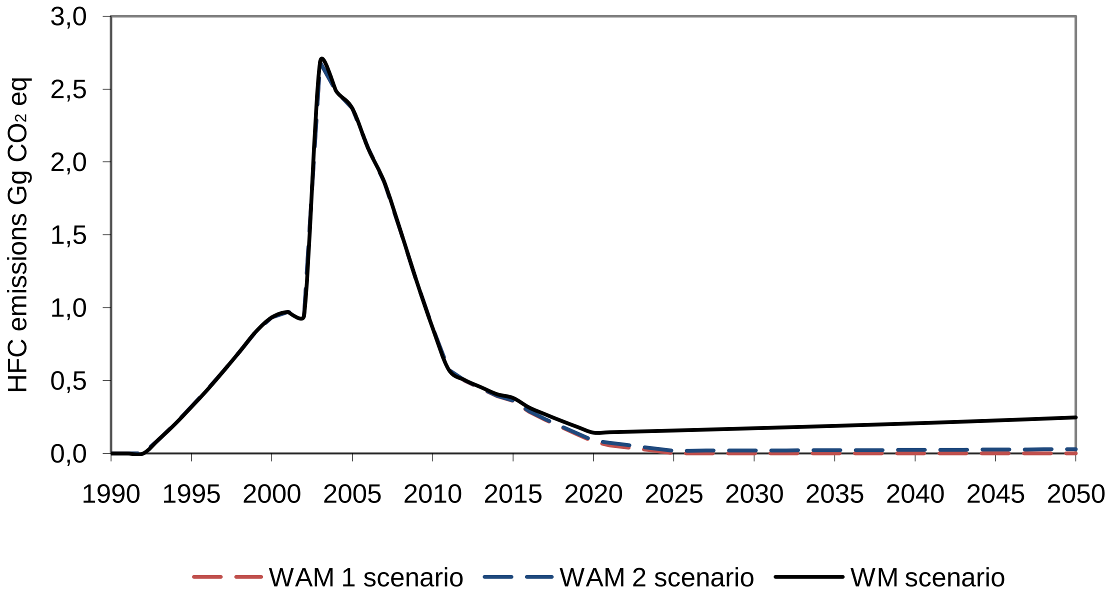

Figure 10. WM and WAM scenarios for HFC emissions from domestic refrigeration in Gg CO_2 eq.

3.12 Ice rinks

3.12.1 Present state of the ice rinks sector

Ice stadiums have one or more indoor ice-skating rinks maintained by refrigeration equipment. In addition, there are artificial outdoor ice rinks in winter use, which also require refrigeration equipment. The refrigeration equipment of ice rinks are typically indirect vapour compression systems. The dominant refrigerant is ammonia, but HFC refrigerant R-404A is used as well (Information from the industry). Ice rinks account for approximately 5% of the total HFC emissions from refrigeration and air conditioning equipment in Finland.

The energy consumption of refrigeration equipment is a main factor in the overall energy efficiency of ice stadiums. The energy efficiency of ice stadiums can be improved in the planning processes of new stadiums or renovations. Best ways for energy conservation are retooling of refrigeration equipment techniques, improved recovery of condensing heat, advanced control and monitoring techniques, improvement of ventilation and moisture control and development of the thermo technical quality of the buildings shell construct. The investments in energy efficiency of ice stadiums usually refund themselves in a few years. (The Finnish Ice Hockey Association 2004.)

The indirect ice rink refrigeration systems in use can provide the requisite capacity with even less than 50 kg refrigerant charges, while the old direct systems used to require about 2 000 kg of ammonia or R-22 (Lavento 2007b). Carbon dioxide is also seen as a potential refrigerant for ice rink refrigeration systems in Finland (The Finnish Ice Hockey Association 2004) and CO_2 ice rink refrigeration applications are already in use in the other European countries (Lavento 2009).

In 2007 there were 210 ice stadiums with 230 ice rinks in use in Finland and an additional three ice stadiums under construction (The Finnish Ice Hockey Association 2008). In the 90's ice stadiums were build at the rate of approximately ten stadiums a year, after which the construction pace has evened out (The Finnish Ice Hockey Association 2004). The Finnish Ice Hockey Association has the construction of 30 new ice rinks in new stadiums with two to three rinks each as their goal for the years 2007–2010 (Paavola 2006). If this goal is realized, the number of indoor ice rinks would be 260. The number of artificial outdoor ice rinks has been decreasing from 63 in 1999 (Oinonen and Soimakallio 2001) to 38 in 2003 (The Finnish Ice Hockey Association 2004).

Most of the ice stadiums have been constructed between 1980–2000 and there are extensive renovations expected for the buildings and the refrigeration systems (Paavola 2006). The problem with the stadiums built in the 70's and the 80's is ventilation and moisture control. The original R-22 and NH_3 systems will need to be renovated, the R-22 systems mostly by 2010. Even the more recent stadiums are going to need renovating to improve energy efficiency. At latest the refrigeration equipment of an ice rink has to be renovated when it reaches the age of 25 years. (Lavento 2007.) The construction years and renovation years of indoor ice rinks by Paavola (2006) are presented in Table 12.

Table 12. Indoor ice rinks by the time of construction and the times of renovation (Paavola 2006).

Time of construction	Quantity	Structure renovation	Equipment renovation
1965–1969	2	2005	1985
1970–1974	9	2010	1990
1975–1979	10	2015	1995
1980–1984	20	2020	2000
1985–1989	24	2025	2005
1990–1994	44	2030	2010
1995–2000	84	2035	2015
2001–2005	37	2040	2020

3.12.2 Key assumptions of the ice rinks emission scenarios

The emission scenarios for ice rinks are based on the construction quantities of new indoor ice rinks in Table 12. The yearly construction quantities are estimated to change linearly between the five to six year intervals. The total number of indoor ice rinks is expected to increase to 260 by 2010 and to stay constant after that. The old ice rinks are assumed to be renovated at the end of refrigeration equipment lifetime. The average equipment lifetime is set at 20 years, expect for the ice rinks constructed between 1990–1994, which are assumed to have a lifetime of 16 years. The 16 year lifetime was set because of the 2010 deadline for the use of virgin R-

22, even though the use of recycled R-22 in service work is allowed to the end of 2014. The HFC refrigerant use in ice rinks is estimated to have started from 1993 and increased linearly during 1993–1999. The main parameters for the HFC emission scenarios of ice rinks are presented in Table 13.

In 1999 70% of the yearly refrigerant charge of constructed and renovated ice rinks is expected to have been R-404A and the remaining 30% ammonia. This proportion is estimated to change to 80% ammonia or other natural refrigerants and 20% R-404A by 2010. The questionnaire responses from the refrigeration industry indicate that 70–75% of the initial refrigerant charge of ice rinks was natural refrigerants in 2008. The average refrigerant charge in new systems is estimated have reduced from 140 kg in 1999 to 50 kg in 2007 and to stay constant thereafter. The WAM 1 and WAM 2 scenarios are calculated based on the main assumptions described above in Section 3.3.3.

The number of artificial outdoor ice rinks is not separately taken into account in the scenario calculations. Outdoor ice rinks are in use only seasonally for about four months, if the outdoor temperature is low enough. The refrigeration equipment is expected to be lower in capacity and have smaller charges than the systems in indoor ice stadiums. On the other hand there is uncertainty in the charge amounts of indoor ice rinks as well, particularly if the refrigeration of several ice rinks in a stadium can be managed more efficiently with one centralized refrigeration system.

Table 13. Main parameters for the scenarios of ice rinks.

Ice rinks	
Indoor ice rinks in use 2010	260
Average charge per system 1999	140 kg
Average charge per system 2007	50 kg
Refrigerant proportions of initial charge amount 1999	
R-404A	70.0%
R-717 (NH_3)	30.0%
Refrigerant proportions of initial charge amount 2010	
R-404A	20.0%
R-717 (NH_3) or other natural refrigerant	80.0%
Emission factors 2002	
Initial emission factor	0.02
Annual emission factor	0.15
End-of-life emission factor	0.15
Emission factors 2011	
Initial emission factor	0.01
Annual emission factor	0.075
End-of-life emission factor	0.075
Equipment lifetime 1989 and before	20 years
Equipment lifetime 1990–1994	16 years
Equipment lifetime 1995 and after	20 years

3.12.3 WM and WAM emission scenarios for ice rinks

The HFC emission scenarios for ice rinks are represented in Figure 11. After the peak of 4.2 Gg CO_2 eq in 2003 the emissions decrease, because of the reducing emission factors due to the EC F-gases Regulation and the further substitution of R-404A with natural refrigerants, mainly ammonia. In 2010 the trend turns to a slight rise caused by the continuing increase of R-404A banked in equipment. The emission trend turns down again after 2014, when the retiring amounts of R-404A start diminishing the refrigerant bank in use. The WM scenario emissions even out around 2030, but keep fluctuating slightly, because of the changes in the number of yearly ice rink renovations. The WM scenario emission for 2050 are 0.80 Gg CO_2, while the WAM 1 scenario of HFC refrigerant ban reduces the emission to zero by 2035 and the WAM 2 scenario of GWP 150 refrigerant to about 0.041 Gg CO_2 eq by 2035.

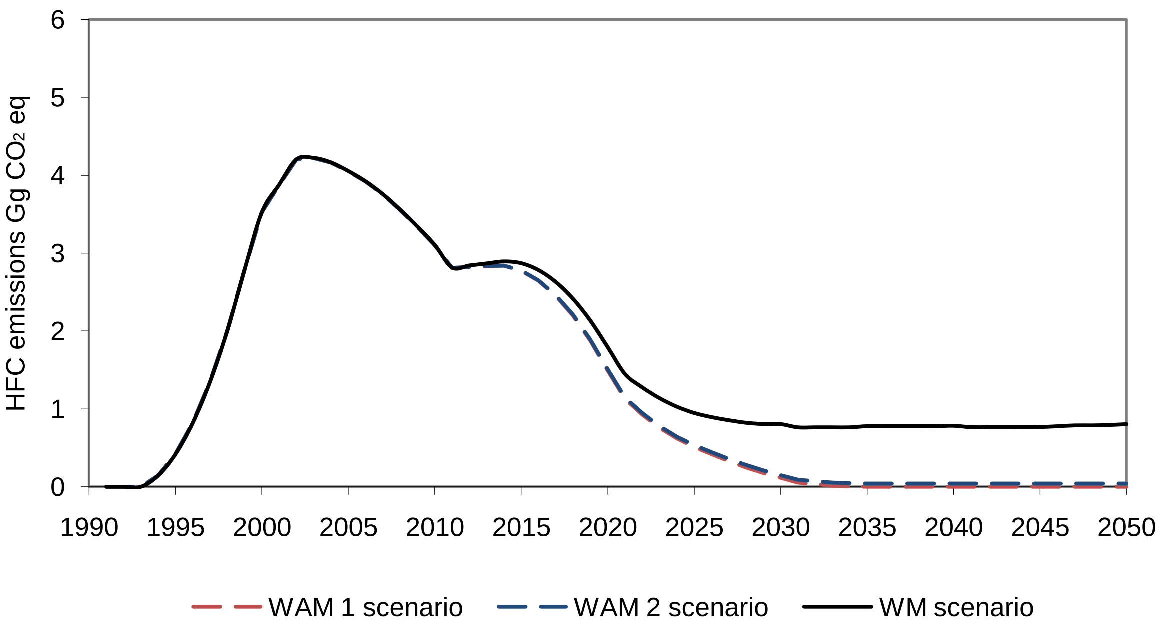

Figure 11. WM and WAM scenarios for HFC emissions from ice rinks in Gg CO_2 eq.

3.13 Total HFC emission projections for refrigeration and air conditioning equipment

3.13.1 Composition of the WM emission projection for refrigeration and air conditioning equipment

The total HFC emission projections for refrigeration and air conditioning equipment are sums of the subsector scenarios described in detail in the previous sections. The total WM scenario for refrigeration and air conditioning equipment and the subsector scenarios it is composed of are presented in Figure 12.

In the WM scenario HFC emissions mount up from 1993 as the substitution of ODS refrigerants advances. The turning point is reached in 2006 and from then on the emissions start decreasing mainly due to the EC F-gases Regulation. The assumed emission reducing factors are the decrease of emission factors as a result of improved containment, end-of-life recovery and refrigerant handling practices as well as the increased use of natural refrigerants. In addition, emissions are reduced by the decrease of average refrigerant charges per unit, because of the transition from direct to indirect systems, especially in the commercial refrigeration sectors. The EC MAC Directive is estimated to affect the emissions during a longer period of time, while the required transition to lower GWP refrigerants takes place.

