

# The Role of Non-CO<sub>2</sub> Greenhouse Gases in Meeting Kyoto Targets<sup>1</sup>

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## Abstract

Preliminary analysis indicates that careful consideration of non-CO<sub>2</sub> greenhouse gas emissions and sinks from a variety of sources as provided in the Kyoto Protocol is warranted. Sources, projections, abatement options and uncertainties in these estimations are investigated in support of Post-Kyoto assessments of burden sharing in the European Union. Despite large uncertainties, evidence is given that in particular methane, nitrous oxide and hydrofluorocarbons play a significant role in meeting Kyoto targets by EU member states. Their emission reduction is forecast to contribute one quarter to the total emission reduction in 2010, given the emission reduction goals of individual European countries.

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<sup>1</sup> Paper prepared for the workshop: "Climate Change and Economic Modelling: Background Analysis for the Kyoto Protocol". OECD Headquarters, Paris, 17-18 September, 1998.

## 1. Introduction

The Kyoto protocol covers six categories of greenhouse gas (GHG) emissions: carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphurhexafluoride (SF<sub>6</sub>). Apart from the emissions, biomass carbon sinks are taken into account [1].

Table 1: *Non-CO<sub>2</sub> GHG characteristics and emission sources (EU-15)*

Substance	Chemical formula	GWP 100 years <sup>2</sup>	Main sources in Western Europe. Percentage indicates the relevance for the reference year.
Methane	CH <sub>4</sub>	21	Ruminants 40%, landfills 40%, fugitive fuel 20%
Nitrous oxide	N <sub>2</sub> O	310	Fertilizers 40%, chemical industry 35%, combustion processes 25%
HFC-23	CHF <sub>3</sub>	11700	CFC <sup>3</sup> alternatives: insulation and packaging foams, cooling
HFC-32	CH <sub>2</sub> F <sub>2</sub>	650	equipment, fire extinguisher, dry cleaning, aerosol . Some
HFC-41	CH <sub>3</sub> F	150	process emissions in the chemical industry (HFC-23)
HFC-43-10	C <sub>5</sub> H <sub>2</sub> F <sub>10</sub>	1300	
HFC-125	C <sub>2</sub> HF <sub>5</sub>	2800	
HFC-134	CHF <sub>2</sub> CHF <sub>2</sub>	1000	
HFC-134a	CH <sub>2</sub> FCF <sub>3</sub>	1300	
HFC-143	CHF <sub>2</sub> CH <sub>2</sub> F	300	
HFC-143a	C <sub>2</sub> H <sub>3</sub> F <sub>3</sub>	3800	
HFC-152a	C <sub>2</sub> H <sub>4</sub> F <sub>2</sub>	140	
HFC-227ea	C <sub>3</sub> HF <sub>7</sub>	2900	
HFC-236fa	C <sub>3</sub> H <sub>2</sub> F <sub>6</sub>	6300	
HFC-245ca	C <sub>3</sub> H <sub>3</sub> F <sub>5</sub>	500	
HFC-356	C <sub>4</sub> H <sub>4</sub> F <sub>6</sub>	unknown	
Perfluoromethane	CF <sub>4</sub>	6500	Primary Aluminium production 80%, CFC alternatives
Perfluoroethane	C <sub>2</sub> F <sub>6</sub>	9200	
Sulphurhexafluoride	SF <sub>6</sub>	23900	High voltage switches 80%, magnesium casting

The body of knowledge regarding emission quantities, emission trends, sources and abatement options is less well developed for non-CO<sub>2</sub> GHGs than for CO<sub>2</sub>. This paper discusses non-CO<sub>2</sub> GHG emissions and emission reduction options for Western Europe. Table 1 details the gases that are involved in these categories. The Global Warming Potential (GWP) of these gases is significantly higher than for CO<sub>2</sub>. As a consequence, it is more relevant to reduce one tonne of non-CO<sub>2</sub> GHG emissions. The main emission sources are also indicated in Table 1. Note that the relevance of emission sources differs per country.

Emission sources for these gases are diverse (Table 1). As a consequence, different strategies must be developed for effective emission reduction in all categories. Note that the bulk of the non-CO<sub>2</sub> emissions is not related to energy use but to a wide array of economic activities. CO<sub>2</sub> emissions are predominantly an energy policy issue, but the reduction of other GHG emissions will involve a number of other policy areas.

