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Construction of abatement cost curves: The case of F-gases

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Summary

Most of scientific research on Greenhouse Gases (GHG) focuses on CO₂ emissions. But non-CO₂ gases (mainly F-gases in the form of HFCs, PFCs, and SF₆) are more potent at trapping heat within the atmosphere. Currently, F-gases constitute a small proportion of GHG emissions but they are extremely high Global Warming Potential gases. At the same time, they are expected to increase massively due to the expansion of some emitting industries, while the atmospheric lifetimes of PFCs and SF₆ are very long. This study analyzes the economic and technical assumptions in abatement cost calculation in the case of the F-gases. The important factors for differences among countries in average mitigation costs are discussed and the least cost curve of F-gases control for the EU-27 and for the year 2020 is derived. It seems that it is more cost-effective to start abating SF₆ first, and then moving to PFCs and then applying control methods to HFCs.

Keywords: F-gases; control methods; emissions; GWP.

JEL Classifications: L52, Q01, Q00, Q53, L95.

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Abbreviations (alphabetically in codes)			
CFC	Chlorofluorocarbons	CF₄	Perfluoromethane
C₂F₆	Perfluoroethane	C₄F₈	Octafluorocyclobutane
C₃F₈	Perfluoropropane	CH₄	Methane
CO₂	Carbon dioxide	CVD	Chemical Vapour Deposition
DOM	Domestic	F-gases	Fluorinated gases
GHGs	Greenhouse gases	GIS	Gas Insulated Switchgear
GWP	Global Warming Potential	HCFC	hydrochlorofluorocarbons
HCFC-22	Chlorodifluoromethane	HC-290	Propane
HC-600a	Isobutane	HFC	Hydrofluorocarbon
HFC-23	Trifluoromethane	HFC-32	difluoromethane
HFC-125	ethane	HFC-134a	tetrafluoroethane
HFC-143a	trifluoroethane	HFC-152a	difluoroethane
HFC-236fa	hexafluoropropane	HFC-245fa	pentafluoropropane
HFC-365mfc	pentafluorobutane	HFC-43-10mee	decafluoropentane
HFC-227ea	heptafluoropropane	HSS	Horizontal Søderberg
IND	Industrial	MA/C	Mobile airconditioning
N₂O	Nitrous oxide	NF₃	Nitrogen trifluoride
OCF	One component foam	ODS	Ozone Depleting Substance
PFC	Perfluorocarbon	PFPB	Point-Feed Prebake
PFPEs	Perfluoropolyether	PTFE	Polytetrafluoroetene
PU	Polyurethane	R-717	Ammonia
REF	Refrigeration	SA/C	Stationary airconditioning
SF₆	Sulphur hexafluoride	SO₂	Sulphur dioxide
SWPB	Side Work Prebake	TRA	Transport
VSS	Vertical Søderberg	PM	Particulate matter

1. Introduction

Greenhouse gases (GHGs) include carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and a number of high Global Warming Potential gases such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF₆), also known as F-gases. The Kyoto Protocol regulates all these GHGs. CO₂ emissions from the burning of fossil fuels and the change in the use of human land may be considered as the most important anthropogenic effect.

The rest of the GHGs (the non-CO₂ gases) are also important. Methane and nitrous oxide are naturally present in the atmosphere while the F-gases are industrial gases. The F-gases are used as substitutes for the Ozone Depleting Substances (ODS, chlorofluorocarbons CFCs and hydrochlorofluorocarbons HCFCs) that were faced out under the Montreal Protocol. They are also used and emitted from a number of

industrial sources like the use of PFCs in aluminium smelting or in semiconductor manufacture or the use of SF₆ as an insulating gas in various electrical systems.

The full set of fluorinated gases (CFC, PCFC, HFC, PFC, and SF₆) comprised almost 25% of the added anthropogenic radiative forcing of the climate in 1980 and 1990 (IPCC, 1990). The main responsibility for this percentage may be attributed to the chemically related anthropogenic gases CFCs and PCFCs. Due to their depleting influence on stratospheric ozone, CFCs and PCFCs were regulated, as mentioned, by the Montreal Protocol but were not considered in the Kyoto Protocol.

The majority of scientific research concerns CO₂ emissions, although non-CO₂ gases, especially F-gases, are more potent at trapping heat within the atmosphere. F-gases are expected to rise quickly due to the rapid expansion of some emitting industries such as semiconductor manufacture and magnesium production, and the replacement of ODSs (CFCs and HCFCs) with HFCs in various applications like air-conditioning, fire fighting, foams, refrigeration, solvents and aerosols. Moreover, the atmospheric lifetimes of PFCs and SF₆ are very long, ranging from 3200 years for SF₆ to 50000 years for CF₄ (Schaefer *et al.*, 2006). For these reasons, F-gases are considered extremely harmful for the environment, so they have been included in the Kyoto-Protocol.

Although HFCs emissions in the European Union were almost zero until 1990, they rose to 37000 tones in 1998 and it is estimated that they will reach 129000 tones in 2012 (Greenpeace, 2003). Furthermore, in the absence of additional regulatory actions, it is estimated that F-gases will constitute 15% of GHGs until 2040 and 40% until 2100 (Greenpeace, 2003). Even if F-gases constitute only a small fraction of present GHG emissions they are responsible for a more considerable amount of

climate degradation, compared to other GHGs, because of their high Global Warming Potentials¹ (GWPs). These GWPs range from 140 to 23900 as presented in Table 1.

Table 1: 100-year Global Warming Potentials of F-gases

Gas	GWP		Gas	GWP
HFC-23	11700		HFC-4310mee	1300
HFC-125	2800		CF ₄	6500
HFC-134a	1300		C ₂ F ₆	9200
HFC-143a	3800		C ₄ F ₈	10000
HFC-152a	140		C ₃ F ₈	7000
HFC-227ea	2900		SF ₆	23900
HFC-236fa	6300		HFC-32	650
HFC-245fa	950		NF ₃	10800

Source: IPCC (1996); Schaefer *et al.*, (2006).

It is worth mention that if we consider all the non-CO₂ gases together with the banned chlorofluorocarbons then their significance is almost similar to CO₂ (Reilly *et al.*, 2003). To limit climate change in the most effective way, then climate policies have to cope with all of them simultaneously. A significant benefit that non-CO₂ GHGs provide is their quite low abatement cost per carbon equivalent. Especially, the marginal costs of achieving reduction of high-GWP gases, such as F-gases, are less than achieving reductions of CO₂ gases. According to several studies, the inclusion of the abatement of non-CO₂ GHGs reduces dramatically the overall implementation cost of the Kyoto Protocol (Reilly *et al.*, 1999, 2000, 2006; Jensen and Thelle, 2001).

The purpose of this study is twofold. First, to show the main steps and assumptions implemented in the construction of abatement cost curves and second, to apply these principles in the construction of the F-gases control cost curve for the year

¹ Global Warming Potentials is an index which measures the emissions of different greenhouse gases with different atmospheric lifetimes and different radiative properties. Ideally, maintaining the climate impact constant, GWP measures allow for comparison and substitution among different gases in order to achieve the desirable target (Fuglestvelt *et al.*, 2003). CO₂ has a GWP equal to 1 for reasons of comparison. CH₄ and N₂O have GWPs equal to 25 and 298 respectively.