Supermarket refrigeration systems is by far the largest emission source subsector and the ongoing transition to indirect compression systems, that reduces the annual initial refrigerant charge amounts in the sector, has a substantial impact on the total WM projection of refrigeration and air conditioning equipment. The other main subsector is clearly mobile air conditioning, which has a strongly decreasing WM scenario as well. On the other hand there is considerable growth in the emissions of the heat pumps subsector and the emissions from stationary air conditioning and transport refrigeration are also expected to be growing. The increasing emissions from these subsectors overturn the total WM projection emission trend to a moderate growth from 2025 onwards.

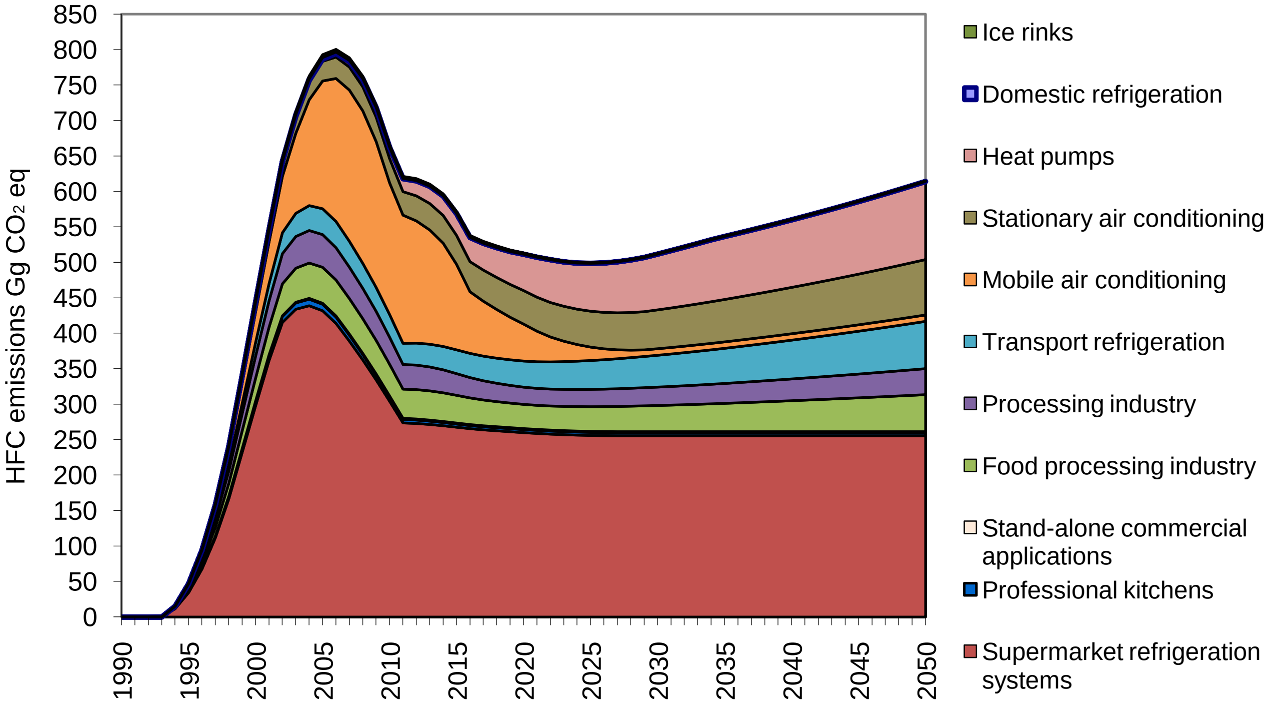

Figure 12. Total WM projection for HFC emissions from refrigeration and air conditioning equipment in Gg CO_2 eq by subsector scenarios.

3.13.2 Total WM and WAM emission projections for refrigeration and air conditioning equipment

The total WM and WAM HFC emission projections for refrigeration and air conditioning equipment are presented in Figure 13. The projected emissions are compared with the reported actual HFC emissions from refrigeration and air conditioning equipment of the national F-gas inventories. The projection follows the highest points of the annual F-gas inventory emission estimates leaving the yearly fluctuation of emissions out of account. The highest point of the calculated scenario is 801 Gg CO_2 eq in 2006, the highest F-gas inventory estimate so far being 819 Gg CO_2 eq in 2007, while the F-gas inventory estimate for 2006 is only 659 Gg CO_2 eq. The lowest point of the WM projection is reached in 2025 with emissions of 500 Gg CO_2 eq, which is roughly in the level of 2001. From 2025 onwards the WM projection emissions increase slowly, reaching 615 Gg CO_2 eq by 2050. The total WAM 1 projection of HFC refrigerant ban reduces the emissions to zero by 2035. The total WAM 2 projection of GWP 150 refrigerant, which as an exception includes the WM scenario of MACs, reaches its lowest point of 39 Gg CO_2 eq by 2030 and increases to 46 Gg CO_2 eq by 2050.

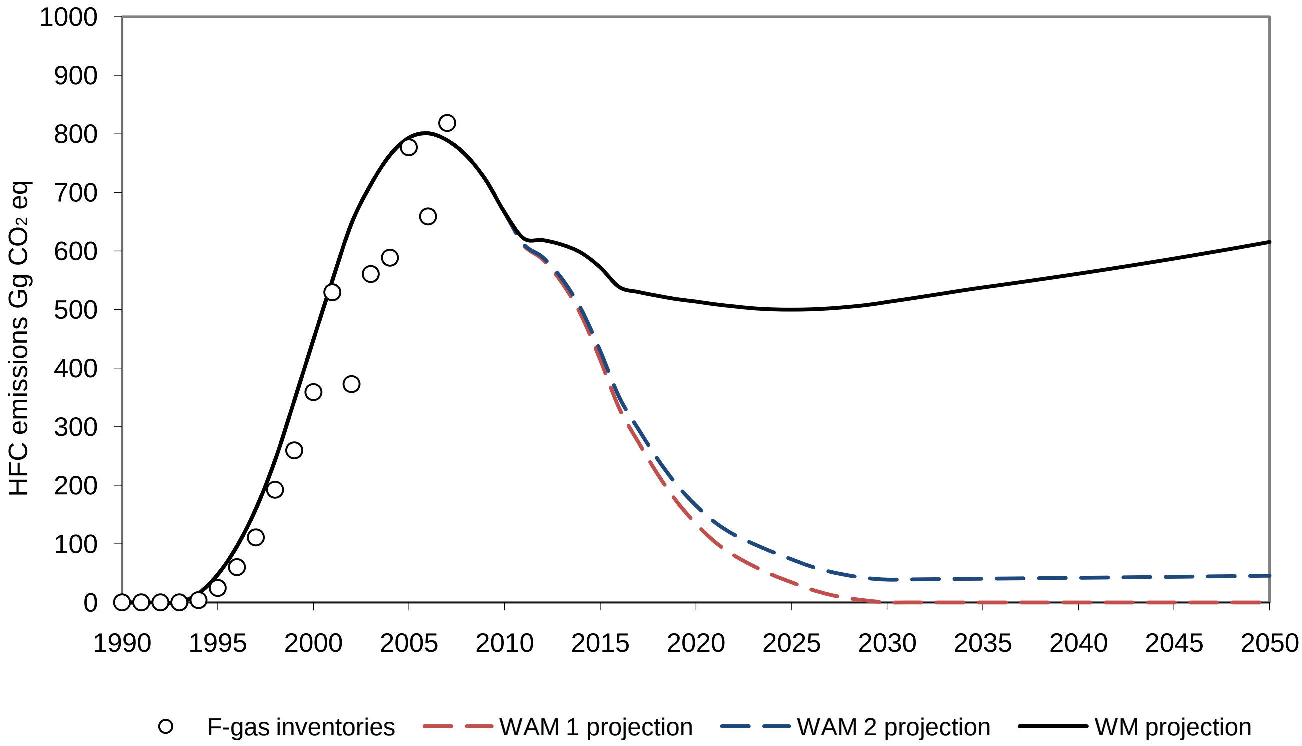

Figure 13. Total WM and WAM projections for HFC emissions from refrigeration and air conditioning equipment in Gg CO_2 eq with the reported actual emission estimates of F-gas inventories.

The projected HFC emission reductions for refrigeration and air conditioning equipment are compiled in Table 14. The two WAM projections are compared with the WM projection of the years 2010, 2015, 2020 and 2050 as well as the reported emissions of 2006 (F-gas inventory 2006). The achieved emission reductions are given in Gg CO_2 eq and in addition as the percentage change from the WM projection.

Table 14. Projected HFC emission reductions for refrigeration and air conditioning equipment.

Year	WM projection Gg CO_2 eq	WAM 1 projection Gg CO_2 eq	Emission reduction from WM Gg CO_2 eq	Diff. from WM %	WAM 2 projection Gg CO_2 eq	Emission reduction from WM Gg CO_2 eq	Diff. from WM %
2006	659	659			659		
2010	666	666			666		
2015	572	415	157	28	430	142	25
2020	514	135	379	74	166	348	68
2050	615	0	615	100	46	569	93

4 Foam blowing and foam products

4.1 Emissions, current technology and abatement options for foams

4.1.1 Present state of foam blowing agents and manufacturing of foam applications

Foamed cellular polymers are used in a wide variety of applications. Cellular polymers have either rigid or flexible structure. Flexible or open-celled polyurethane (PU) is used for example in mattresses and cushioning and rigid closed-cell polyurethane in insulation of buildings, pipes and refrigeration appliances (Järvinen 2008). Integral PU foams have a cellular core structure with a non cellular skin structure (Järvinen 2008). Extruded polystyrene (XPS) and expanded polystyrene (EPS), also known as Styrofoam, are mainly used in insulation, EPS as a packaging material as well (Järvinen 2008). One-component polyurethane foam cans (OCF) are aerosol like products used in seam insulation. OCF products have been included in the aerosols subcategory in the Finnish F-gas inventory and are therefore discussed further with aerosols in Chapter 5.

The dominant blowing agents in Finland are HCs, mainly pentane, and CO_2/water, but HFC blowing agents HFC-134a, HFC-245fa and HFC-365mfc are also used. EPS is expanded with pentane (Järvinen 2008) and CO_2 is used in the expanding of XPS in Finland (F-gas inventory 2007, Oinonen and Soimakallio 2001). Most of the PU manufacturers also use pentane as the blowing agent. There are less than ten Finnish companies still reporting usage of HFC blowing agents in the manufacturing of PU products (F-gas inventory 2007 and 2008). The HFC emissions from foam blowing and foam products account for less than 1% of the total F-gas emissions in Finland (F-gas inventory 2007). The usage of new blowing agents HFC-245fa and HFC-365mfc has started in the recent years and the information from the foam blowing industry indicates that the remaining use of HFC-134a could be at least partially replaced by them in the future.

In Finland HFC blowing agents are mainly used in the manufacturing of rigid closed-cell polyurethane products. Rigid PU is used in the insulation of domestic refrigeration equipment and other appliances, in pipe insulation, block foam and sandwich elements (F-gas inventories 2007 and 2008). Sandwich elements are rigid PU panels with rigid, often metal, facings (Bing 2006). Block foam can be cut to form insulation boards or sections for different uses and appropriate facings can also be applied to them (Bing 2006). In addition, HFC blowing agents are used in the expanding of sprayed rigid PU, integral skin foams and small amounts of HFC-365mfc in the expanding of moulded flexible PU products as well (F-gas inventories 2007 and 2008).

The two base components of PU are isosyanate and polyol, both derivatives of petroleum (Harvey 2007). The base materials are in liquid form and react directly on mixing building a polymer matrix. The reaction releases heat, which causes the evaporation of the blowing agent and foams the polymer matrix. The volume of expanding and density of the foam can be managed by the quantity of added blowing agent. In addition, the material formulations of the foam are modified with various additives and catalysts can be utilized in tuning the foaming process. The surface of the foam structure retains its adhesive capacity for a time after the foaming process enabling the attachment of permanent facings. (BING 2006.)