## 2. Western European emissions

### Current emissions and future emissions

Table 2 shows the GHG emissions in the countries of the European Union (EU-15) for the reference year<sup>4</sup> and the autonomous trend until 2010 according to the official national reporting<sup>5</sup>. The table shows that CH<sub>4</sub> and N<sub>2</sub>O constitute the bulk of the non-CO<sub>2</sub> GHG emissions in the reference year. The emissions of both gases are expected to decline autonomously until 2010 due to changing

<sup>2</sup> In accordance with the Kyoto Protocol emissions for non-CO<sub>2</sub> GHG are converted into CO<sub>2</sub> equivalents, based on a GWP for 100 years (GWP values are based on IPCC guidelines).

<sup>3</sup> CFC = ChloroFluoroCarbons.

<sup>4</sup> The reference year is 1990 for CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O, 1995 for HFCs, PFCs and SF<sub>6</sub>.

<sup>5</sup> The Kyoto protocol refers actually to the average emissions for the period 2008-2012, hence 2010 is used as an "indicator year" for this period.

agricultural activities, decreasing coal mining and decreasing waste disposal. However, they remain dominant. The relevance of HFCs increases significantly in the same period due to the ongoing substitution of CFCs with HFCs. PFC emissions and SF<sub>6</sub> emissions remain relatively insignificant. Based on these forecasts, policies for non-CO<sub>2</sub> GHG emissions should focus on CH<sub>4</sub>, N<sub>2</sub>O and HFCs.

Table 2: *Current emissions and autonomous trend in CO<sub>2</sub> and non-CO<sub>2</sub> GHGs, EU-15 [2]*

Category	Emission reference year [Mt CO <sub>2</sub> eq.] <sup>6</sup>	Emission 2010 [Mt CO <sub>2</sub> eq.]
CO <sub>2</sub>	3137	3310
CH <sub>4</sub>	457	354
N <sub>2</sub> O	328	272
HFCs	41	70
PFCs	11	7
SF <sub>6</sub>	12	13
Total	3986	4026

Table 3 shows the relative importance of the non-CO<sub>2</sub> GHGs for individual countries. Their contribution ranges from 17% (Germany, Greece and Sweden) to 47% (Ireland).

Table 3: *Contribution of CO<sub>2</sub> and non-CO<sub>2</sub> GHG emissions in the reference year for individual EU-15 countries [2]*

	CO <sub>2</sub>	Non-CO <sub>2</sub>
Austria	78%	22%
Belgium/Luxembourg	82%	18%
Denmark	71%	29%
Finland	83%	17%
France	75%	25%
Germany	83%	17%
Greece	83%	17%
Ireland	53%	47%
Italy	80%	20%
Netherlands	74%	26%
Portugal	67%	33%
Spain	71%	29%
Sweden	83%	17%
United Kingdom	77%	23%
Total EU-15	79%	21%

As a consequence of the different contribution to the national emission budget, the relevance for GHG emission reduction policies differs per country. Generally speaking, the contribution is high for more “agricultural” countries (Austria, Denmark, Portugal and Spain). For the Netherlands, the large chemical industry explains the relevance. In the cases of France and Finland, low CO<sub>2</sub> emissions due to the use of renewables and nuclear energy explain the comparatively high relevance of non-CO<sub>2</sub> GHG emissions.

### Uncertainties

The uncertainty regarding non-CO<sub>2</sub> GHG emissions is higher than the uncertainty regarding CO<sub>2</sub> emissions. The problem is largely neglected by policy makers, but it might cause serious problems for the monitoring of the emission reduction goals. The higher uncertainty compared to CO<sub>2</sub> is caused by the different accounting practice. CO<sub>2</sub> emissions are proportional to the consumption of fossil energy carriers (plus some corrections, e.g. for cement production and for non-energy use [3]). Energy statistics are well established for all Western European countries and CO<sub>2</sub> emissions per unit of fossil energy are fixed. The uncertainty in CO<sub>2</sub> emissions is estimated to be in the range of 2-5%. Non-CO<sub>2</sub> GHG emissions are either calculated on the basis of the consumption of substances that are

<sup>6</sup> Megatonnes CO<sub>2</sub> equivalents. 1 Mt = 10<sup>6</sup> metric tonnes

themselves GHGs<sup>7</sup> (part of the HFCs, part of PFCs, SF<sub>6</sub>) or they are calculated on the basis of a proportionality to certain economic activities (CH<sub>4</sub>, N<sub>2</sub>O, PFCs, part of the HFCs). However the coefficient of proportionality is often uncertain. Main emission categories and sources will be discussed individually to illustrate the problem.