2020 and for the EU-27. Thus the structure is as follows. Section 2 reviews the existing relative efforts of research and academic institutions on constructing abatement cost curves for F-gases. Section 3 sets the basic hypotheses behind the construction of abatement cost curves as well as the principles of calculation. Section 4 explains the estimation of F-gases emissions by activity and sector. Section 5 derives the stepwise abatement cost curve in the case of F-gases. The last section concludes this research emphasizing the main steps in the construction of abatement cost curves and the existing limitations and comments on the F-gases marginal abatement cost case study and the associated policy implications.

2. Review of existing abatement efforts

In previous studies attention was given mainly to CO₂ mitigation with a number of studies using a single gas case (Hourcade and Shukla, 2001; Morita *et al.*, 2001). In the absence of extensive cross-country data, until recently, a few comprehensive studies examining non-CO₂ gases have been conducted (Chesnaye *et al.*, 2001). The weakness of earlier studies is that they used exogenous marginal abatement cost functions instead of incorporating non-CO₂ gases in analytic models (Hyman *et al.*, 2002).

The simultaneous examination of CO₂ and non-CO₂ abatement options may have significant advantages on the so-called multi-gas control strategies. Among these advantages, we may refer to the significant cost reductions compared to a CO₂-only strategy as we may have much cheaper abatement options for several non-CO₂ GHGs (Harmelink *et al.*, 2005; Blok *et al.*, 2001), while they offer a greater flexibility in the mitigation options (Lucas *et al.*, 2005; Manne and Richels, 2001; Van Vuuren *et al.*, 2003; Hyman *et al.*, 2002). The Energy Modeling Forum (EMF) has performed a model comparison study on the understanding of multi-gas control strategies (EMF-21). Van Vuuren *et al.*, (2006) and Weyant and De la Chesnaye (2006) claim that on

average and across models a multi-gas strategy may lead to a reduction in cost of approximately 30-60% compared to abating only CO₂ emissions.

The 21st study of Energy Modelling Forum (EMF-21) at Stanford University assemble modelling teams from around the world in order to assess the cost-effectiveness of non-CO₂ greenhouse gas abatement options and costs and the results have been published in a special issue of the Energy Journal (Rose *et al.*, 2008). In this issue, Schaefer *et al.*, (2006) investigate future emissions and potential reductions of F-gases. They summarize the abatement options under six categories: substitution, improved containment, recovery and recycling, modified product design, process optimization and destruction. They claim that F-gases emissions are likely to continue their massive increase and the share of developing countries' F-gases emissions will also continue to increase as a result of their rapid economic growth. They argue that developing countries will provide some of the largest and low-cost abatement opportunities for F-gases.

Following the methodology of EMF-21 study, the USA Environmental Protection Agency conducted a comprehensive report about non-CO₂ greenhouse gases and they provide a set of marginal abatement curves (MAC) which allow for improved understanding of the abatement potential of non-CO₂ GHG (USEPA, 2006a). Gallaher *et al.*, (2005) include technology development in their study, measured by changes in input costs, productivity and abatement efficiency of mitigation options and extract marginal control cost curves using EMF-21 set. Lucas *et al.*, (2005) present a methodology to assess the potential long-term contributions of non-CO₂ GHGs in various control options. They rely on EMF-21 projects MAC curves and find that along with the F-gases, energy related methane emissions constitute the highest share of total non-CO₂ control potential representing a large

emission source with a large potential reduction (about 90% compared to baseline in 2100).

In March 2007, the European Council decided to set an autonomous target for European climate policy, a reduction of 20% of GHG emissions until 2020, compared to 1990. IIASA developed an analytical tool, the GAINS model, which quantifies the potential reductions and costs of six greenhouse gases, CO₂, CH₄, N₂O, HFC, PFC and SF₆, for 43 European regions (IIASA, 2008).

To finalize our review on F-gases research, let us discuss the existing estimates of control methods available and the resulting emissions reductions and the associated costs. Thermal destruction of HFC-23, generated as a byproduct of HCFC-22 production is an important reduction option with a maximum feasible abatement efficiency of 98% (Irving and Branscombe, 2002; Klein Goldewijk *et al.*, 2005). 90% of the reduction can be achieved at cost approximately 1\$/tCe_q and the 98% at cost of almost 100\$/tCe_q (Harnisch and Gluckman, 2001). Additional reductions in HFC-23 emissions from the HCFC-22 production demands extra equipment. Thus after achieving the technically efficient reduction through process optimization, a thermal afterburner incinerating the hydro fluorocarbon in furnaces fuelled by gases, like natural gas, may be installed.²

Control in the case of HFCs can be achieved by better sealed applications in commercial refrigeration and in mobile A/C with a potential annual reduction in leakage rates of approximately 20% and 10% respectively (Schwarz and Leisewitz, 1999). Moreover HFC recovery with product disposal may decrease these emissions by almost 25% while substitution of HFCs with hydrocarbon which substances with zero GWP as in commercial refrigerator and in foam blowing (isobutane, propane or

² The capital cost of a typical plant of 10,000 tones per year is €3 m with an annual operating and maintenance cost of €0.2 m (Harnisch and Hendriks, 2000).

mix of both) by 100% (Heijnes *et al.*, 1999). Improvement in collecting (recycling) discarded refrigerators and freezers may be expected to reduce emissions by 80% till 2020.

The maximum control of HFC emissions may be around 95% with 80-90% control in stationary refrigeration at cost less than 250\$/tCeq in 2050 and 95% reduction at cost up to 500\$/tCeq in 2100 (Harnisch and Hendriks, 2000; Harnisch and Gluckman, 2001). Similarly for foam blowing reduction of 80-90% in 2050 and 100% in 2100 may be achieved at cost less than 50\$/tCeq in both years. In the case of mobile A/C emissions control can reach 100% in 2050 at cost less than 200\$/tCeq. For PU foams, conversion cost may vary from 0.5 to 4 m € per company without taking into consideration the potential cost savings from the replacement of expensive HFC with cheaper CO₂ blends (USEPA, 2006a, b).

The leakages in transport refrigeration, say due to vibrations, may be reduced by regular checks in detecting early leaks at least once a year.³ The increased use of natural refrigerants (like ammonia and carbon dioxide) in industrial refrigeration may lead to 7% potential reduction compared to 2020 business as usual emissions and 15% in 2030 with estimated associated cost at a €34 per tone abated CO₂ in 2020 and 2030 (Rhiemeier and Harnisch, 2009).

Perfluorocarbon (PFC) emissions (CF₄ and C₂F₆) are byproducts of primary aluminium production. Main mitigation options use modern process technology for aluminium production like Point-Feed Prebake (PFPB). At the moment, almost one third of total aluminium production is achieved by using old Vertical and Horizontal Søderberg (VSS, HSS) methods. According to Heijnes *et al.*, (1999) almost 80%

³ Costs for a system check are around €50 per vehicle per hour of service implying a control cost of €32 per tone abated CO₂ eq in 2020 (Rhiemeier and Harnisch, 2009). Control costs of €40 per t controlled is assumed for maritime transport leakage reduction in 2020.

reduction can be achieved globally from aluminium production. Control cost for VSS conversions are almost 200\$/tCeq while for conversions or retrofitting of Side Work and Centre Work Prebake (SWPB, CWPB) methods the cost may be negative (Harnisch and Hendriks, 2000). In the semiconductor manufacturing and solvents reductions of 50%-80% can be achieved at less than 100\$/tCeq (Harnisch and Hendriks, 2000)⁴.

In addition, efforts in the future have to concentrate on converting the existing less efficient smelters using SWPB and VSS methods. According to Rhiemeier and Harnisch (2009) the conversion of the last European smelters using SWPB and VSS technologies led to a 661 kt CO₂ eq PFC reduction, assuming that conversion to PFBS method for plants using VSS will reduce emissions by a factor of 10 and for plants using SWPB method by a factor of 27.