4.1.2 Emission sources and abatement options for foams

Emissions of blowing agent occur in all stages of the product life cycle. The leakage rates differ between applications and blowing agents. From open-celled foams nearly all of the blowing agent is released in manufacturing, whereas the blowing agent of closed-cell foams is mostly banked in the foam structure and diffunds from them slowly during the decades of product usage (Oinonen and Soimakallio 2001). The end-of-life emissions depend on the method of disposal. Bacterial degradation of the blowing agent in landfills is thought to be negligible and essentially all of the remaining blowing agent will eventually be emitted to the atmosphere (Harvey 2007), if the foam product ends up in a landfill. In Finland PU foam insulation is often re-used as frost insulation (Information from the industry), where from the leakage of the blowing agent can be expected to continue. If the foam product is incinerated essentially the entire remaining blowing agent can be destroyed (Harvey 2007). It is also possible to shred foam products and collect the remaining blowing agent at least partially (Information from the industry). However, the separation of the foam from the end product can be difficult. For example the proportion of foam insulation of the demolition waste of a building is small and its separation would be laborious (Information from the industry). Some of the remaining blowing agent will be released in the demolition process anyway (Harvey 2007).

Optimal insulation can improve energy efficiency and thus result in considerable GHG emission reductions. The thermal resistance of insulation varies with the thermal conductivity of the material and the thickness of insulation (Harvey 2007). The insulation properties of rigid PU foam are achieved with the low thermal conductivity of the blowing agent that remains in the closed cells of the foam structure (BING 2006). Halocarbon expanded PU insulation tends to have lower thermal conductivity than the non-halocarbon expanded foams or most non-foam insulation. Even though the blowing agent leaks and is replaced by air over time, the halocarbon expanded foam insulation provides greater long term resistance of heat loss for a given thickness than the other alternatives. Thickness of insulation also affects the loss rate of the blowing agent, thicker panels experiencing a smaller relative loss. (Harvey 2007.)

However, according to Harvey (2007) a tradeoff exists between the savings in heating energy related emissions gained with insulation and the emissions of blowing agent from the insulation and the embodied energy of the insulation. The embodied energy of insulation is the energy consumed in its manufacturing, which also increases in proportion to the thickness of insulation. In a climate of moderately cold winters like Toronto and Zurich the climatic impact of foam insulation was found to depend mainly on the initial blowing agent loading and the leakage rates, differences in thermal conductivity being of minor importance. Even with relatively large differences in thermal conductivity the additional savings in heating energy gained by halocarbon blowing agents can be overridden by the larger impact of the blowing agent leakage. Thus from a climate point of view non-halocarbon, pentane or CO_2, expanded foam insulation would be better than the halocarbon expanded insulation. However, the other insulation materials like cellulose, fiberglass and rock wool have significantly lower embodied energies than foam insulations and would be preferable when possible, in the light of Harvey's study. (Harvey 2007.) In the cooler climate of Finland the indoor heating requiring season is considerably longer and the significance of heating energy reductions of insulation can be expected to be greater than in Harvey's calculations, though.

New low GWP hydrofluoroolefin (HFO) blowing agents are under development (Honeywell 2009c, Arkema 2009). A new blowing agent developed by Honeywell is a non-flammable liquid, which is expected to offer performance benefits comparable to those of other fluorocarbons. It has a GWP of less than 15 and an atmospheric lifetime of only a few days. It is expected to provide the high insulation performance, dimensional stability and compressive strength needed in PU foams. The new blowing agent is going to be an alternative for hydrocarbons and the other HFCs. Limited sample quantities of the product are expected to be available for customers by the end of 2009. Honeywell has recently commercialized a gaseous blowing agent for OCFs and aerosol propellant, HFO-1234ze, in Europe and announced the new refrigerant HFO-1234yf for MACs. (Honeywell 2009c.)

4.2 Emission abatement costs for foams

4.2.1 Emission abatement costs of blowing agent substitution

HFC blowing agents are expensive and pentane or CO_2/water based foam blowing is cost effective with large production volumes. This is why pentane and CO_2/water have gained widespread use in Finland and Europe. However, the substitution of halocarbon blowing agents with pentane in PU production sites requires significant re-engineering, because of pentanes flammability. The use of CO_2 is also technically challenging and modification of product lines is necessary. The substantial costs of these investments can prohibit the change of blowing agent in small and medium sized companies. The relevant factor is the volume of production, which determines the magnitude of the cost reductions gained by cheaper blowing agent and the payback time of the investment. (Information from the industry 2009, Harvey 2007.)

Emission abatement costs for substitution of HFCs with a non specified natural blowing agent are estimated based on one questionnaire response from the foam blowing industry. The respondent gave an estimation of investment costs for changes required to substitute 1 000 kg a year of HFC-245fa consumption in foam blowing with an investment lifetime of 10 years. The HFC emission reduction gained by the investment was estimated assuming that all of the used blowing agent will eventually leak out to the atmosphere. In the calculation the emission reduction gained in a given year was assumed to be equal to the amount of blowing agent, that would have been consumed in manufacturing in the given year without the investment. The estimated emission abatement costs for substitution of HFCs with natural blowing agents range between 99–120 €/t CO_2 eq. However, this estimate does not take into account the price of the blowing agent, changes in energy efficiency or other maintenance costs. If the savings gained with cheaper blowing agent would be taken into consideration the estimated abatement cost would decrease.

The assumed timing of emission reductions in the previous cost estimate is true for the open-celled foams, from which the blowing agent is released immediately. On the other hand, the emissions from closed-cell foams occur, for the most part, during the product lifetime. The product lifetime of sandwich elements, for example, is as long as the buildings they are used in and often stated to be 50 years (see IPCC 2006, IPCC 2000). Thus the emission reduction effect of the investment will often greatly exceed the investment lifetime. If only the emissions, which would have been realized during the investment lifetime, are approved as the yearly emission reductions of the investment, the abatement costs of closed-cell foams are substantially higher. For the reduction of these yearly emissions in the ten year investment lifetime, the abatement costs for sandwich elements, would be in the range of 793–969 €/t CO_2 eq, while the assumptions of the previous estimation are not altered otherwise.

The commercialization of new HFO blowing agents can provide a more cost effective way to emission abatement in the remaining field still using HFC blowing agents, assuming they do not require significant modifications of the foam blowing process. Modest emission reductions in manufacturing can also be achieved by changing from HFC-134a to lower GWP blowing agents HFC-245fa and HFC-365mfc, where possible.

4.2.2 Emission abatement costs of other abatement options

The manufacturing processes are expected to be efficient in the use of HFC blowing agents, because the gas is intended to stay in the foam products and additional leakage is expensive. However, there are possibilities in the abatement of end-of-life emissions of foam products. In IPCC/TEAP (2005) the end-of-life treatment of appliances is estimated to cost 10–50 US$/t CO_2 eq with blowing agent recovery level of 80% of the original blowing agent load and to be in the same range for buildings, but with only a 20% recovery expectation. Converted to 2009 Euros the costs would be 8–41 €/t CO_2. On the other hand, in Finland the present practice of re-using the foam insulation from buildings as frost insulation, thus lengthening the lifetime almost infinitely, can be expected to be preferable from the GHG emission abatement point of view.

4.3 Emission projections for foam blowing and foam products

4.3.1 Key assumptions for the emission projections of foams

The HFC emission projections for foam blowing and foam products are based on the activity data of F-gas inventories. The data consists of the yearly amounts of HFCs used in the manufacturing of foam products, imported in foam products and exported in foam products. There was no indication of growth of the HFC blowing agent consumption in the information from the Finnish foam blowing industry. Thus, with no additional measures, the consumption in manufacturing as well as the import and export in products are expected to stay constant from 2007 onwards. The main assumptions of the emission projections are presented in table 15.

Only HFC-134a emissions have been calculated in the F-gas inventories (NIR 2009). Emissions of the new blowing agents HFC-245fa and HFC-365mfc have been considered to be negligible, on the grounds of the small amounts imported and used in manufacturing (NIR 2009). However, in 2007 the amount of R-134a consumption decreased considerably and the consumed proportions of HFC-245fa and HFC-365mfc actually exceeded the proportion of HFC-134a. Thus, emissions of HFC-245fa and HFC-365mfc are included in the projections from 2007 onwards. The proportions of the different blowing agents are expected to stay at the level of 2007, even though it is possible that at least some of the remaining HFC-134a consumption will be replaced by the other blowing agents. However, the effect of this transition on the emission scenarios would be very small and is covered by the other uncertainties in the assumptions, like the probable year-to-year fluctuation of manufacturing volumes.

The emission factors for foam blowing, which are also used in the F-gas Inventory, are from IPCC Good Practice Guidance 2000 (p. 3.96). The first year loss is expected to include HFC leakage from manufacturing and leakage from the blowing agent banked in the foam product during the first year. After that, the emissions of the banked HFC blowing agent are defined by the annual loss factors. The EC F-gases Regulation (842/2006/EC) is not expected to affect the emission factors of foam blowing and foam products. The end-of-life emissions are not specified, because the foam products are expected to be either re-used as frost insulation or placed in a landfill and the emissions to continue at the same annual emission rate until the entire blowing agent has leaked out. With this assumption the average lifetimes of different foam products are not needed in the projections.

In addition to the WM projection two WAM projections are made. The WAM projections have similar assumptions as the ones established for refrigeration and air conditioning equipment. In the WAM 1 projection the use of HFC blowing agents is expected to be forbidden from the beginning of year 2015 as a result of the re-evaluation of the EC F-gases Regulation. In the WAM 2 projection a similar restriction is expected to apply to HFC blowing agents with GWP over 150. In both WAM projections the effects of the restrictions are calculated linearly between years 2011–2015, because the foam blowing industry is expected to start reacting to the assumed changes of regulation in their preparatory state. The WAM 2 projection is calculated as a maximum emission scenario for the assumption, with an imaginary HFC blowing agent of GWP 150 and emission factors of HFC-134a.

Table 15. Main parameters for the emission projections of foams.

Foam blowing		
Change of consumed blowing agent amount 2008–2050	0% /year	
Emission factors HFC-134a applications	First year loss	Annual loss
XPS	0,40	0,03
Integral skin	0,95	0,025
Injected	0,125	0,005
Appliance	0,075	0,005
Sandwich	0,125	0,005
Emission factors HFC-245fa and HFC-365mfc applications	First year loss	Annual loss
Injected	0,100	0,005
Appliance	0,040	0,0025
Sandwich	0,100	0,005
Continuous panel	0,075	0,005

4.3.2 WM and WAM emission projections for foams

The WM and WAM HFC emission projections for foams are presented in Figure 14 together with the reported actual emissions of F-gas inventories. The calculation model gives slightly lower emissions for the reported years than the model used in the inventories. The noticeably larger difference in 2000 is caused by a calculation error in the inventory resulting in a high reported emission estimate. The year-to-year fluctuation of the emission estimates are due to changes in the volume of HFC blowing agents consumed in manufacturing as different companies have changed their production into and out of HFC usage (NIR 2009). In the WM projection the emissions decline slowly from 2007 onwards as the amount of gas banked in foam products decreases. From the peak of 59 Gg CO_2 eq in 2000 the emissions decrease to the level of 5.6 Gg CO_2 eq by 2050. In the WAM 1 and WAM 2 projections the downward trend is slightly stronger, since the emissions from manufacturing decrease substantially in the WAM 2 and end totally in the WAM 1 by 2015 due to the assumed restrictions of HFC blowing agent consumption. However, the HFC emissions from the blowing agent banked in the foam products continues and there is only a small difference in the emissions of the two WAM projections by 2050. The WAM 1 projection reduces the annual emissions to 3.2 Gg CO_2 eq and the WAM 2 projection to 3.6 Gg CO_2 eq by 2050.