The main CH<sub>4</sub> emission sources are livestock, waste, and fugitive fuel. The uncertainty is not as high as for the other non-CO<sub>2</sub> GHGs. It is estimated that the uncertainty is  $\pm 25\%$  [ ]. The main uncertainty relates to the emissions from waste. It is interesting to note the different accounting practices for CH<sub>4</sub> from landfill use. Either actual emissions or potential emissions are accounted. In the potential emission accounting practice, an emission coefficient (kg CH<sub>4</sub>/t disposed waste) is applied to the waste that is annually disposed of. This coefficient represents the emissions for this waste during the whole period beyond disposal. Significant differences exist regarding national CH<sub>4</sub> emission factors for landfilling [4]. For example the emission factor in Germany is ten times higher than the emission factor in the UK. Some countries such as the Netherlands use a more accurate actual emission accounting practice. This approach is based on dynamic simulation models for methane emissions from landfill sites: methane emissions are estimated on the basis of waste disposal in earlier years. Actual and potential emissions can differ significantly in a situation with a changing waste handling practice. This is the case in many Western European countries. Such accounting differences are largely neglected in the current discussion. However a different accounting practice has consequences for the relevance of emission reduction options. If the potential emission approach is applied, reduction of waste disposal will result in a more rapid decline of emissions than in case an actual emission approach is applied. The difference can be significant in the framework of the Kyoto protocol.

The most important N<sub>2</sub>O sources are agriculture, combustion processes (including catalytic conversion in cars), and industry. The use of nitrogen fertilizer in the agricultural sector is a source of 30-50% of the total emission. This emission depends highly on the soil type. Agricultural N<sub>2</sub>O emissions are related to the use of nitrogen (N) fertilizers (both synthetic fertilizers and manure). In some Western European countries, net degradation of organic soils adds to the N<sub>2</sub>O emissions from fertilizer use (this is not accounted for in the IPCC guidelines). For example the degradation of Swedish cultivated peatland which represents less than 10% of the total agricultural land, accounts for 25% of the N<sub>2</sub>O from agricultural land [5]. The relation between fertilizer use and N<sub>2</sub>O emissions is still poorly understood. Recently grazing animals on managed pastures and rangelands have been identified as significant contributors to the global N<sub>2</sub>O budget. The effects of grazing animals on N<sub>2</sub>O emissions are brought about by the concentration of herbage N in urine and dung patches, and by the compaction of the soil due to treading and trampling. The limited amount of experimental data indicates that 0.1 to 0.7% of the N dung and 0.1% to 3.8% of the N in urine is emitted to the atmosphere as N<sub>2</sub>O. The average mean of the N excreted that is converted to N<sub>2</sub>O is 2% [6]. This is substantially higher than the 1.25% of the nitrogen input that is accounted for according to IPCC emission accounting guidelines, starting from fertilizer use. The application of fertilizer on grassland with high groundwater levels (such as parts of the Netherlands) results in emissions that are one order of magnitude higher than the emissions from the same fertilizer, applied on dry cropland. It is not clear to which extent these differences are accounted in the current national emission estimates. It is estimated that the uncertainty regarding N<sub>2</sub>O from agriculture is a factor 2-3.

Regarding industrial emissions, the production of adipic acid and the production of nitric acid (HNO<sub>3</sub>) are major emission sources. These emissions depend to some extent on the applied technology. The uncertainty in the emission estimates is a factor 1.5. Regarding emissions from transportation, the use of catalytic converters will result in increasing emissions. The uncertainty is estimated to be a factor 1.5. In conclusion, the uncertainty in the total national N<sub>2</sub>O emissions is estimated to be a factor 2.