To replace C₂F₆ and CF₄ the industry has developed NF₃ remote plasma clean systems which may have an installation cost of around €50000 with extra net annual cost of around €12000 per chamber (USEPA, 2006b). Similarly to abate emissions from the plasma etching process that account to around 20% of all semiconductor emissions, a capital cost of around €30000 per etching chamber is required for the purchase and installation of the system (USEPA, 2006b).

If we assume conversion cost of €500 / t aluminium for converting SWPB to SFPB and €100 for converting VSS to PFPB then Harnisch and Hendriks (2000) estimate a total investment cost of around €220 m, leading to abatement cost of €6.5 / t abated CO₂ eq for the conversion of smelters using VSS and €109 / t abated CO₂ eq for conversion of smelters using SWPB technologies.

⁴ There are no SWPB smelters left in Europe as the plants in Vlissingen and San Ciprian have been converted to PFBB (Rhiemeier and Harnisch, 2009).

In the case of sulphur hexafluoride emission controls the main methods are improved recovery, minimization of leakages and optimal use. Investment costs for internal monitoring with a centralized SF₆ supply system combined with installation flow meters at a single workstation equals to around €30000 with operating cost of €5000 per year. Central gas storing has an investment cost of €100000 per site with extra operating and maintenance cost of €150000 per site per year. Improved filling processes may have an investment cost of €60000 per site. Leakage detection with helium applies only to manufacturing process and investment cost is assumed to be on average €500000 per site with annual operating and maintenance cost of around €50000 (Rhiemeier and Harnisch, 2009).

An important control method is the substitution of SF₆ by SO₂ with abatement efficiency of 100%. An investment of €100000 to switch to SO₂ is required and this cost is not negligible if we think that most of the metalworks are small and medium companies.

Emissions from magnesium production and magnesium die casting, may be controlled by almost 90% at cost up to 200\$/tCe_q while in the case of semiconductor manufacture and other applications we may expect 90% reduction in 2050 at cost less than 100\$/tCe_q and almost 100% at cost up to 400\$/tCe_q (Harnisch and Hendriks, 2000; Heijnes *et al.*, 1999).

3. Economic and technical assumptions in cost calculation

Abatement technologies differ both as to cost and applicability. The important initial assumptions are the following.

1. Control costs are independent of order of introduction and control technologies are scale specific. There are fixed abatement coefficients (implying constant returns to scale) over the abatement range at which each technology is potentially efficient.

2. Fuel use and costs are assumed given independently of abatement policy.
3. There is a competitive market for chemical control methods accessible to all European countries at the same conditions. Country specific conditions may include average operating hours, fuel prices, capacity/vehicles utilization and emission factors.
4. It is assumed that regulatory authorities seek to maximize abatement subject to a budget constraint: a cheaper option will always be preferred over a more costly one. It would be economically inefficient to introduce relatively costly control options unless opportunities for using cheaper alternatives had already been exhausted. The relative economic efficiency of alternative options is compared by reference to "cost-effectiveness" which, for a given option at a given site, is the total annualized cost divided by the annual tonnes of chemical removed.

Within each step the marginal cost is taken equal to average cost and then extra technologies are added up in order to get the maximum feasible reduction. To rank the options in the most cost-effective way requires that MC should increase with TAC. We look for an efficient frontier (minimal cost envelope) which will give us the optimal total cost function. For any specified level of total emissions reduction, the corresponding point on the marginal cost curve specifies the set of plant-specific abatement technologies that minimize overall cost; i.e. in the first step in ranking the technologies used in each plant (boiler) we take the lowest MC equal to the average cost for the first technology used and then, we add up extra technologies to get the maximum feasible abatement that can be achieved by the plant/boiler under consideration.

Marginal costs increases are due to the effect of switching between technologies as the scale or level of abatement rises. The marginal cost curve has a staircase shape (i.e. it is a discontinuous step function) with each step representing a particular discrete

abatement technology. The level of each step indicates the incremental cost of a technology relative to the maximum incremental amount of chemical removed by introducing that technology. The sequence of efficient technologies gives us the long run marginal cost of abatement.

To calculate the marginal cost per tonne of chemical removed (MC/t ChR or simply MC) we need the total annualized cost (TAC) of all methods which can be applied to the country in question and the number of tonnes of chemical removed (ChR) by applying the technology. The figures needed to produce the marginal least cost curve for an individual plant (or sector) in a country are then the MChR and MC. It can be seen that the marginal technology cost (MTC) is given as

$$MTC_t = (MC_t) * (MChR_t)$$

This indicates that the total cost of abatement (TC) may be calculated as:

$$TC_t(ChR_t) = \sum MTC_t = \sum [(MC_t) * (MChR_t)]$$

This procedure generates a series of points which are connected in the form of a step function with many small steps. The height of each step is the incremental cost of moving to the next abatement technology. Figure 1 presents the analytic steps in extracting the stepwise control cost curve.

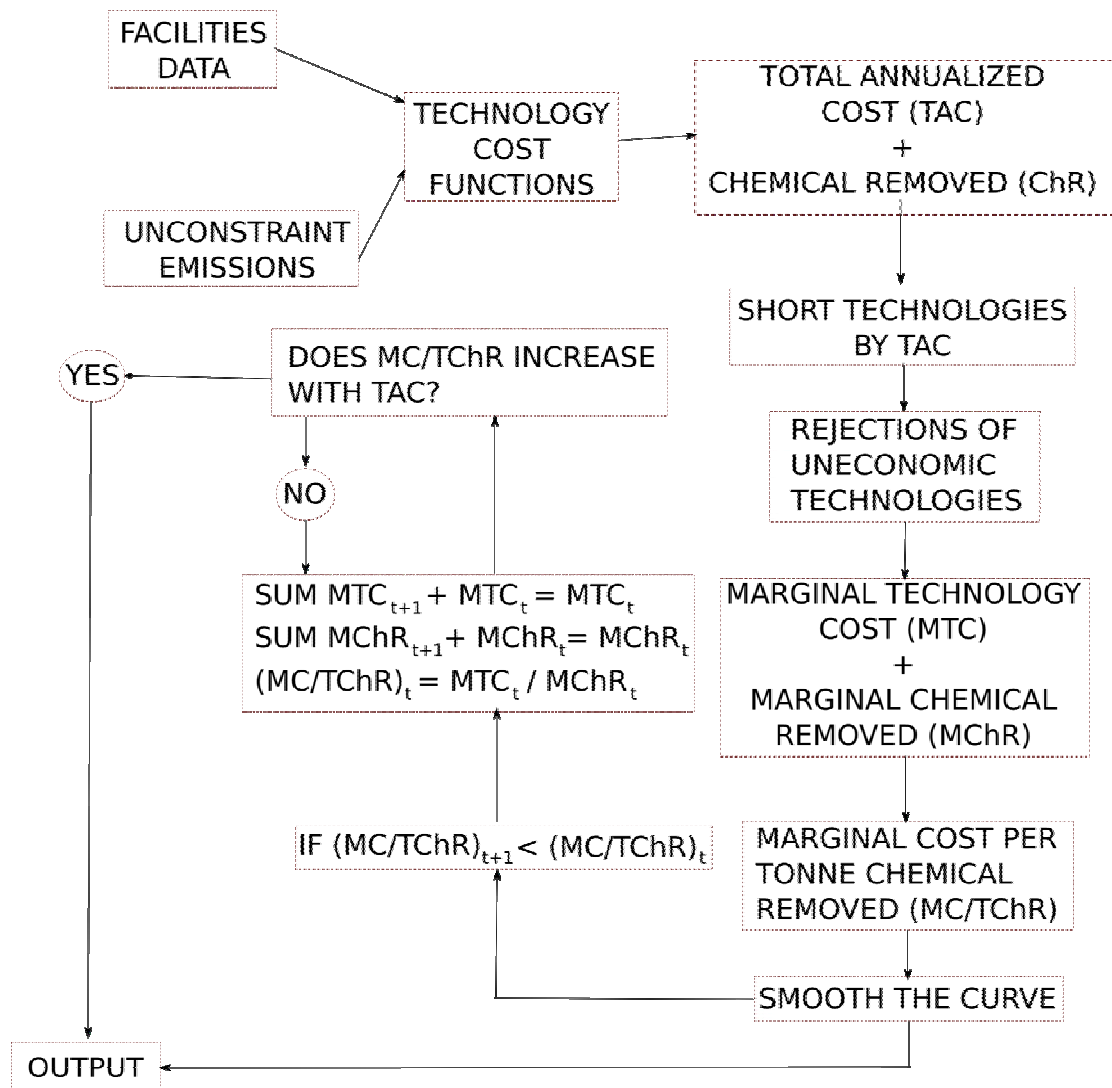
4. Estimation of F-gases emissions by activity and sector