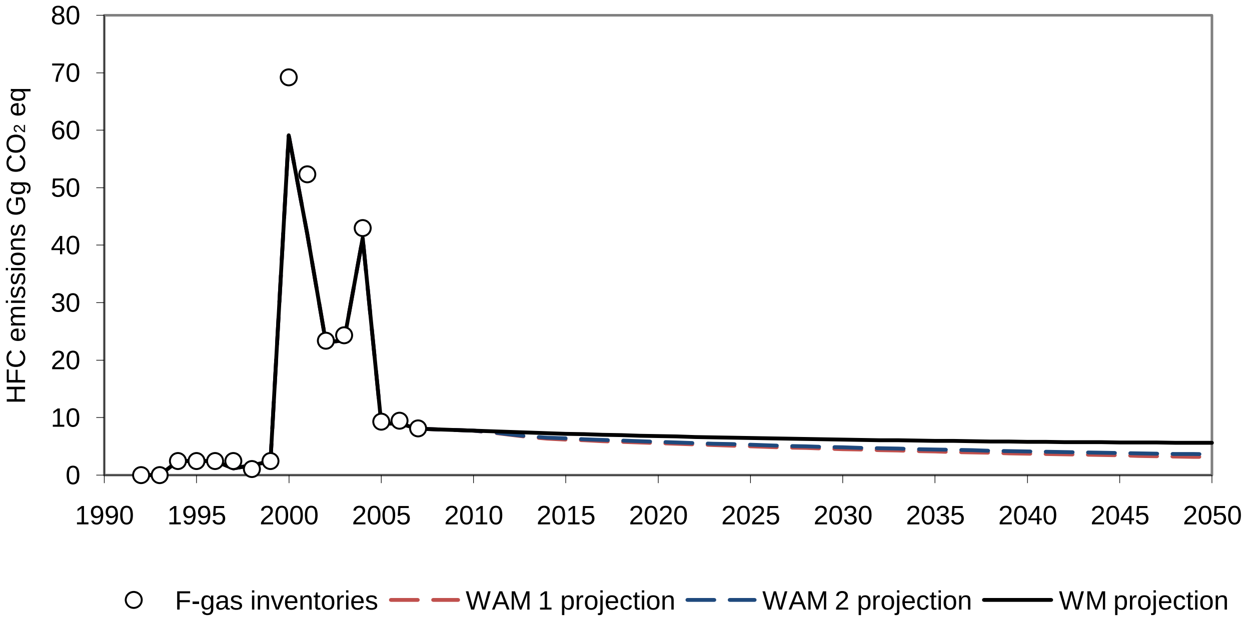

Figure 14. WM and WAM projections for HFC emissions from foam blowing and foam products in Gg CO_2 eq with the reported actual emission estimates of F-gas inventories.

The projected HFC emission reductions for foam blowing and foam products are assembled in Table 16. The two WAM projections are compared with the WM projection of the years 2010, 2015, 2020 and 2050 as well as the reported emissions of 2006 (F-gas inventory 2006). The achieved emission reductions are given in Gg CO_2 eq and in addition as the percentage change from the WM projection.

Table 16. Projected HFC emission reductions for foam blowing and foam products.

Year	WM projection Gg CO_2 eq	WAM 1 projection Gg CO_2 eq	Emission reduction from WM Gg CO_2 eq	Diff. from WM %	WAM 2 projection Gg CO_2 eq	Emission reduction from WM Gg CO_2 eq	Diff. from WM %
2006	9.5	9.5			9.5		
2010	7.7	7.7			7.7		
2015	7.2	6.2	1.0	14	6.4	0.80	11
2020	6.8	5.6	1.2	18	5.8	1.0	15
2050	5.6	3.2	2.5	45	3.6	2.0	36

5 Aerosols and one-component foams

5.1 Emissions, current technology and abatement options for aerosols and OCFs

5.1.1 Present state of aerosols and OCFs

The active ingredients of aerosol products are sprayed with the pressure of a propellant gas inducing a controlled droplet size and quantity. Medical aerosols are used in the treatment of asthma and chronic obstructive pulmonary disease (COPD). Technical aerosols are used for varying industrial and consumer needs, for example in cleaning, maintenance, testing and disinfecting appliances as well as in safety signal horns. In addition, there are cosmetic, convenience and novelty aerosol products like silly string and artificial snow. The active ingredients can be in liquid, paste or powder form and the common gas propellants are HFC-134a, HFC-152a, hydrocarbons, dimethylether, carbon dioxide and nitrogen. (IPCC/TEAP 2005.) One-component foam (OCF) cans are used in seam insulation. OCFs are open-celled polyurethane foams (IPCC 2006 GL), but as an aerosol like product OCF cans have been included in the aerosols subcategory in the Finnish F-gas inventory and in this report as well.

There are three possibilities in delivering inhaled respiratory drugs, pressurized metered dose inhalers (MDI), dry powder inhalers (DPI) and nebulisers, which are electrical devices for liquid droplet dispersal and inhalation (Mitchell and Nagel 2009). Metered dose inhalers are aerosols and based solely on the propellant HFC-134a in the Finnish market (F-gas inventories). There is no MDI production in Finland and all of the marketed products are imported (F-gas inventories). In Finland there has been a strong transition to the use of DPIs in the last twenty years. Now DPIs clearly dominate the market with about 70% share and the proportion of MDIs of the total sales of inhalated respiratory drugs is about 20%. Nebulisers are mainly used in hospitals and emergency situations. In recent years the market shares of different inhalers have stayed quite constant. The share of DPI use in Finland is high compared to the level of Europe and DPIs are not suitable for all patients. Especially the treatment of children and the elderly often requires MDIs or liquid inhalation. The advantages of MDIs are ease of use, time saving and price. (Information from the industry 2009.)

In Finland HFC propellant gas is used in technical aerosols only when it is critical for safety reasons, mainly flammability. HFC-134a is used in non flammable cold spray, air duster and precision cleaning products utilized in the maintenance of electronics, electrical- and automation equipment and IT equipment with high voltage or temperatures. When there is no risk of inflammation other cheaper aerosol alternatives are used. (Information from the industry 2009.) There are only a few companies manufacturing HFC-134a based aerosol products in Finland (F-gas inventory 2008).

The EC F-gases Regulation (842/2006/EC) banned HFCs from novelty aerosol products by a prohibition of placing on the market in 2009. The placing on the market of HFC containing OCFs, except when required to meet national safety standards, was also prohibited, in 2008. There is one Finnish OCF producer using HFC-134a and HFC-152a (F-gas inventories). The products are mainly exported outside of EU and only a small proportion of the manufactured HFC-152a based OCFs are still placed on the Finnish market (Information from the industry, F-gas inventory 2008).

5.1.2 Emission abatement options for aerosols and OCFs

The remaining HFC containing aerosol and OCF product consumption in Finland is considered critical on the grounds of safety and health factors. The usage is also limited by cost, because HFCs are five to eight times more expensive than hydrocarbons (IPCC/TEAP 2005). All of the propellant is emitted during aerosol usage and even though there might be some potential for efficiency improvements in the ratio of propellant for active ingredients, the main emission abatement option seems to be in transferring to new lower GWP propellants.

Honeywell launched its new hydrofluoroolefin aerosol propellant and blowing agent HFO-1234ze in the end of 2008. HFO-1234ze has a GWP of six and zero ozone depleting potential and it is not flammable. It can serve as a direct replacement of HFC-134a in some aerosol applications. (Honeywell 2008, Honeywell 2009d.) As a near drop-in solution the cost of substitution in technical aerosols and OCFs should not be overly high, even if the new propellant can be expected to be more expensive than the old ones, at least for a time after commercialization.

The criteria for a new propellant in medical aerosols, however, are strict and subject to extensive regulation. The potential reformulation of MDIs involves full clinical trials and the developing process is essentially the same as in the development of a new drug. (IPCC/TEAP 2005.)

5.2 Emission projection for aerosols and OCFs

5.2.1 Key assumptions for the emission projection of aerosols and OCFs

The HFC emission projection for aerosols and OCFs is based on the reported emissions of F-gas inventories and the activity data of 2007. The data consists of the imported and exported amounts of HFCs contained in aerosol products and HFCs used in aerosol or OCF production. The rates of increase or decrease of import and export of HFC-134a and HFC-152a are estimated separately for medical aerosols, technical aerosols and OCFs. The estimations are based on the information compiled from the industry agents by personal contacts. These main assumptions are round up in Table 17.

The amount of HFC-134a imported in medical aerosols is expected to grow annually 2% between the years 2008–2020 and 1.8% between 2021–2050. This growth is estimated to reflect the total growth of the sales of inhaled respiratory drugs and the share of MDIs to stay at its recent level. The production, import and export of technical aerosols are assumed to stay constant at the level of 2007.

The amount of HFC-152a used in OCF manufacturing is expected to decrease with an annual rate of 10% between 2008–2020 and stay constant from there on. The proportions of export and national consumption are expected to stay at the 2007 level. The placing of HFC-134a in OCF products on the Finnish market is assumed to have been a quarter of the 2007 amount in 2008 and cease completely afterwards.

WAM projections are not established for aerosols and OCFs, because the remaining use of HFC propellant and blowing agent in Finland is seen as critical for safety and health reasons. However, the recent commercialization of HFO-1234ze provides an additional emission abatement option for at least technical aerosols and OCFs.

Table 17. Main parameters for the projection of aerosols and OCFs.

Aerosols and OCFs	
Change of HFC-134a import in MDIs 2008–2020	+2.0% /year
Change of HFC-134a import in MDIs 2021–2050	+1.8% /year
Change of HFC-134a import for OCFs placed on the Finnish market	ceased in 2008
Change of HFC-152a import for OCFs 2008–2020	–10.0% /year
Change of HFC-152a import for OCFs 2021–2050	0.0% /year
Change of HFC-152a export in OFCs 2008–2050	0.0% /year
Change of HFC import in or for technical aerosols 2008–2050	0.0% /year
Change of HFC export in technical aerosols 2008–2050	0.0% /year
Emission factors	
First year loss	0.5
Second year loss	0.5

5.2.2 WM emission projection for aerosols and OCFs

The WM projection for HFC emissions from aerosols and OCFs is presented in figure 15. The reported F-gas inventory emission estimates are used until 2007. The emission trend increases sharply from the middle of the 1990's due to the substitution of ozone depleting substances. After 2007 the emissions decrease due to the restrictions of the EC F-gases Regulation. From 2020 onwards the expected growth of MDI sales turns the emission trend to slight a rise. The projected emissions reach 59 Gg CO_2 eq by 2050, while the peak of the realized emissions in 2006 is 77 Gg CO_2 eq. The projected emissions for the years 2010, 2015, 2020 and 2050 as well as the reported emissions of 2006 (F-gas inventory 2006) are displayed in Table 18.

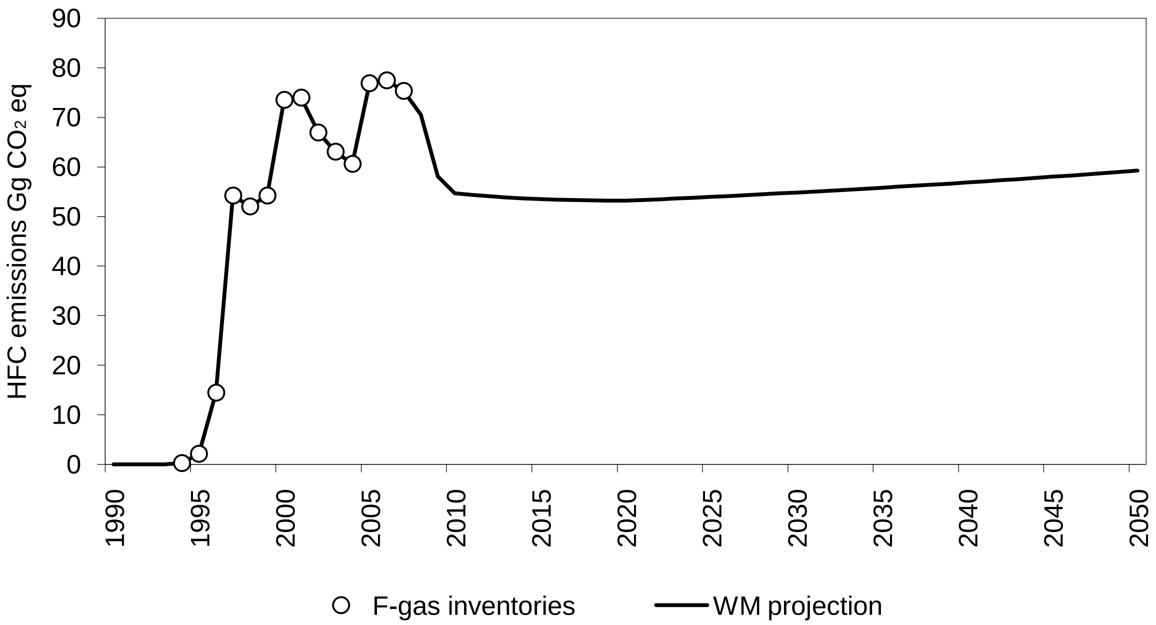

Figure 15. WM projection for HFC emissions from aerosols and OCFs in Gg CO_2 eq with the reported actual emission estimates of F-gas inventories.

Table 18. Projected HFC emissions for aerosols and OCFs.

	2006	2010	2015	2020	2050
WM projection Gg CO_2 eq	77	55	54	53	59

6 Electrical equipment

6.1 Emissions, current technology and abatement options for electrical equipment

6.1.1 Present state of electrical equipment

Electrical transmission and distribution networks consist of switchgear, transformers and overhead lines and cables. Switchgear connects and disconnects networks and protects the equipment from overloads and short circuit currents. Different voltage steps are needed in minimizing network losses and the voltage changes are employed by transformers. Sulphur hexafluoride is used for both switching and insulation in electrical equipment. (Wartmann and Harnisch 2005.)