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<sup>7</sup> With some corrections for substance storage in products, see below

The PFC emissions for new or refurbished aluminium smelters with point-feeders is one order of magnitude lower than the emission from older type smelters. Some countries account for such differences, others use a more crude emission estimate. The emission is further influenced by the housekeeping of the smelter (control of the smelting bath composition). This adds another factor 2 to the uncertainty. The total uncertainty is a factor 3-4.

The emissions related to the consumption of substances that are themselves GHGs (HFCs and SF<sub>6</sub>) are measured according to different methods. In some cases/countries, the apparent consumption is measured (Tier 1-A method, potential emissions). In other cases/countries, the apparent consumption is adjusted for imports and exports of the substances within products (extended Tier 1-A method). Finally, some countries report estimates for actual emissions (on the basis of leakages and/or waste product statistics) (Tier 2 method). Different methods result in different estimates. If different countries use different calculation methods, the comparability of emission reductions is limited. Assuming that the actual emission is the 'correct' value, the difference between the accounted and the reported emission may be a factor 2-5 in the current situation with rapidly growing emissions. The different accounting practice can influence the emission reduction that is calculated for 2010. The actual emission should be considered a superior accounting guideline, because it is thought to be most in line with the IPCC guidelines.

Given the composition of the non-CO<sub>2</sub> GHG emissions and of their sources in the EU member states, the uncertainties regarding non-CO<sub>2</sub> GHG emissions are in the range of a factor 1.5-2. This fact was stressed during the EU climate negotiations in the first half of 1998, during which period several countries adjusted their emission data for non-CO<sub>2</sub> GHGs significantly, both upward and downward. Further adjustments seem likely.

### **3. Abatement options**

This section focuses on key emission abatement options per emission category. Generally speaking, the emissions that are a by-product of economic activities require a different approach than the use of substances that are themselves GHGs. For the first type, end-of-pipe (conversion) and prevention strategies apply (develop other activities, reduce emissions per unit of activity through process adjustments). For the second type, integrated chain management strategies can be applied apart from end-of pipe technology and prevention:

- substitute substances
- reduce consumption (more efficient use, reduce losses)
- recycle/reuse

#### **3.1. CH<sub>4</sub>**

##### *Waste*

CH<sub>4</sub> emissions from landfill sites are related to the decomposition of organic waste. The decomposition rate depends on the waste type. Kitchen waste decomposes rapidly. Paper and wood require more time. Plastics and other synthetic organic materials do not decompose within a period of 100 years. Cellulose and hemicellulose decompose, while the decomposition of lignin is more difficult. As a consequence, a changing waste composition (e.g. because of separate collection) will change the landfill gas production. Landfill gas is generally produced for 20-30 years after the closure of the landfill site. As a consequence, the landfill gas recovery potential in 2010 is partially determined by existing disposal sites and partially determined by landfilling policies until 2010. Existing disposal sites and new disposal sites pose different options for emission abatement.

Nowadays waste disposal is declining in many Western European countries because of waste policies that favour prevention, recycling and incineration. This results in an autonomous decline of the methane emissions. This trend could be further accelerated, e.g. through higher waste disposal fees and a simultaneous construction of new incineration, composting and/or digestion facilities. However it seems unlikely that CH<sub>4</sub> emissions from landfills alone will pose sufficient incentive for major changes in waste policy.

The second option is landfill gas recovery. The recovered gas can be used for energy purposes and thus create financial benefits; flaring is another option. The total landfill gas potential in the EU-15 countries is approximately 170 PJ (200 Mt CO<sub>2</sub> equivalents) [7]. In 1993, the amount of landfill gas extracted was roughly equivalent to 20 PJ (based on [8]).

Costs for methane recovery from waste disposal sites (landfills) range from 0.12 to 0.49 ECU per kg methane (i.e. 6-23 ECU/t CO<sub>2</sub> equivalents). The maximum recovery efficiency for the whole landfill life cycle is 55%, with low recovery rates in the beginning and higher recovery rates in the middle and end stage of the landfill life cycle [9]. The closer the drainage pipes, the higher the efficiency, but the higher the costs. The costs of this type of emission reduction option are well below 10 ECU/t CO<sub>2</sub> equivalents [2]. This option is already successfully applied in a number of European countries and should be developed in the other countries.