To calculate the chemicals emitted from each source (ChE_p) we estimate the total annual emissions for a given chemical in each sector for each European country. The ChE_p is determined by:

$$ChE_p = \sum [PR_{ijt} \times (1 - AE_t) E_{p,ij} \times AR_{ijtf}]$$

Where i represents country, j sector, t technology, f fuel and p pollutant. PR stands for production levels; AE_t the abatement efficiency of method t; AR application rate.

Figure 1: Steps in constructing Abatement Cost Curves



Source: Halkos (1992)

If an abatement technology is introduced which has a lower marginal cost at some level of abatement than the technology applied before, then this technology has to be applied first. The control methods applied before are not taken into consideration. Building up the source cost functions we eliminate any technology choices which yield non-convex regions of the cost curve. National cost curves therefore will exhibit non-decreasing marginal costs and the most cost-effective techniques will be the proper abatement techniques for the national decision maker.

Table 2 presents the chemicals emitted by twelve source categories (either ODS substitutes or industrial) and the reasons of these emissions (in parentheses).

Table 2: Chemicals emitted by source category

ODS Substitutes (emissions causes)	
Source Category	Emitted Chemicals
<i>A/C and REF</i> (system leakages and emissions during equipment service and disposal)	HFC-32, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-236fa
<i>Foams</i> (blowing agent released during foam manufacture, use and disposal)	HFC-134a, HFC-152a, HFC-245fa, HFC-365mfc
<i>Solvents</i> (leakages from cleaning equipment and evaporation from open-air use)	HFC-43-10mee, various PFCs and PFPEs
<i>Metered-dose inhalers</i> (Propellant released in delivering medicine to lungs)	HFC-134a, HFC-227ea
<i>Aerosol</i> (Propellant released to deliver product)	HFC-134a, HFC-152a
Fire control (agent emitted from system leakages and in fire extinction)	CF ₄ , HFC-23, HFC-227ea, HFC-236fa
Industrial (emissions causes)	
Source Category	Emitted Chemicals
<i>HCFC-22 production</i> (byproduct of incidental overfluorination)	HFC-23
<i>Aluminium production</i> (byproducts formed)	CF ₄ , C ₂ F ₆
<i>Semiconductor manufacture</i> (fluorine sources for etching circuits, cleaning chambers)	CF ₄ , C ₂ F ₆ , C ₃ F ₈ , C ₄ F ₈ , SF ₆ , HFC-23, NF ₃
<i>Magnesium production and casting</i> (cover gas to prevent oxidation of magnesium. Various leakages)	SF ₆
<i>Electrical equipment manufacture</i> (gas equipment insulation)	SF ₆
<i>Electrical equipment use</i> (Insulating gas emitted from leaks and during equipment service and disposal)	SF ₆

Source: Modified from Schaefer *et al.*, (2006, p. 65)

Next we now examine the available sectors and the associated activities. For HFCs emissions, the following activities may be considered

- **Emissions of HFC-23 gas as by-product from the production of HCFC-22.**

The latter is produced both for the final use as for instance in refrigeration and air-conditioning systems and foam manufacturing or as a feedstock for the production of other fluoroorganics like PTFE. The formation of HFC-23 depends

on process and manufacturing conditions adopted and may vary from 1.5% to 4% of the HCFC-22 production (Rhiemeier and Harnisch, 2009).

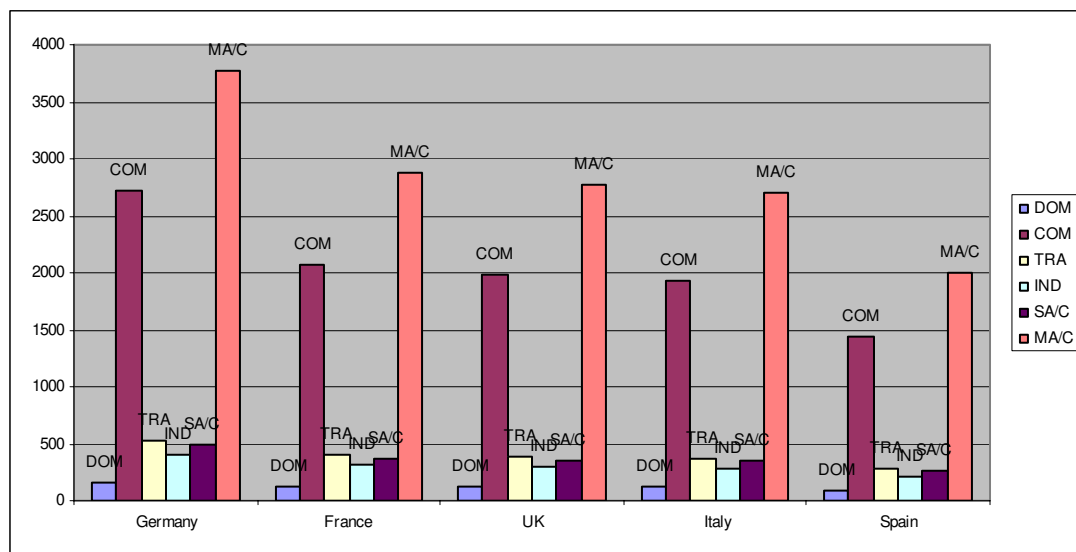
- **Cooling and stationary air conditioning.** To differentiate among emissions and cost differences among sources, five sub-sectors are considered. Namely, domestic small hermetic refrigerators; commercial refrigeration; refrigerated transport; industrial refrigeration; and stationary air conditioning.

Commercial refrigeration is the second largest emitter due to leakages during installation, maintenance and disposal of systems. It consists of three categories of equipment: stand-alone, condensing units and centralized systems. Commercial refrigeration main control method is the leakage reductions, the regular inspections (say twice a year) and the installation of leak detectors in refrigerants over 300kg. Due to CFC ban, commercial refrigeration use HCFC-22 and HCFC blends. Since 2000, the European Regulation 2037/2000 banned HCFC in all refrigerating equipments. Industrial refrigeration applications involve food processing, heat recovery, process refrigeration and industrial heat pumps. Main refrigerants are ammonia and HFC (replacing CFC and HCFC). According to UNEP (2006), the annual leakage is approximately 8-10%.