In Finland SF_6 is banked in high and medium voltage gas insulated switchgear (GIS), circuit breakers and ring-main units (RMU). The first GIS application was installed in Helsinki in 1977 and the bulk of the banked SF_6 is in high voltage GIS equipment. (Finnish Energy Industries 2008.) Voluntary actions of the European electricity industry have reduced the emissions of SF_6 from electrical equipment significantly and resulted in a reduction of 40% between 1995 and 2005 (Wartmann and Harnisch 2005). Emissions of SF_6 from electrical equipment amount to less than 1% of the total F-gas emissions in Finland (F-gas inventory 2007).

The SF_6 electrical equipment can be divided to sealed pressure systems and closed pressure systems. Sealed pressure equipment are medium voltage gas insulated switchgear, circuit breakers and ring-main units. The equipment is sealed with a metal enclosure and maintenance inside the gas compartment is usually not required during the equipment lifetime of about 40 years. The amount of SF_6 contained in sealed pressure gas compartments is typically in the range of 0.25–10 kg. Closed pressure systems are high voltage equipment designed for maintenance work and gas handling when required. Gas handling requiring maintenance work is usually needed every 20 to 25 years and in addition replenishing the gas can be required several times during the equipment lifetime of 40 to 50 years. Detection and elimination of leaks requires continuous monitoring. The operation pressure of closed systems is high and the amount of gas in a compartment can vary between 2–200 kg. Closed pressure equipment is typically filled up to the operating pressure at the site of installation. (Wartmann and Harnisch 2005.)

The main advantages of SF_6 are good dielectric, thermal and arc quenching properties, inertness, non-flammability, non-toxicity and enabling compact applications. Air is also used for insulation, but requires a lot of space by itself. High voltage SF_6 insulated equipment can be constructed in 10–20% of the space required by air insulated equipment. Oil has good insulation properties, but its use is restricted to specific applications, like transformers, by flammability and the risk of environmental pollution. In addition, polymeric insulation materials have been used, but the applications required high maintenance efforts. In medium voltage equipment circuit-breaking can be employed by vacuum and it is widely used besides SF_6. In high voltage circuit breakers SF_6 is the state-of-the-art arc-quenching medium. The systematic search for a lower GWP alternative to SF_6 in electrical equipment is ongoing, but suitable alternatives have not yet been identified. (Wartmann and Harnisch 2005.)

6.1.2 *Emission abatement options for electrical equipment*

Emissions of SF_6 from electrical equipment occur during the manufacturing process and in the use-phase as design related leakage from the equipment, whenever the gas is handled during maintenance, filling, recovering or testing and from faulty equipment, failures and arc faults. The containment of SF_6 is essential to the functioning of the equipment and gas tightness is a basic requirement in the technology designs. The design related annual leakage from sealed pressure systems is less than 0.1% and usually below 0.5% from closed pressure systems. In the decommissioning phase SF_6 is recovered from the equipment and usually re-used directly or recycled for re-use, if the quality of recovered gas is not suitable for immediate re-use. (Wartmann and Harnisch 2005.)

The SF_6 charge amounts of closed pressure equipment have already decreased by about 80% and even originally compact sealed pressure equipment charges have been reduced by some 10%. The present equipment are close to their technical optimum and further improvements are unlikely. The reduced charge amounts decrease the growth of the gas bank and emissions from it while new equipment is installed. Other emission abatement options are related to improved gas handling practices, leakage detection, and control and monitoring of emissions. These issues have been reckoned with in the voluntary actions of the industry and the EC F-gases Regulation (842/2006/EC). In 2005 further emission reduction options excluding alternative technologies were estimated to be available in Europe at costs ranging between 0.4–40 €/t CO_2 eq. (Wartmann and Harnisch 2005.) Converted to 2009 Euros the costs are approximately 0.4–43 €/t CO_2 eq.

The compactness of SF_6 insulated electrical equipment allows transmission and distribution network designs, where high voltage networks are closer to urban consumers. This reduces energy losses in the transmission and distribution of electricity. In addition, the compact designs reduce resistance losses within the equipment. These indirect emission savings due to energy loss reductions by SF_6 technology are of the same magnitude as direct SF_6 emissions projected for an equipment life cycle with appropriately managed manufacturing and decommissioning. Thus emission abatement options for SF_6 from electrical equipment need to be considered as net GHG emission reductions bearing in mind the effect of indirect emissions. (Wartmann and Harnisch 2005.)

6.2 Emission projection for electrical equipment

6.2.1 *Key assumptions for the emission projection of electrical equipment*

The emission projection for SF_6 from electrical equipment is based on the previous F-gas inventory emissions estimates and activity data and the summarized emission estimates and activity data of emission and gas bank evaluations 2002–2007 by Finnish Energy Industries. The F-gas inventory activity data is compiled in annual surveys from Finnish electrical equipment manufacturers, importers and exporters of SF_6 containing equipment and bulk importers and exporters of SF_6. There are about a dozen companies reporting such activities (F-gas inventory 2007). Finnish Energy Industries' estimates are based on data acquired with yearly surveys from over a hundred electricity network bearers (Finnish Energy Industries 2008). The emission estimates of Finnish Energy Industries have been lower than those of the F-gas inventories. However, the Finnish Energy Industries' estimates do not include emissions of manufacturing and maintenance work by subcontractors is not entirely accounted for either (Adato Energia Oy 2009).

The main parameters of the WM projection for SF_6 emissions from electrical equipment are presented in Table 19. There was 71 468 kg of SF_6 banked in the Finnish electricity network in

2007 (Finnish Energy Industries 2008). This gas bank was estimated to grow with 2 688 kg a year until 2012, based on the mean growth of the two previous years in the data of Finnish Energy Industries. Only a trace amount of gas is assumed to retire from decommissioned equipment between the years 2007–2012. In 2013 the oldest equipment reach a lifetime of 35 years and the amount retiring from decommissioned equipment is expected to grow to 1 890 kg a year. Simultaneously the yearly growth of the gas bank is assumed to decrease to 970 kg a year. The retiring amount is based on the average yearly bank growth of 2 100 kg prior to the year 2000 estimated by Oinonen and Soimakallio (2001) and the amount of gas left in the equipment after 35 years, when refilling is not taken into account. The amount of SF_6 used in manufacturing of electrical equipment in Finland is assumed to stay constant at the 2007 level acquired from the confidential activity data of the F-gas inventory. Between the years 1990–2006 the emission estimates of F-gas inventory are used in the scenario.

The emission factors are estimated based on international literature and in the case of annual emission factor, also on the actual emission rate estimates of Finnish Energy Industries. The operation emission factor includes the emissions of installations and the manufacturing emission factor is used solely for equipment manufacturing in Finland. The end-of-life emission factor accounts for the gas handling emissions of SF_6 recovery.

No WAM projections are established for SF_6 emissions from electrical equipment. Voluntary actions of the industry have already reduced the emissions significantly and there is no viable alternative to the SF_6 technology in sight.

Table 19. Main parameters for the projection of SF_6 from electrical equipment.

Electrical equipment	
Gas banked in equipment 2007	71 468 kg
Change of gas banked in equipment 2008–2012	+2 688 kg /year
Change of gas banked in equipment 2013–2050	+970 kg /year
Emission factors 2007	
Manufacturing	0.07
Operation and installation	0.003
Decommissioning	0.025

6.2.2 WM emission projection for electrical equipment

The WM emission projection for SF_6 from electrical equipment is presented in Figure 16. The used calculation method and assumptions result an emission estimate of 306 kg SF_6, equal to 7.3 Gg CO_2 eq for 2007, while the F-gas inventory estimate is 308 kg and the estimate of Finnish Energy Industries 79 kg. The emissions have decreased sharply from the level of 1990 l due to voluntary actions of the industry. From 2007 onwards the emission trend is slightly increasing, because of the continuing growth of the gas bank. The projected SF_6 emissions for the years 2010, 2015, 2020 and 2050 as well as the reported emissions of 2006 (F-gas inventory 2006) are displayed in Table 20.

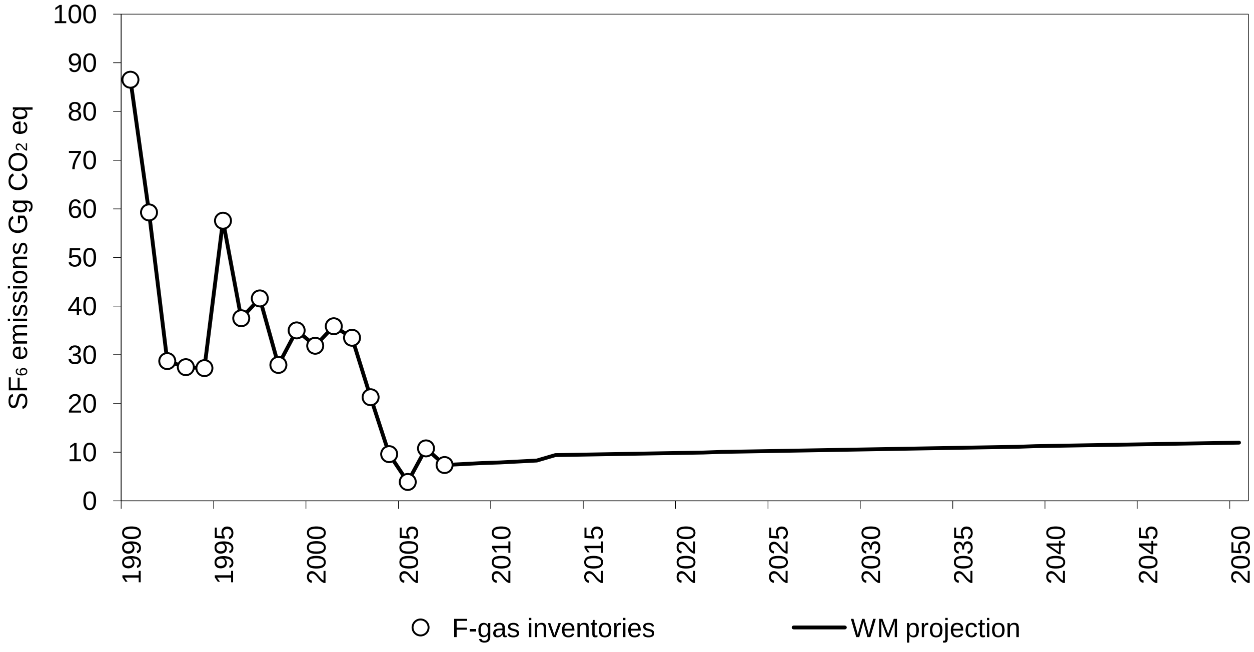

Figure 16. WM projection for SF_6 emissions from electrical equipment in Gg CO_2 eq with the reported actual emission estimates of F-gas inventories.

Table 20. Projected SF_6 emissions from electrical equipment.

	2006	2010	2015	2020	2050
WM projection Gg CO_2 eq	11	7.9	9.5	9.9	12

7 Other emission sources

7.1 Emissions, current technology and abatement options for other emission sources

7.1.1 Semiconductor manufacturing

Semiconductor products are required in a whole range of consumer products like electronic devices and systems and information technology network solutions and services. The semiconductor industry uses gaseous fluorinated compounds in a number of different process steps. The submicron patterns of advanced integrated circuits are created with plasma etching where PFCs are used as etching gases. The decomposing of SF_6 in the etching process also allows the cleaning of etching chambers. Chemical Vapor Deposition (CVD) tool chambers are cleaned of process deposits with rapid chemical cleaning using fluorinated compounds as well. In addition, SF_6 is used as an insulator in the power device testing of semiconductor devices. In the testing process SF_6 is kept in a closed cycle for reuse. (EECA-ESIA 2006.)

PFCs provide highly effective process performance in etching and a safe and reliable source of fluorine for the cleaning purposes (EECA-ESIA 2006). The Finnish semiconductor manufacturing industry uses tetrafluoromethane (CF_4), octofluorocyclobutane (c-C_4F_8), sulfur hexafluoride (SF_6) and trifluoromethane (CHF_3) also known as HFC-23 (F-gas inventory 2007). In Europe hexafluoroethane (C_2F_6), octofluoropropane (C_3F_8) and nitrogen trifluoride (NF_3) are also used by the semiconductor manufacturing industry (EECA-ESIA 2006).