### *Agriculture*

Agricultural emissions represent one third to two thirds of the CH<sub>4</sub> emissions in the individual countries. Ruminants and manure storage are main emission sources. The ratio of the emissions from ruminants and manure storage is worldwide 8:1.5. In the Netherlands, the ratio is 4:1 [10]. The average Western European ratio is probably in between both values.

Methane emissions associated with enteric fermentation in ruminants range from 3-8% of gross feed intake. For the vast majority of the world's domestic ruminants consuming a wide range of diets under common production circumstances, CH<sub>4</sub> emissions fall near 6% of diet gross energy. Opportunities for reducing CH<sub>4</sub> emissions from intensively managed cattle are generally aimed at higher product yields per unit of food intake [11]:

- genetic improvement (-10%),
- use of bovine growth hormones (-10%),
- improved feed formulation (-10%),
- a higher protein gain/fat gain ratio (-20%).

Together, these measures can decrease CH<sub>4</sub> emissions from ruminants by 30%. Most of these measures will have limited costs once they are developed. However, genetic engineering and growth hormones face consumer opposition in Europe. As a consequence, the potential for Europe is thought to be limited to a 10% improvement (3% of total CH<sub>4</sub> emissions) at zero cost. One must add that this is a fairly optimistic estimate for 2010. Moreover, these options are well in line with autonomous trends towards increased production efficiency, so the relevance of GHG policies is in this area probably limited.

Concerning manure storage, covered lagoons pose a major reduction option. Approximately 40% emission reduction is possible (2-3% of total CH<sub>4</sub> emissions). Centralized biogas plants exclusively based on the digestion of animal manure are not profitable under the present technological and economic conditions [12]. If 10-25% easily convertible organic matter is added, the plants can achieve break-even conditions, as examples in Denmark show. However, the profitability depends critically on the electricity revenues. In other countries with lower electricity prices the situation is less favourable [13]. Experiences with decentralized agricultural digestion plants were in the past not favourable.

### *Fugitive fuel*

Two main sources exist for fugitive fuel emissions in Western Europe: coal production and transportation and distribution of natural gas. Both will be dealt with separately.

#### **Coal mining**

CH<sub>4</sub> emissions during fossil fuel mining in Western Europe are mainly accounted for by deep coal mining (2-6 Mt CO<sub>2</sub> equivalents for oil and gas production). The emissions are in the range of 5-15 kg CO<sub>2</sub> equivalents/GJ coal, depending on the mine depth (generally higher for deeper mines, open pit mines emit less than 0.5 kg CO<sub>2</sub>/GJ). This adds 5-10% to the emissions in coal combustion. Total emissions from Western European coal mining were approximately 40 Mt CO<sub>2</sub> equivalents (presumably 1995 data) [7]. However, deeper mines are being closed all over Europe because they cannot compete with imported coal. Mine closures in Germany and the UK are considered in the estimates for autonomous emission trends. According to a recent IEA study, coal production in OECD Europe is assumed to fall to less than half its 1993 level by 2010, i.e., to about 80 Mt [14]. Given stable lignite production levels, the remaining hardcoal production will be in the range of 10-20 Mt. The related CH<sub>4</sub> emission is less than 10 Mt CO<sub>2</sub> equivalents, which will further decrease beyond 2010. The reduction of methane emissions from the remaining deep mines is problematic because methane concentrations in the mine off-gases are generally low because of safety reasons (prevent underground explosions). An option may be methane recovery before the coal is mined. Given the technological problems and the ongoing trends towards decreased emissions, Western European policies for this emission source seem less relevant.

#### **Natural gas transmission and distribution**

Western European emissions in gas transportation and gas distribution amount to 20-40 Mt CO<sub>2</sub> equivalents (based on [15]). These emissions are mainly caused by old cast iron and steel distribution networks in cities. These networks are being replaced gradually. Costs for more rapid replacement are high [26].

## **3.2. N<sub>2</sub>O**

### *Industry*

Industrial N<sub>2</sub>O emissions arise in the chemical industry during production of nitric acid (HNO<sub>3</sub>), the production of adipic acid (an intermediate in the nylon 6,6 production) and from a number of other nitrification processes (that are of secondary importance). The countries of the European Union (excluding Italy, Spain, Portugal) reported for 1990 an industrial N<sub>2</sub>O emission of 95 Mton CO<sub>2</sub> equivalents [16].