In the case of transport refrigeration a study by Schwarz and Rhiemeir (2007) showed that for the EU-27 transport emissions in the maritime and railway sectors were 447 kt CO₂ eq in 2006, reaching the level of 2.8 m t of CO₂ eq or 7% of the total HFC emissions from refrigeration and A/C sector in 2010. In stationary A/C main refrigerants used are HFC-407C, R134a and R410. Emissions take place during installation, operation and disposal.

Figure 2 presents HFC emissions from refrigeration and A/C in 2005 for a number of industrialized countries (modified from Rhiemeier and Harnisch (2009)).

Figure 2: HFC emissions from refrigeration and A/C in 2005 for main pollutants



- Mobile air conditioning.** Mobile A/C are the major source of fluorocarbon emissions due to their increased use and their large leakages. Emissions from this activity may be calculated as a function of vehicles and the annual use of the refrigerant (approximated by the average lifetime of the vehicle). GAINS estimates the use of HFC as a function of the total of light-duty vehicles, the penetration of HFC-based air-conditioners, the vehicle lifetime (around 12 years) and the average charge of HFC per car (0.67 kg HFC-134a per vehicle) (Tohka, 2005). Currently 97 m air conditioned cars were in use in the EU-27 (Rhiemeier and Harnisch, 2009; Eurostat, 2006; IPCC/TEAP, 2005).
- Aerosols.** HFCs may be emitted from applications where HFCs are used as propellant (aerosol propellant cans, metered dose inhalers in medical cases like the asthma inhaler).
- Aerosol foams.** They are used in cavities joining inner fixtures in housing construction. They are also called polyurethane (PU) one component foam (OCF). Since 2008, OCFs that use HFCs is banned by EC Regulation No 842/2006. According to UNEP (2006) in Europe and in 2005 almost 85% of the propellants used were hydrocarbons like propane and butane.

- **Other foams.** They may include a number of different polyurethane foams (PU appliances, PU blocks, PU sprays, PU pipe, etc). Their end of use emissions are a function of the end of life treatment. The estimation of these emissions is very difficult. For PU foams, CO₂ alone or in combination with ethanol, hydrocarbon or water may be mainly used as blowing agents instead of extruded polystyrene (XPS). This method may have even 100% abatement efficiency.

Under the Montreal Protocol and after the ban of chlorofluorocarbons, hydro fluorocarbons are mainly used in the production of foams as blowing agents in a solidifying matrix of a polymer. The two main types are polyurethane (PU) and extruded polystyrene (XPS). PU one-component foams (OCF) are found in pressurized cans. HFC-134a and HFC-152a may be used as propellants in the case of OCF. Three fourths of the emissions are emitted with the use of foams and the rest of leakages take place within a year from the foam. XPS is mainly used in buildings for thermal insulation like in roofing or in exterior walls. Other PU foams are met in refrigerators and freezers.

- **Other HFC emission sources.** Here we may have fire extinguishers, specific air-conditioning and refrigerator cases, etc.

PFCs comprises various substances like CF₄, C₂F₆, C₃F₈ and c-C₄F₈ and emissions come from the production of aluminium and semiconductors. Specifically:

- **Primary aluminium production.** This is the main source of two anthropogenic types of PFCs emissions (CF₄ and C₂F₆). PFC is produced during the “anode effects”, which are upset conditions taking place when the level of aluminium oxide is reduced to very low level and the electrolytic bath starts to go through electrolysis.

- **Semiconductor industry.** This industry uses among others HFC-23, CF₄, C₂F₆, C₃F₈, SF₆, NF₃ in the production of plasma etching thin films (etch) and plasma cleaning chemical vapour deposition (CVD) tool chambers.

According to ESIA (2006), the European semiconductor industry emitted 2090 kt CO₂ eq in 2003. For the production of semiconductor devices, industry demands gaseous fluorinated compounds, silanes and other inorganic gases. Semiconductor processes use PFCs in the form of C₂F₆, C₃F₈, CF₄ and c-C₄F₈ as etching gases for plasma etching or in order to perform a rapid chemical cleaning on Chemical Vapour Deposition (CVD) tool chamber (mainly C₂F₆ and CF₄). CVD chamber cleaning emissions account for 80% of semiconductor emissions (USEPA, 2006b).

For SF₆ the main sources of emissions are the following:

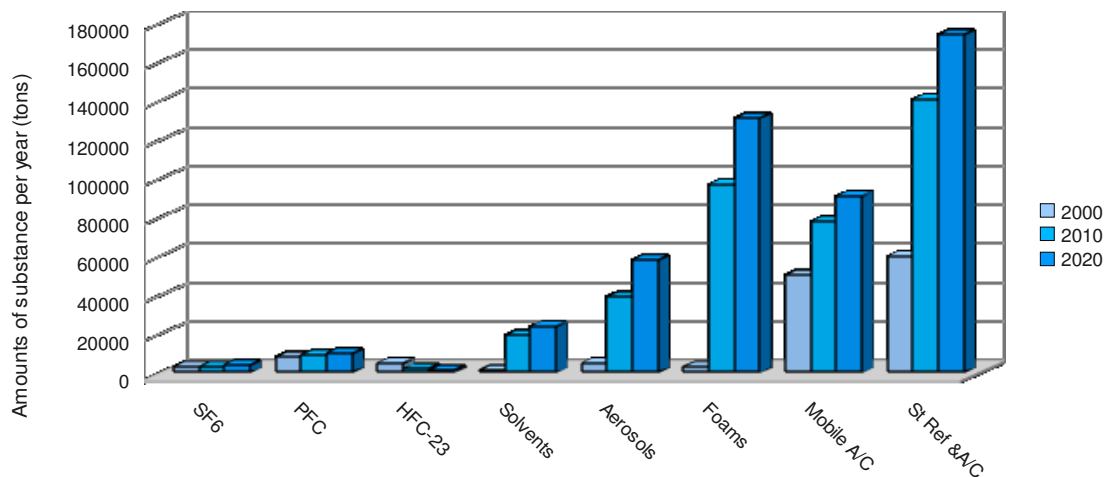
- **High- and mid-voltage switches.** Most of the SF₆ is stored in gas-insulated switchgears in the case of high and mid-voltage electrical networks. Emissions are a function of the age of the gas insulated switchgear (GIS).
- **Magnesium production and casting.** Production as well as casting of magnesium in primary and secondary magnesium are important sources of SF₆ emissions. SF₆ is used as gas in magnesium metalworks to sustain the molten magnesium from oxidation. That is SF₆ is used as a component to protect the surfaces of molten magnesium from igniting in the air with explosion. It may be used in casting operations at primary and secondary magnesium smelters, die casting plants and gravity casting plants.

To calculate the activity of F-gases we must include the emissions of the whole life cycle of equipment (e.g. a refrigerator). The life cycle consists of three phases: installation/manufacture, lifetime of the equipment (bank) and the end of its use (scrap). Emission during installation and manufacture are considered negligible. Emissions during lifetime are assumed as a fixed percentage of the stock (bank) of the

gas under investigation, mainly HFC in our case, in the lifetime (bank) of appliances. Emissions at the end of the use of the equipment occur when the product is scrapped and their measure depends on number of appliances being scrapped in that year.