The European Semiconductor Industry Association (ESIA) has set a voluntary goal to reduce the absolute PFC emissions of the European industry by 10% of the baseline emissions of 1995 by 2010. This regional goal is a part of the initiative of the World Semiconductor Council (WSC) to contribute to the global GHG emission reduction efforts. The emissions of semiconductor manufacturing have been reduced with process optimization and use of alternative processes and chemicals, as well as improved capture, recovery and other emission abatement systems like endpoint detection. However, there are no effective substitutes available for the use of fluorinated gases in semiconductor manufacturing and the present utilization is critical for these processes. (EECA-ESIA 2006.)

The voluntary emission reduction goal of ESIA has involved significant investments of the European semiconductor industry. Process optimization is the only truly cost-effective emission reduction action due to lower gas consumption and its benefits. As a result of the voluntary actions the European semiconductor industry has achieved significant PFC emission reductions between the years 2000–2005 and in 2006 it seemed that the 10% reduction goal would be met by 2010. (EECA-ESIA 2006.) In Finland semiconductor manufacturing is a minor branch of industry and there are only three industry actors currently reporting usage of fluorinated gases in their production (F-gas inventory 2008).

7.1.2 Fire fighting equipment

A wide variety of fire fighting systems have been introduced as alternatives to the different halon-based applications (Rinne and Vaari 2005/VTT). In Finland HFCs are used in fixed fire suppression systems (F-gas inventory 2007). The benefits of HFC systems are fast discharge and suppression times, non-toxicity, compact applications and no damage to the equipment or materials of the protected space (AEA Technology 2004). Gas based suppression systems are used to avoid property damage and in critical areas of risk like computer and electronic control rooms and archives (Kidde 2009). HFC suppression systems are suitable for occupied spaces and do not endanger personnel (Kidde 2009, Are 2009).

In Finland the common HFC suppression systems use HFC-227ea or a mixture of HFC-134a, HFC-125 and CO_2 (F-gas inventory 2007). There is also a next-generation suppression system available on the Finnish market (Kidde 2009, Are 2009). The fluoroketone ($CF_3CF_2(O)CF(CF_3)_2$) fire protection fluid is liquid at room temperature, but applied as gas, it has a GWP of one and a five-day atmospheric lifetime combined with the functional benefits of the other fluorinated gases (3M Product Information 2009). In addition, inert gases, mixtures of argon and nitrogen, and carbon dioxide are used in fixed suppression systems. The EC F-gases Regulation (842/2006/EC) has already banned PFCs from fire fighting equipment in 2007.

HFC emissions from fire suppression systems occur when the system is discharged in case of fire or accidentally. The emissions from filling or other system maintenance are marginal. (AEA Technology 2004.) In Finland HFCs from decommissioned fire fighting equipment are effectively recovered for re-use (Information from the industry).

7.1.3 Other receding emission sources

In Finland receding or minimal sources of F-gas emissions are research and magnesium die casting. The EC F-gases Regulation restricts the use of SF_6 in magnesium die casting to 850 kg a year. In practice only trace amounts of SF_6 has been imported for magnesium die casting in the recent years and the usage in Finland is expected to cease entirely. The amount of SF_6 consumed in research purposes is almost negligible as well. (F-gas inventories.)

The use of SF_6 in the manufacturing of training shoes was banned in the EC F-gases Regulation in 2006 and emissions from the source have been estimated to have ended in 2007. F-gas usage in solvents has not been detected in Finland. (F-gas inventories.) The amount of SF_6 used as sound insulating glazing for windows has been negligible to begin with (Oinonen and Soimakallio 2001) and other methods of sound insulation substituted even the occasional use of SF_6 containing glazing in Finland years ago (Information from the industry). The use of SF_6 in window glazing has also been banned in the EC F-gases Regulation.

7.2 Emission projection for grouped emission sources

7.2.1 Key assumptions for the emission projection of grouped emission sources

In the Finnish F-gas inventory semiconductor manufacturing, fire suppression systems, magnesium die casting and other minor emission sources like training shoes and research have been grouped due to confidentiality reasons. The grouped emissions also include the emissions of HFC-23 from refrigeration and air conditioning equipment.

The WM projection for grouped emission sources is based on the F-gas inventory information. F-gas inventory emission estimates are used until 2007. The emission estimates and activity data of different sources in 2007 are used as a starting point, where from the development of emissions from separate sources are forecasted. The projection of grouped emission sources includes emissions of HFC substances, HFC-23, HFC-125, HFC-134a and HFC-227ea, and PFCs, CF_4 and $c\text{-}C_4F_8$, as well as SF_6.

The growth estimate of semiconductor manufacturing is based on confidential information from the semiconductor manufacturer with the highest F-gas consumption in Finland. The growth of emissions from semiconductor manufacturing is assumed to be equal to the growth of F-gas amounts used in production. Between the years 2024–2050 the emissions are expected to stay constant.

F-gas emissions of fire suppression systems are expected to stay at the level of 2007, since the average number of fires and accidental releases is estimated to stay constant. However, the proportions of different HFC substances emitted from the systems are expected to even out from the reported emissions of 2007 based on the proportions of imported and installed amounts of gas in 2007. The change is estimated to take place linearly between years 2008–2015. The effect to the CO_2 equivalent emissions is slightly increasing.

The emissions of magnesium die casting are expected to end by 2010 and the decrease is calculated linearly between the years 2008–2010. The emissions from training shoes are estimated to have ended in 2007. The emissions of SF_6 from research and HFC-23 from refrigeration and air conditioning equipment are expected to stay constant at the 2007 level.

WAM projections are not established for grouped emission sources. The emissions of semiconductor manufacturing have already been reduced by voluntary actions and there are no clear alternatives to the diverse F-gas usage in the sector. HFC usage in fire suppression systems is seen as critical use, although there might be emission reduction potential in substituting HFCs with the available fluoroketone application. The emissions of HFC-23 from refrigeration and air conditioning equipment and SF_6 from research are almost negligible and the calculation of WAM projections based on them was not seen worthwhile. However, the emissions of HFC-23 from refrigeration and air conditioning equipment would be reduced by the assumptions of the WAM projections presented for the refrigeration and air conditioning sector.

7.2.2 WM emission projection for grouped emission sources

The F-gas emission projection for grouped emission sources is represented in Figure 17. The downward slope of the emission trend in the recent years is an effect of the restrictions placed by the EC F-gases Regulation. The increase of emissions from 2009 onwards is driven by the growth of semiconductor manufacturing and the lesser effect of HFC substance changes in emissions of fire suppression systems. The growth evens out and emissions stay constant at 36 Gg CO_2 eq from 2023 onwards. The projected F-gas emissions for the years 2010, 2015, 2020 and 2050 as well as the reported emissions of 2006 (F-gas inventory 2006) are displayed in Table 21.

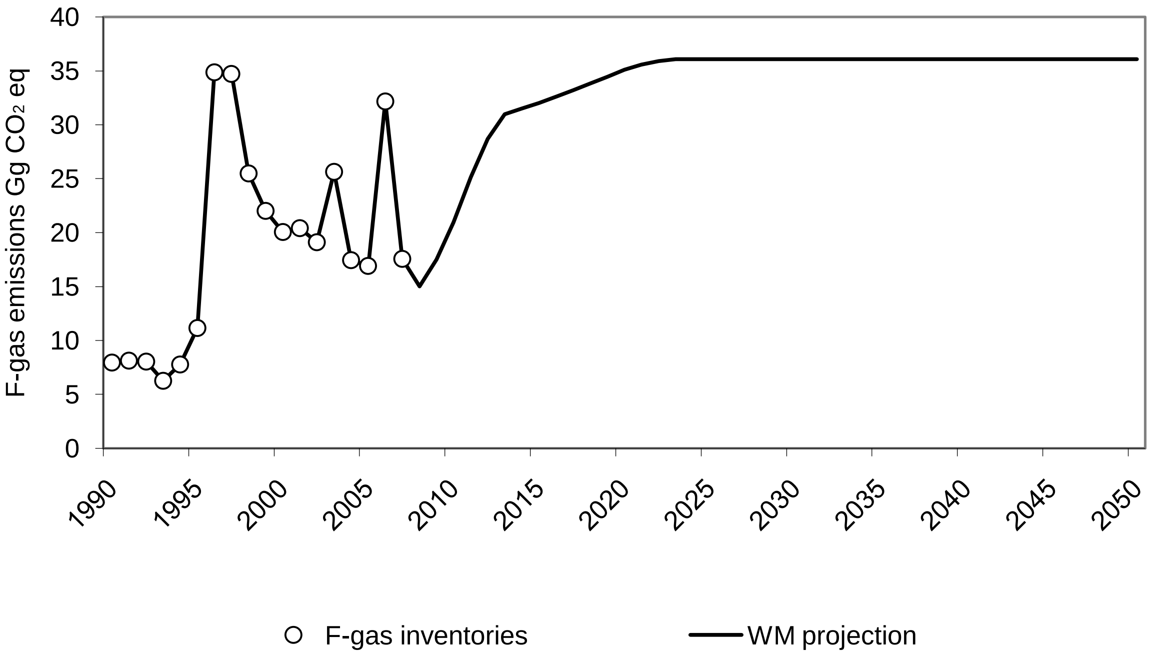

Figure 17. WM projection for F-gas emissions from grouped emission sources in Gg CO_2 eq with the reported actual emission estimates of F-gas inventories.

Table 21. Projected F-gas emissions from grouped emission sources.

	2006	2010	2015	2020	2050
WM projection Gg CO_2 eq	32	21	32	35	36

8 Summarized emission projections for F-gases

8.1 F-gas emission projections of 2009

8.1.1 WM emission projection for F-gases

The development of total F-gas emissions in Finland is projected by adding up the WM emission projections of the different source categories. PFC emissions from refrigeration and air conditioning equipment are also included in the projection. The total WM emission projection for F-gases by source category is represented in Figure 18. The projection is dominated by the emission trend of refrigeration and air conditioning equipment, because emissions from this source presently account for close to 90% of the F-gas emissions in Finland. The emissions are projected to decrease after the peak of 2006 as a joint effect of the EC F-gases Regulation (842/2006/EC), the EC MAC Directive (2006/40/EC) and the technical tendency towards indirect refrigeration systems resulting in smaller refrigerant charges. The trend is reversed around 2025 by the increasing amount of refrigeration and air conditioning equipment installations.

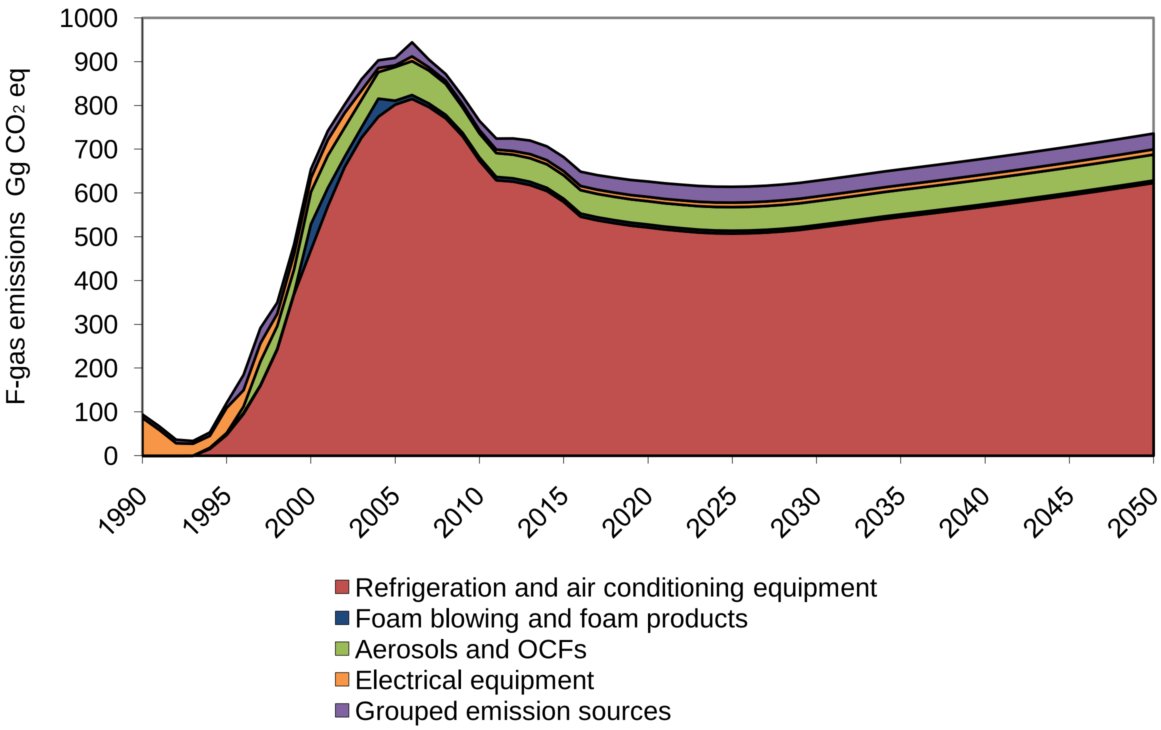

Figure 18. WM projection for F-gas emissions by source category in Gg CO_2 eq.