#### ***Nitric acid production***

Western European HNO<sub>3</sub> production amounted to 18.3 Mt in 1989. Production is relatively stable, because the bulk of this substance is used for N-fertilizer production, which declined in the last decade. The process emission is approximately 3 ton CO<sub>2</sub> equivalents per ton HNO<sub>3</sub>. The total Western European emission from this source is approximately 60 Mt CO<sub>2</sub> equivalents per year. Two options exist to reduce emissions: process integrated measures that require new plants or end-of-pipe measures. The latter type is more promising on the short term. Emissions can be reduced by more than 90% through end-of-pipe equipment, based on catalytic conversion. The concentration of N<sub>2</sub>O in the off-gases is so low that special ovens must be installed to heat the off-gases to the minimum temperature of 300 °C. Emission abatement costs can be calculated on the basis of a case study for a specific plant: 1.5-2.7 ECU per tonne CO<sub>2</sub> equivalents [17]. A pilot plant in Norway resulted in a 70% emission reduction. Further research is aimed at the development of catalysts and temperature optimisation that can achieve an even further emission reduction [20, pp. 55].

### ***Adipic acid production***

Western European adipic acid production amounted in 1992 to 650 kt [18]. Adipic acid is produced in 10-20 industrial plants. Adipic acid is an intermediate in the production of nylon 6,6. Its chemical structure is  $\text{COOH}(\text{CH}_2)_4\text{COOH}$ . Two catalyst systems are applied in the production. One uses  $\text{HNO}_3$ , the other one uses oxygen. In the system that uses  $\text{HNO}_3$ , significant amounts of  $\text{N}_2\text{O}$  are generated as by-product. The  $\text{N}_2\text{O}$ -concentration in the off-gases is 20 volume %. The  $\text{N}_2\text{O}$  emission amounts to 180 kg/t  $\text{N}_2\text{O}$ . This equals a  $\text{CO}_2$  emission of 60 t/t adipic acid (based on [18,19]). For the whole of Western Europe, the emission equals 40 Mton  $\text{CO}_2$ . If oxygen is used, no  $\text{N}_2\text{O}$  is produced. However, this new process is not yet widely applied. Other new process routes start from butadiene. New process routes can eliminate the  $\text{N}_2\text{O}$  emissions on the long term. On the mid-term (the next 10 years), catalytic reduction of  $\text{N}_2\text{O}$  in exhaust gases poses the most attractive alternative [17]. Emission reduction costs are 1 ECU/t  $\text{CO}_2$  equivalents. The major adipic acid producers agreed to a voluntary reduction of their emissions by 90% by the end of 1998 [20, pp. 50-52].

In conclusion,  $\text{N}_2\text{O}$  abatement constitutes for both industrial sources a cost-effective option for greenhouse gas emission reduction. The catalysts are available, retrofit of existing production plants is feasible before 2010. Retrofit can reduce the emissions by more than 90%. Emission reduction costs are low: between 1 and 2.7 ECU/t  $\text{CO}_2$  equivalents. Industry is actively involved and introduction seems imminent.

### ***Agriculture***

Reduction of agricultural  $\text{N}_2\text{O}$  emissions can be achieved through reduced application of fertilizers. Significant differences exist in regional fertilizer use. European synthetic N-fertilization rates range from 195 kg in the Netherlands to values below 50 kg/ha in Southern European countries (Table 4, this excludes manure). These differences can be attributed to different agricultural practices. Generally speaking, the higher the fertilization rate, the higher the fraction of losses.

Recent results show substantial reductions in emissions from grassland by matching fertilizer type and nitrification inhibitors. Also, better timing and placement of N, application of the minimum amount of N to achieve satisfactory yield, and optimization of soil physical conditions, particularly avoidance of excessive wetness and compaction, would be expected to reduce the average emission factor for  $\text{N}_2\text{O}$  [21]. A reduction of 20% seems feasible on a global scale; the effect in Western Europe could be more substantial, given the fertilizer application rates and agricultural  $\text{N}_2\text{O}$  emissions per hectare that are well above the global average.