Figure 3 presents estimates for the European substance amounts of HFC, PFC, SF₆ distinguished by single applications for the years 2000, 2010 and 2020. The projections have been produced according to the model of Harnish *et al.*, (2001). Applications in stationary refrigeration and air-conditioning (St Ref & A/C), mobile air-conditioning (Mobile A/C), as well as production of insulation foams have the greatest weight concerning amounts of substance per year in tons. Generally, we can conclude that the highest amounts of substances are observed in 2020 in contrast to 2000 and 2010 in almost all applications. In all cases but in HFC-23 we can observe an increasing trend.

Figure 3: Estimates for the European substance amounts of F-gases for 2000-2020



Similarly and after modifying the information and the projections provided by Rhiemeier and Harnisch (2009) for F-gases emissions by sector and activity for European countries and the EU-27, Figures 4-5 provide interesting information on the trend of these gases. Specifically, Figure 4 presents F-gases emissions in 2020 for the

European countries. Figure 5 presents the HFC, PFC and SF₆ emissions for EU-27 in the years 2005, 2020 and 2030.

Figure 4: F-gases emissions in 2020

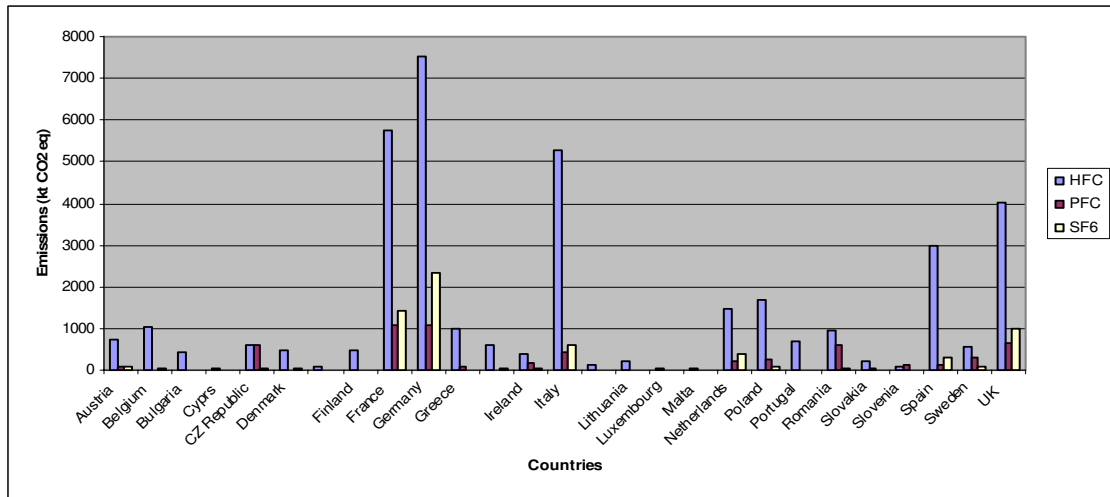
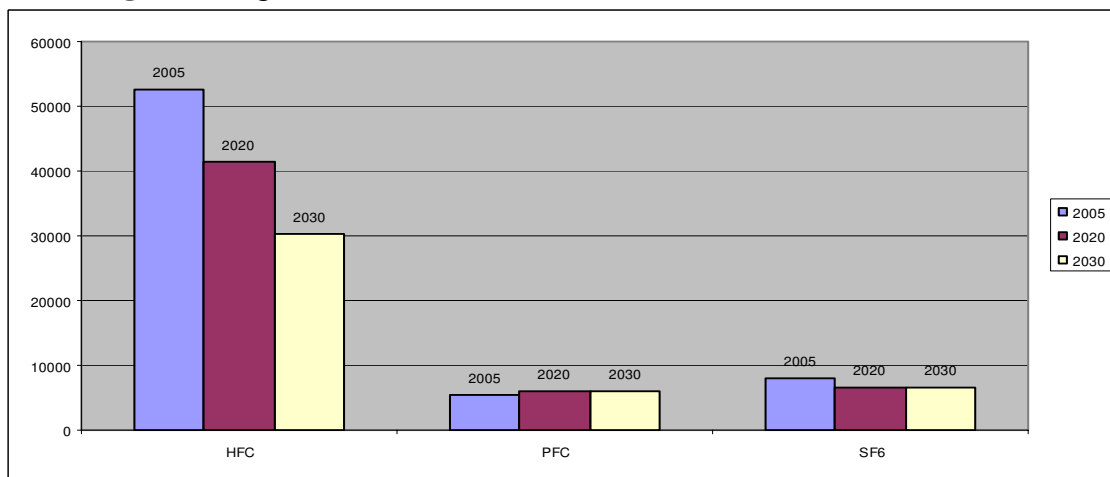


Figure 5: F-gases emissions for EU-27 in 2005, 2020 and 2030



Let us now present an example for calculating average lifetime emissions for each of the five sub-sectors of cooling and stationary air conditioning sector. Table 2 summarizes the emission factors assumed by activity together with the emissions control methods adopted as well as the associated GWP. Similarly Table 3 presents the main parameters in estimating the average lifetime emissions. From Table 3, it can be seen that the average lifetime emissions of industrial refrigerators is 0.115 kg, representing total stock and total amount of scrapped HFC in a given year. The same explanation may be given in all other cases.

Table 2: Emission factors assumed by activity

Activity	Emission control	Emission Factor t F-gases	Emission factor t/CO ₂ eq /t F gases used	GWP
HCFC-22 production	Thermal oxidation	0.02		11700
Domestic end of life	Good practice	1	1300	1300
Commercial lifetime	Good practice	0.2	545	2726
Commercial end of life	Process Modifications	1	2726	2726
Transport lifetime	Good practice	0.2	400	2000
Transport end of life	Use of open CO ₂ REF	1	2000	2000
Industry lifetime	Good practice	0.15	390	2490
Industry end of life	Process Modifications	1	2600	2490
A/C lifetime	Good practice	0.1	163	1627
A/C end of life	Process Modifications	1	1627	1627
Mobile A/C lifetime	Good practice	0.1	130	1300
Mobile A/C end of life	HFC134a replaced by pressurized CO ₂	1	1300	1300
OC	Alternative blowing agent	1	1300	1300
OF	Alternative blowing agents	1	815	815
Aero	Alternative propellants	1	1300	1300
PFC Aluminium	PFPB	0.06		
	CWPB	0.4		
	SWPB	1.9		
	VSS	0.7		
	HSS	0.7		
PFC Semiconductor	Alternatives	1	6500	6500
SF₆				
GIS	Good practice	1	23900	23900
Magnesium	SF ₆ replaced by SO ₂	1	23900	23900
Windows	Alternatives	1	23900	23900
SF ₆ Other	Alternatives	1	23900	23900

Source: Modified from Tohka (2005).

Table 3: Parameters for calculating average lifetime emissions per sector

	Domestic	Commercial	Transport	Industry	Stationary A/C
Lifetime emission factor	0.01	0.15	0.20	0.15	0.1
End of life emission factor	1	1	1	1	1
Mean lifetime of equipment (years)	15	10	7	15	15
Average refrigerant charge (kg HFC/unit)	0.1	30 - 300	6	80	60 g/m ³
Average lifetime losses of HFC ¹ (in kg)	0.115	Small Ref 75 Big ref 750	14.4	260	150

Source: Modified from Tohka (2005).¹ Personal calculation.