In Figure 19 the WM projection for F-gases is presented combined to the reported emission estimates of national F-gas inventories between the years 1990–2007. This figure illustrates the annual variation of the reported emission estimates. The inter-annual fluctuation in the 2000's has been as high as 34% mostly due to changes in the activity data. Intense changes in the activities of even a few of the major companies in their subsectors can have a forceful impact on the emission level. Therefore the uncertainty of the emission projection is considered to be quite high.

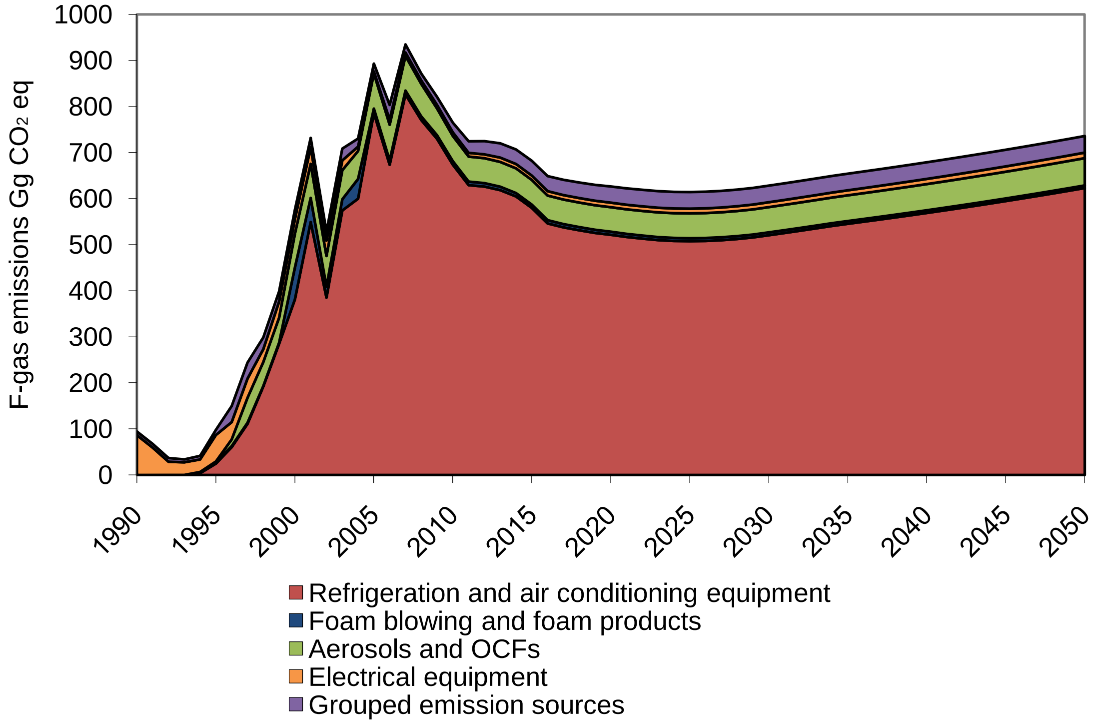

Figure 18. WM projection for F-gas emissions by source category combined to the reported emission estimates of 1990–2007 in Gg CO_2 eq.

The WM emission projection is divided by substances and represented in Figure 19 separately for HFCs, PFCs and SF_6. The bulk of the projected emissions are HFC emissions from refrigeration and air conditioning equipment. The projected emission estimates for different substance groups are detailed in Table 22 for the years 2010, 2015, 2020 and 2050 together with the reported emissions of the 2009 PM Report base year 2006.

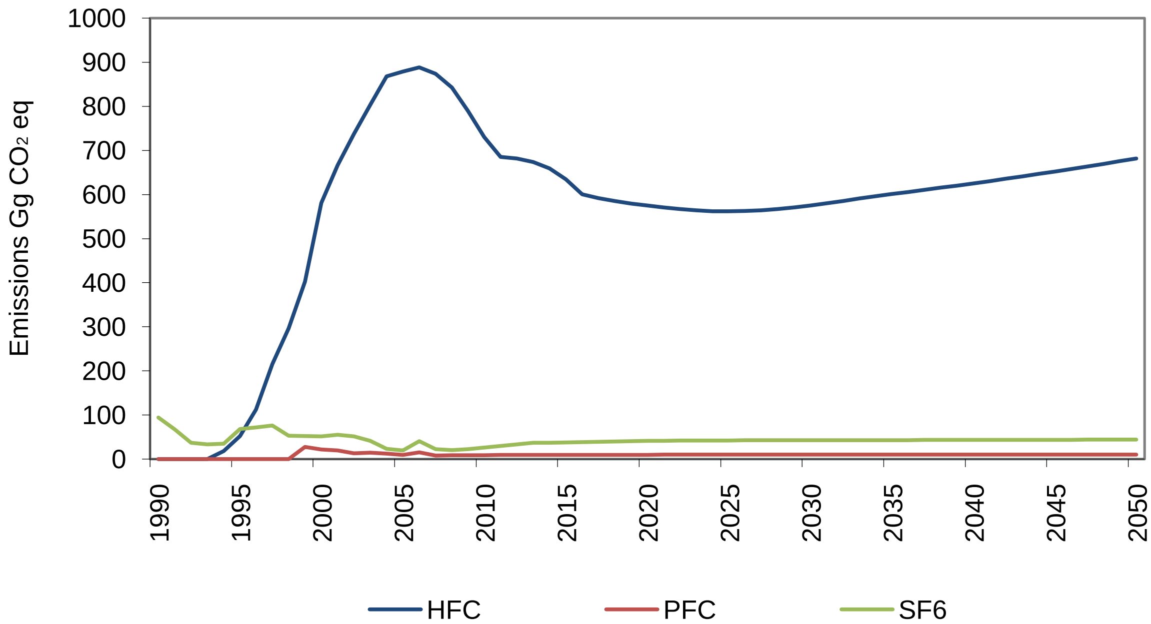

Figure 18. WM projection for F-gas emissions by substance group in Gg CO_2 eq.

Table 22. Projected F-gas emissions by substance groups.

	2006	2010	2015	2020	2050
HFC emissions Gg CO_2 eq	748	730	634	575	682
PFC emissions Gg CO_2 eq	15	9.0	9.8	10	10
SF_6 emissions Gg CO_2 eq	40	26	38	41	44

8.1.2 WAM emission projections for F-gases

The total WAM emission projections for F-gases are calculated from the WAM projections of refrigeration and air conditioning equipment and foam blowing and foam products and the WM projections of other emission sources, which WAM scenarios were not established for. The WAM projections for F-gases are based on the assumption that the Commissions reassessment of the EC Regulation on F-gases and the MAC Directive in 2011 will lead to additional regulatory measures. Further restrictions of use are expected for all applications technically feasible and in line with safety and health concerns. In the WAM 1 projection the use of HFC substances is assumed to be forbidden in foam blowing and new refrigeration and air conditioning equipment from the beginning of the year 2015. The WAM 2 projection presupposes, that the use of HFC substances of GWP higher than 150 is respectively forbidden in these two source sectors in 2015. In both WAM projections the use of HFCs is assumed to be permitted in old equipment to the end of their product lifetimes.

The WAM 1 and WAM 2 projections are represented in Figure 19 with the reported emission estimate combined WM projection. The WAM 1 projection reduces the emission by 380 Gg CO_2 eq in 2020 and 618 Gg CO_2 eq in 2050 compared with the WM projection estimates. The emission reduction is 61% and 84% for the years 2020 and 2050 respectively. The WAM 2 projection reduces the emission by 349 Gg CO_2 eq in 2020 and 572 Gg CO_2 eq in 2050. The reduction is 56% in 2020 and 78% in 2050 of the WM projection estimates. The difference between the WAM 1 and the WAM 2 emission reduction is only 5% and 6% of the WM projection estimates for the years 2020 and 2050 respectively. The projected F-gas emission reductions together with the reported emissions of 2006 are compiled in Table 23. The two WAM scenarios are compared with the WM scenario emissions of the years 2010, 2015, 2020 and 2050.

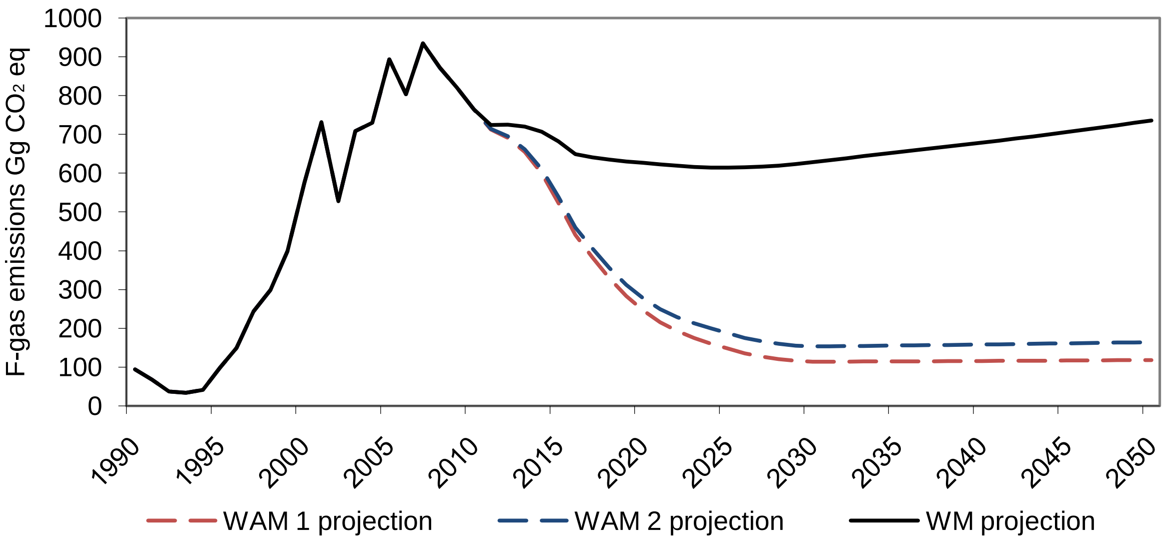

Figure 19. WM and WAM projections for F-gas emissions in Gg CO_2 eq.

Table 23. Projected F-gas emission reductions.

Year	WM projection Gg CO_2 eq	WAM 1 projection Gg CO_2 eq	Emission reduction from WM Gg CO_2 eq	Diff. from WM %	WAM 2 projection Gg CO_2 eq	Emission reduction from WM Gg CO_2 eq	Diff. from WM %
2006	804	804			804		
2010	765	765			765		
2015	682	524	158	23	539	143	21
2020	626	246	380	61	278	348	56
2050	736	118	618	84	165	571	78

8.2 F-gas emission projections of 2009 compared with previous projections

8.2.1 Total F-gas emission projections of 2009 compared with previous projections

The F-gas emission projections of 2009 differ from the previously established projections, because of the differences in calculation methods and main assumptions. In Figure 20 the 2009 projections are compared with the projections of 2007 made in SYKE for the preparation of the Finnish Long Term Climate and Energy Strategy 2008 (Toikka 2007), the projected emission estimates of the Reporting of Implemented Policies and Measures in 2007 and the reported emission estimates of the F-gas inventories.

In the Policies and Measures Report 2007 the effects of the EC F-gases Regulation and the EC MAC Directive are assessed in the WAM projection correspondingly to the WM projection of 2009. The emission estimates for the year 2020 are at the same level, approximately 630 Gg CO_2 eq, in both projections.

The 2007 WM projection for the Climate and Energy Strategy assesses the effects of the EC F-gases Regulation and the MAC Directive similarly to the WM projection of 2009, but deems the effects less stringent than the 2009 projection. The assumed additional measures in the 2007 WAM 1 projection are also similar to the 2009 WAM 1 projection. In the 2007 WAM 1 projection the use of F-gases was assumed to be totally restricted in refrigeration and air conditioning equipment, foam blowing, fire suppression systems and aerosols, excluding medical aerosols and other critical usage (Toikka 2007). In the 2007 WAM 2 projection the use of F-gases was assumed to be allowed in 25% of these applications, for which replacement was estimated to be hard to accomplish (Toikka 2007). In the 2009 WAM projections all of the remaining HFC usage in aerosols and fire suppression systems in Finland is seen as critical for safety or health reasons and only activities in refrigeration and air conditioning equipment and foam blowing are expected to be affected by the restrictions. Therefore the WAM 1 projection of 2009 does not reach the lowest emission level of the WAM 1 projection of 2007 in 2050.