Table 4: *Synthetic fertilizer use and specific  $\text{N}_2\text{O}$  emissions per ha agricultural land, 1990 [22,23,24].*

Country	N-fertilization [kg/ha]	Emission [t $\text{CO}_2$ equiv./ha]
Belgium	123	2.45
Finland	80	1.20
France	80	0.55
Germany	104	1.72
Ireland	66	1.28
Netherlands	199	3.44
Sweden	63	1.83
UK	82	1.81

Policies must be developed on a regional level, grasslands and cropland require a different approach. Costs are uncertain and will highly depend on the system boundaries (accounting of reduced yields, subsidies etc.).

### ***Transportation***

$\text{N}_2\text{O}$  is generated by catalytic conversion of  $\text{NO}_x$  in exhaust gases. Emissions and reduction strategies are still highly uncertain. Emissions for cars with new 3-way catalysts are 4-5 times higher than emissions for cars without catalyst. Ageing catalysts cause emissions that are even 10-16 times higher



[25]. As a consequence, the relevance of this category will increase with an ageing catalyst stock. Emissions are probably in the range of 10-20 Mt CO<sub>2</sub> equivalents. This issue is currently handled in a European framework.

### 3.3. HFCs

HFC emissions can be split into emissions in production (the bulk of HFC-23 emissions) and emissions during use (in refrigerators, air conditioning equipment etc.). For example the high HFC emission for the Netherlands is accounted for by HFC-23 that is produced as by-product from HCFC-22 production [26]. The emission can be reduced by 90% through installation of cracking installations and after-burners. The other HFC emissions are related to the consumption of substances. Integrated chain management policies should be developed (reduce consumption, substitute and/or recycle). Regarding substitution, alternatives exist for most applications. Substitution of high-GWP HFCs with low-GWP HFCs is a short-term solution. However, as industries moved from CFC to HFC in the last decade, there may be opposition to new policy initiatives. In the meantime, recycling systems should be developed for all cooling equipment, and leakages should be reduced. Estimates suggest a potential emission reduction by 70-80% [25]. Dutch estimates are in Table 5 extrapolated to the European situation.

Table 5: *Options to reduce HFC emissions in 2010 (cost estimates based on [26])*

Measure	Potential 2010 [Mt CO <sub>2</sub> eq.]	Cost [ECU/t CO <sub>2</sub> eq.]
After-burners HCFC-22 production	<10	0.5
Other cooling agents stationary	20	5
Other cooling agents mobile	10	4
Reduce leakages stationary cooling	10-20	50
Reduce leakages mobile equipment	<10	<10

### 3.4. PFCs

PFC emissions are predominantly related to primary aluminium production (aluminium smelters). Some PFCs are used as substitute for CFCs: strategies are for these applications similar to the strategies for HFCs. Some PFCs are used in computer chips manufacturing. However the relevance of these applications is still limited (below 10% of total PFC emissions). Basically, the same strategy should be developed such as for HFCs: substitutes should be developed and materials flow cycles should be closed. This emission category will not be discussed in more detail.

#### *Primary aluminium smelters*

These emissions arise during periods when the alumina concentration in the smelter bath is too low. This causes short-circuiting of the cell, the so-called 'anode effect'. Two major routes exist to reduce these emissions: reduce primary aluminium production or reduce the specific process emissions. Primary aluminium production can be reduced through improved waste recycling; however recycling cannot cover more than 30-40% of the global production, given the rapid increase of aluminium consumption. The losses are currently below 30% of the waste arising. European primary aluminium imports are increasing autonomously. This trend could be further accelerated, simultaneously reducing the CO<sub>2</sub> emissions related to electricity production for aluminium smelters [27]. The effect can be a global emission reduction, if the electricity at the new production locations is based on renewable or nuclear energy. Basically, the same strategy could be applied within Western Europe (e.g. relocation to Iceland, Norway, or France). However, such structural policies are not popular with national policy makers.

Reduction of process emissions is a more promising strategy on the short term. Improved control of the alumina concentration can reduce the anode effect by one order of magnitude. Modern smelters

use so-called point feeders for improved alumina concentration control. This measure is primarily introduced because it reduces the electricity consumption. Autonomous replacement of existing aluminium smelters or upgrading of existing smelters will result in a considerable reduction of these emissions. On the long run, the development of inert anodes can reduce PFC emission to zero. However, successful development of inert anodes before 2010 seems unlikely. The average life of an aluminium smelter is between 25 and 30 years. An autonomous reduction by 75-90% in the next two decades seems likely in the countries with ageing smelters, either through upgrading or through relocation.