5. Deriving a stepwise marginal abatement cost curve for F-gases

Given the generic engineering capital and operating control cost functions for each efficient abatement technology, total and marginal costs of different levels of chemical reduction at each individual source and in the national (country) level can be constructed. According to Halkos (1995), the cost of an emission abatement option is given by the total annualized cost (TAC) of this abatement option, including capital and operating cost components. Specifically:

$$TAC = \left\{ (TCC) \left[r / (1 - (1 + r)^{-n}) \right] \right\} + VOMC + FOMC$$

Where TCC is the total capital cost; VOMC stands for the variable operating and maintenance cost; FOMC is the fixed operating and maintenance cost; $r/[1-(1+r)^{-n}]$ is the capital recovery factor at real discount rate r , which converts a capital cost to an equivalent stream of equal annual future payments, considering the time value of money (represented by r). Finally, n stands for the economic life of the asset (in years).

The estimation of the annual operating and maintenance costs requires a great deal of information and consists of a fixed portion that is dependent on the use of the plant and a variable portion dependent on the prices and the specific demand for energy due to abatement process. Particularly, some parameters are common to all countries like technology specific data (abatement efficiency, unit investment costs) while some others differ per country like the average size of installations in a sector, the chemical content, the additional demand for energy, increased/decreased energy demand for running the device (fans, pumps, etc), annual operating hours, annual fuel consumption, mileage for vehicles, prices for labour, electricity, construction and waste disposal.

Additional, important factors for differences among countries in average mitigation costs are due to differences in HFC compounds used in every country,

unabated emission factors and load factors of annual use of equipments. Unabated emission factors may be calculated relying on the instructions given by the Intergovernmental Panel on Climate Change (IPCC).

Table 4 presents the abatement efficiencies, the capital, the O and M costs as well as the average costs of PFC and SF₆ control. Similarly, Table 5 presents the abatement efficiencies, the capital costs, the fixed and variable O and M costs as well as the average costs of HFC control options.

Table 4: Costs of PFC and SF₆ control options.

Abatement measure	Abatement efficiency (%)	Investment costs [€/t aluminium]	O&M costs [€/t aluminium /year]	Average costs (€/t CO ₂ eq.)
PFC				
VSS to PFPB conversion	92	2,200	0	39.0
VSS retrofitting	26	250	-10	-2.0
SWPB to PFPB conversion	97	5300	-75	-3.0
SWPB retrofitting	26	592	0*	-4.9
Semiconductor	99			26
SF₆				
GIS	84			3.6
Magensium	100			0.1
Wind	100			0.1
SF ₆ Other	100			0.1

Modified from Tohka (2005). Assumed interest rate 4%, process lifetime 20 years and 20 €/activity transaction costs. **Sources:** Harnisch *et al.*, (2004), Harnisch and Hendriks (2000)

In our study we use the methods as proposed by Schaefer *et al.*, (2006), which are depicted in the first column in table 6, and a number of abatement options for F-gases as discussed above. This information is presented in Table 6. Data about emission sources, technologies description and emission removal efficiencies have

been taken from Tohka (2005) for the year 1995 and 43 countries/regions and Total Abatement Costs are calculated by applying Halkos (1995) methodology⁵.

Table 5: Costs of HFC control options

Sector	Technology	Investment (€ /ton of HFC)	Life-time	Control efficiency (%)	Electricity use (% increase)	O&M Costs (€/activity / year)	Average Control Cost in €/tCO ₂ eq
HCFC22 Production	Post combustion	15000	10	95	0	2000	0.35
Industry	Good practice	3333	15	42	0	5000	15.1
	Process modifications	51192	15	100	3	7163	21.3
Commercial	Good practice	10000	10	33	0	5000	18.1
	Process modifications	100000	10	100	15	5250	24.6
Transport REF	Good practice	12500	15	100	0	5000	17.8
A/C	Process modifications	80000	20	30	20	7000	49.8
	Good practice	8333	20	100	0	3000	38.9
Domestic	Recollection	150000	15	50	0	0	14.6
Mobile A/C	Alternatives	50	12	100	0	0	25.6
	Good practice	10	12	80	0	1.24	22.7
OCF	Alternatives			85	0	0.4	4.9
Other Foams	Alternatives			100	0	4.9	1.0

Modified from Tohka, (2005). **Sources:** Devotta *et al.*, 2004; Harnisch and Schwarz 2003; Harnisch and Hendriks 2000; Heijnes *et al.*, 1999; Jyrkonen 2004, USEPA 2001; Oinonen and Soimakallio 2001; Pedersen 1998 and Kaapola 1989.

Post combustion through thermal oxidation is the process of oxidizing HFC-23 to CO₂, hydrogen fluoride and water. Good practice is considered a package of measures including improved components, leak maintenance and prevention and end-of-life recollection of the refrigerant. Process modification changes the process type from ordinary to secondary loop systems and in some cases to alternative refrigerants. Modifications may require lower refrigerant charge, may have lower leak rates and allow the use of flammable or toxic refrigerants. The loss of energy efficiency is the

⁵ In the absence of available data, we have not calculated TAC for PFCs and SF₆.

disadvantage of secondary loop system. We may also consider the use of ammonia and hydrocarbons as alternative refrigerants for stationary cooling and stationary A/C systems. For MA/C and refrigeration transport a major alternative is pressurized CO₂.

The following figure presents the abatement cost curve for the F-gases in total for EU-27 and for the year 2020. In this Figure the order of introduction of the abatement methods is SO₂ cover gas, alternatives, incineration, alternative propellants, SWPB retrofit, alternative refrigeration lifetime and end of life, SWPB to PFPB conversion, good practice, alternative blowing agents, VSS retroffiting, recollection, industry good practice lifetime and end of life, transport good practice lifetime and end of life, commercial good practice lifetime and end of life, mobile A/C good practice lifetime and end of life, semiconductor alternatives, alternative refrigeration lifetime and end of life, process modification lifetime and end of life, good practice lifetime and end of life, VSS to PFPB conversion, process modification lifetime and end of life.

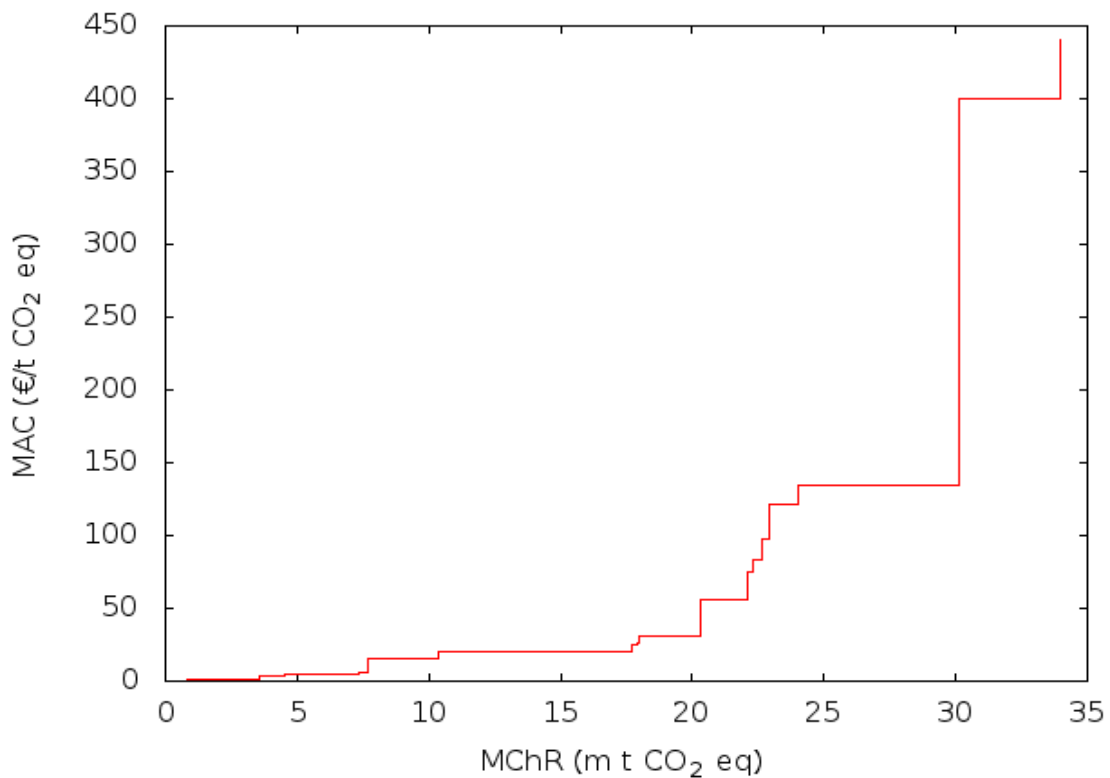
In the case of HFCs, the order of introduction is alternative propellants, transport alternative refrigeration lifetime and end of life, alternative blowing agents, recollection, industry good practice lifetime and end of life, transport good practice lifetime and end of life, commercial good practice lifetime and end of life, mobile A/C good practice lifetime and end of life, mobile A/C alternative refrigeration lifetime and end of life, commercial process modification lifetime and end of life, industrial process modification lifetime and end of life, A/C good practice end of life and lifetime, A/C process modification end of life.