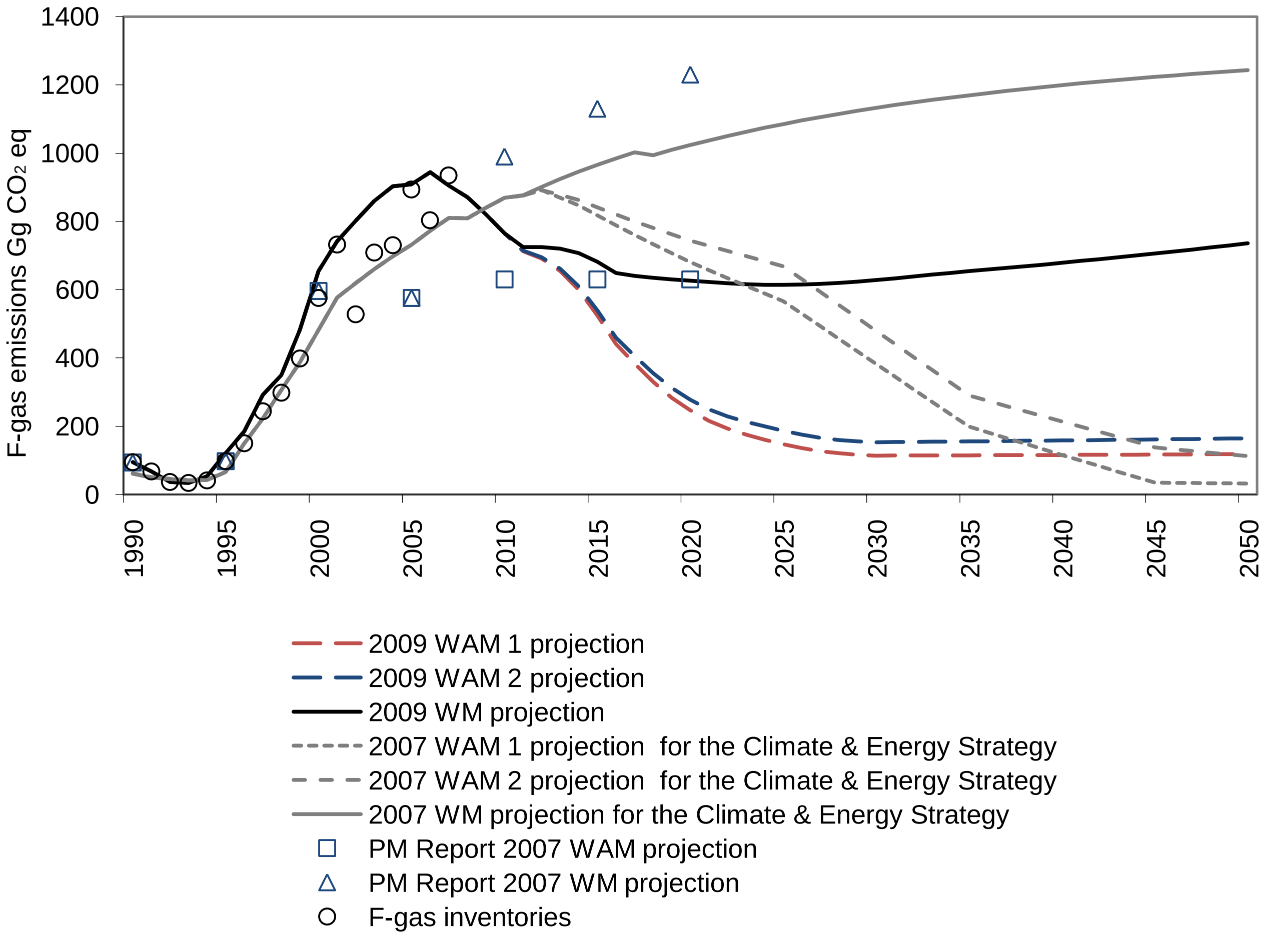

Figure 20. 2009 WM and WAM projections for F-gas emissions compared with previous projections in Gg CO_2 eq.

8.2.2 Emission projections of 2009 for refrigeration and air conditioning equipment compared with previous projections

All of the subsectoral projections of 2007 for the Finnish Long Term Climate and Energy Strategy 2008 differ from the 2009 projections, but most of the difference is due to the emission projections of refrigeration and air conditioning equipment. These projections for refrigeration and air conditioning equipment emissions are compared in Figure 21.

The 2007 projections were established by mathematical modeling of the reported emissions of 1990–2006 and expert assumptions of the future trend development (Toikka 2007). In the 2007 WM projection the EC F-gases Regulation was assumed to reduce the emissions by 55% of the level the emissions could have reached, without these measures, estimated by Oinonen and Soimakallio (2001) (Toikka 2007). The effect on the projected emission level is even and considerably less stringent than the one given by the 2009 calculation method and the principally assumed 50% decrease of the emission factors from the ones used by Oinonen and Soimakallio (2001).

In the 2007 WM projection the EC MAC Directive was assumed to decrease the emissions of refrigeration and air conditioning equipment by approximately 10% (Toikka 2007). In the 2009 WM projection the effect is clearly more extensive, around 25%. The technical development leading to smaller charges is mentioned as an emission reducing factor in the 2007 projections as well (Toikka 2007).

The WAM projections of 2007 and 2009 for refrigeration and air conditioning equipment reach about the same level of emission by 2050. The dissimilar emission trends of the WAM projections of 2007 and 2009 seem to be caused by the basic differences of the WM projections. All in all the WM projections of 2007 and 2009 do asses the same emission reducing factors in principal, but the 2009 method based on the eleven sub scenarios of the refrigeration and air conditioning sector, with more specific assumptions of their own, results in a considerably stronger emission reduction effect.

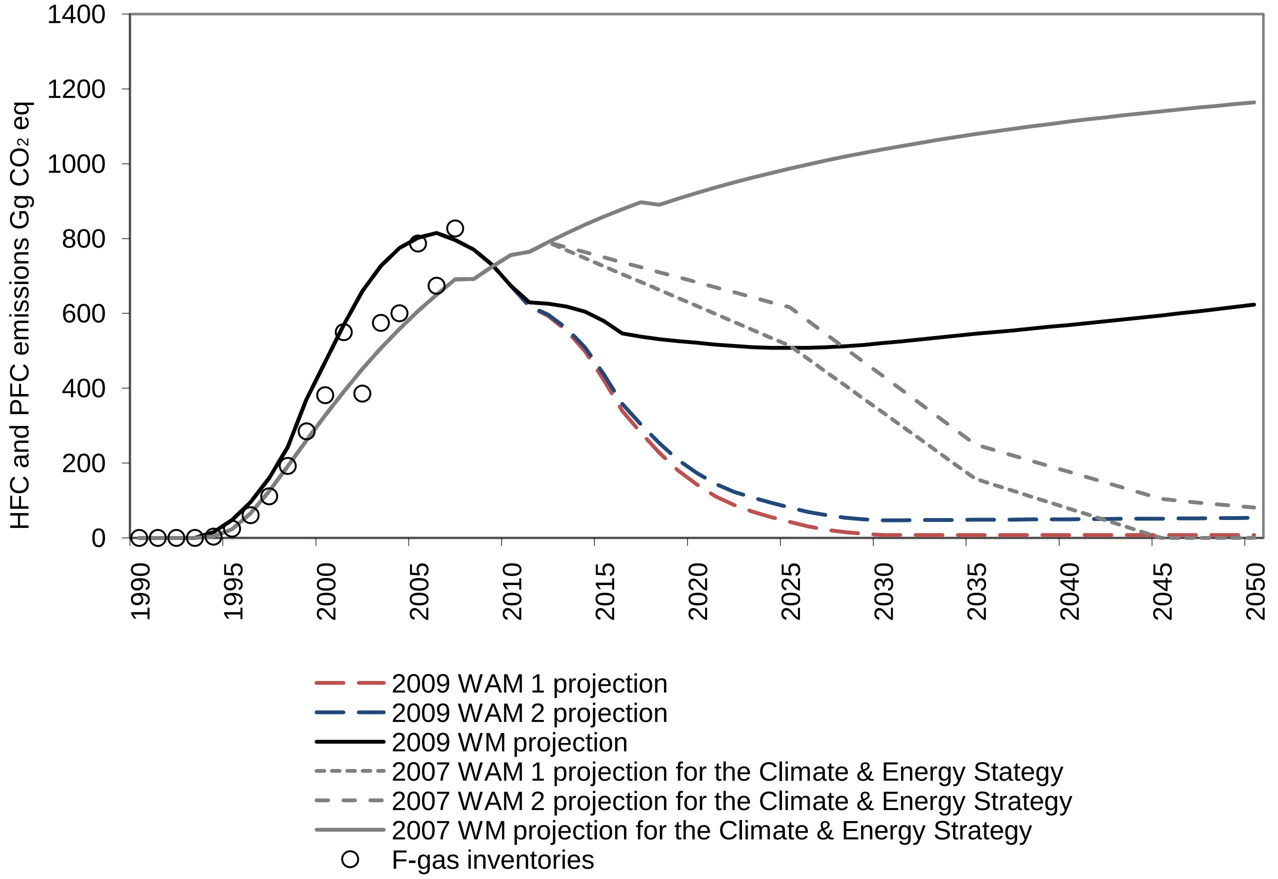

Figure 21. 2009 WM and WAM projections for HFC and PFC emissions from refrigeration and air conditioning equipment compared with previous projections in Gg CO_2 eq.

8.2.3 Concluding remarks

In light of the projections the growing trend of F-gas emissions is expected to be intercepted by the implemented measures and ongoing technical development. In addition, there is substantial potential for further emission reductions with additional measures. The technical development and change in the F-gas emission source sectors is fast, especially in the field of refrigeration and air conditioning equipment. The progress of the industries in question, new low GWP substances and equipment designs, should be closely followed in the future as well.

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List of abbreviations

AKE	The Finnish Vehicle Administration
ATP	Agreement on the international carriage of perishable foodstuff and on the special equipment to be used for such carriage
COPD	Asthma and chronic obstructive pulmonary disease
CVD	Chemical Vapor Deposition
DPI	Dry powder inhaler
EC F-gases Regulation	Regulation (EC) No 842/2006 of the European Parliament and of the Council on certain fluorinated greenhouse gases
EC MAC Directive	Directive 2006/40/EC of the European Parliament and of the Council relating to emissions from air-conditioning systems in motor vehicles and amending Council Directive 70/156/EEC
ESIA	European Semiconductor Industry Association
Evira	Finnish Food Safety Authority
HC	Hydrocarbon
HFC	Hydrofluorocarbon
Horeca	Hotel, restaurant and catering
IPCC	Intergovernmental Panel on Climate Change
MDI	Metered dose inhaler
MTT	Agrifood Research Finland
OCF	One-component foam
ODS	Ozone depleting substance
PFC	Perfluorocarbon
SULPU	The Finnish Heat Pump Association
SYKE	Finnish Environment Institute
TEAP	Technology and Economic Assessment Panel
UNEP	United Nations Environment Programme
VTT	Technical Research Center of Finland
WAM	With additional measures
WM	With measures
WSC	World Semiconductor Council

Appendix 1

HFCs, PFCs, SF_6 and main refrigerant compounds included in the F-gas emission projections.

Refrigerant number		Mass composition of compounds	GWP_{100}
Hydrofluorocarbons			
R-23	HFC-23		11 700
	HFC-32		650
	HFC-125		2 800
R-134a	HFC-134a		1 300
R-152a	HFC-152a		140
	HFC-143a		3 800
	HFC-227ea		2 900
	HFC-245fa		950
	HFC-365mfc		890
R-404A	HFC-125/HFC-143a/HFC-134a	(44.0/52.0/4.0)	3 260
R-407C	HFC-32/HFC-125/HFC-134a	(23.0/25.0/52.0)	1 530
R-410A	HFC-32/HFC-125	(50.0/50.0)	1 725
Perfluorocarbons			
	Perfluoromethane CF_4		6 500
R-218	Perfluoropropane C_3F_8		7 000
	Perfluorocyclobutane c-C_4F_8		8 700
Sulphur hexafluoride			
	Sulphur hexafluoride SF_6		23 900