Similarly the order of introduction of the mitigation methods in the case of PFCs is SWPB retrofit, SWPB to PFPB conversion, VSS retroffiting, semiconductor alternatives, VSS to PFPB conversion, while in the case of SF₆ the order of introduction is magnesium production and casting, windows lifetime, SF₆ other and good practice in gas insulated switchgear.

Table 6: Abatement options approaches for F-gases

Method	Gas	Emission Source	Technology description	Emission removal efficiency	TAC
Substitution	HFC	Transport refrigeration (bank)	Alternative refrigerant: use of open CO2 refrigerant system	100%	1719
		Transport refrigeration (scrap)		100%	1719
	PFC	Primary aluminium production	SWPB to PFPB conversion	97%	-
			VSS to PFPB conversion	92%	-
		Semiconductor manufacture	Alternative solvent: use of NF3	99%	-
SF ₆	Magnesium production and casting	Alternative protection gas: SF6 replaced by SO2	100%	-	
Improved Containment	HFC	Industrial refrigeration (bank)	Good practice: leakage control, improved components	42%	5366
		Commercial refrigeration (bank)		33%	6423
		Transport refrigeration (bank)		80%	6372
		Stationary air conditioning (bank)		30%	3786
Recovery and Recycling	HFC	Industrial refrigeration (scrap)	Good practice: end-of-life recollection	88%	5366
		Commercial refrigeration (scrap)		80%	6423
		Domestic hermetic refrigerators (scrap)		80%	16459
		Transport refrigeration (scrap)		20%	6372
		Stationary air conditioning (scrap)		88%	3786
	SF ₆	High and mid voltage switches	Good practice: leakage control and end-of-life recollection	84%	-
Modified product design	HFC	Industrial refrigeration (bank)	Process modification including alternative refrigerants	100%	12780
		Industrial refrigeration (scrap)		100%	12780
		Commercial refrigeration (bank)		100%	19481
		Commercial refrigeration (scrap)		100%	19481
		Stationary air conditioning (bank)		100%	3786
		Stationary air conditioning (scrap)		100%	14546
Process optimization	PFC	Primary aluminium production	SWPB retrofitting	26%	-
			VSS retrofitting	26%	-
Destruction	HFC	HCFC-22 production	Incineration: post combustion of HFC-23 emitted from production of HCFC-22	95%	4135

Figure 6: F-gases Marginal Abatement Cost curve for EU-27 in 2020



5. Concluding Remarks and limitations

This study presented first the basic hypotheses behind the construction of control cost curves discussing analytically the principles of calculation. The economic and technical assumptions in cost calculation and the specific estimations in the case of F-gases were analytically discussed and a sequence of efficient methods provided us with the long run marginal cost of abatement.

In abating F-gases, it is found as more cost-effective to start abating SF₆ gases first, then moving to PFCs and then applying control methods to HFCs. Important activities emitting F-gases in 2020 are air conditioning and refrigerator sectors and aluminium industry. More than 20 abatement options to mitigate F-gases and their costs were presented. The existing results show average cost per ton CO₂ controlled using these methods to range from 0,11 to 50 €/tCO₂eq. Half of these options have cost below 15 €/tCO₂eq.

The policy implications are interesting. Concerning domestic refrigeration attention must be given to the improvement of recovery efficiency for old equipments containing still HFC-134a instead of isobutane (HC-600a) or propane (HC-290). Better recovery to prevent emissions at the end of life stage is necessary.

In industrial refrigeration, leak detectors are important in order to reduce emissions by leakages while regular service inspections are required. Ammonia (R-717) is used as refrigerant in large installations worldwide while CO₂ can be used as a secondary refrigerant and it can also be used in applications with evaporation temperatures down to -52° C and up to 5° C (Rhiemeier and Harnisch, 2009).

In stationary A/C improvement in the design and installation of systems, maintenance and repairing of systems, refrigerant recovery during servicing, recycling of recovered refrigerants are some of the ways to reduce leakages. In mobile A/C inspections are important. For PU foams a main mitigation option is the use of hydrocarbons instead of HFCs.

In the case of sulphur hexafluoride emission abatement the main control methods are improved recovery, minimization of leakages and optimal use. In the case of the manufacture and use of GIS, the main control methods are proper design, gas recovery, re-use and training of personnel handling SF₆.

A number of uncertainties are associated with the emission factors for mobile and stationary A/C as well large differences in some sectoral GWP values between countries. At the same time, transaction costs are likely to vary significantly and depend on the applicable mitigation technology and other factors. The analysis of cost curves often does not include the transaction costs, given the lack of comprehensive data (USEPA, 2006a). Furthermore, technologies generally improve over time and costs decrease. Option's parameters are not changed according to the technological change. This limitation leads to underestimating abatement potential.

Additionally, MAC curves do not have direct connection with macroeconomic indicators such as GDP and utility losses and represent direct cost effects with no feedback to the overall economy (den Elzen, 2005). Furthermore, a better representation of MACs is the dynamic approach which includes assumptions about rates of technological progress and better baseline projections (USEPA, 2006a). The limited use of regional data is another considerable limitation. Lack of country specific data leads to a reliance on expert judgement because the makeup of the current infrastructure in a given country, in a given sector is uncertain. Incorporating regional data result in enhancing the range of emissions sources as well as mitigation options which are addressed in an analysis (USEPA, 2006a).

At last, it is worth mentioning that, as in any environmental problem, we may expect synergies to be present in the case of F-gases mitigation. Tohka (2005) claims that using alternative refrigerants may increase electricity use in some sectors like commercial, industry and air-conditioning. At the same time, mobile air-conditioning increases both HFCs emissions and fuel consumption leading to more emissions of other gases too. Primary aluminium production is also associated with particulate matter (PM) emissions and its abatement will also influence PM emissions (Klimont *et al.*, 2002). Finally, mitigation of PFC emissions influences also CO₂ emissions (Houghton *et al.*, 1997).

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