### **3.5. SF<sub>6</sub>**

The bulk of SF<sub>6</sub> (about 80%) is used for high voltage equipment where the substance is applied because of its insulating and fire extinguishing properties. The emissions are caused by leakages and waste handling of old equipment. Substituting materials are currently not considered because the inertia of SF<sub>6</sub> is a unique property. However the leakages to the environment can be significantly reduced. The introduction of new sealing materials, the chemical and mechanical treatment of flanges and the improvement of shield welding techniques should help to decrease this leakage rate. Moreover, it is possible to install SF<sub>6</sub> leakage detection cameras. Integrated chain management strategies can be developed for old equipment. The potential for emission reduction is 20-40%. Cost estimates range from 0 to 25 ECU/t CO<sub>2</sub> equivalent [28].

The remainder of SF<sub>6</sub> is mainly used in magnesium casting and aluminium casting in order to prevent metal oxydation. Only magnesium casting results in SF<sub>6</sub> emissions (hence TIER-1 results in an overestimation of emissions). The use of magnesium castings is rapidly growing in the transportation sector due to the weight advantages compared to other metals [29]. While this sector accounts nowadays for less than 5% of the SF<sub>6</sub> emissions, its relevance may increase 2-4 fold during the next decade. No emission abatement options have been encountered for this source.

Finally some SF<sub>6</sub> is used as a solvent in the semiconductor industry (less than 5 Mt CO<sub>2</sub> equivalents in 1995). A rapid growth can be anticipated. This emission can be reduced through improved recovery techniques.

Some SF<sub>6</sub> is used for various applications of secondary importance such as sound insulation glass, sporting shoes, automobile tyres, etc. (together less than 5 Mt CO<sub>2</sub> equivalents). Alternative substances should be investigated.

## **4. Model calculations**

Based on a spreadsheet model for all EU-15 countries [2], the contribution of non-CO<sub>2</sub> GHGs to 8% emission reduction in 2010 has been analysed. The model selects cost-effective emission reduction options to meet a fixed emission target. The emission reduction targets for individual EU countries that were agreed in Luxembourg in the summer of 1998 were applied in this analysis. Figure 1 shows that the contribution of non-CO<sub>2</sub> GHG is 27% to the total emission reduction. Important emission reductions are introduced for CH<sub>4</sub> from landfill sites, N<sub>2</sub>O from the chemical industry, and substitutes for HFCs.

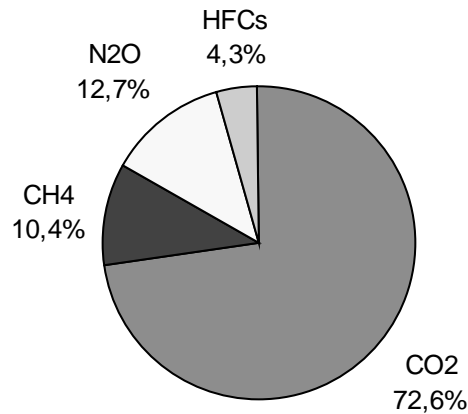


Figure 1: *Contribution of GHGs to 8% emission reduction in 2010, EU-15, based on Luxembourg targets for individual countries*

## 5. Conclusions

Non-CO<sub>2</sub> GHG represent currently 21% of total Western European GHG emissions. They are relevant in the framework of the Kyoto protocol for two reasons. Emissions decrease autonomously and a significant potential exists for further emission reductions, if the proper policies are introduced.

The contribution of non-CO<sub>2</sub> GHG emissions will gradually decrease to 18% due to autonomous developments such as coal mine closures and waste policies. Trends differ per emission category: while CH<sub>4</sub> and N<sub>2</sub>O emissions decrease, HFC emissions will increase significantly. CH<sub>4</sub> and N<sub>2</sub>O represent the bulk of the emissions and remain dominant until 2010 in the autonomous trends.

Significant emission reductions for non-CO<sub>2</sub> GHGs can be achieved within the next decades at relatively low costs (27 % of total GHG emissions below 25 ECU/t CO<sub>2</sub> equivalents). Prime targets are the industrial N<sub>2</sub>O emissions, CH<sub>4</sub> emissions from landfill sites, and HFCs in cooling and airconditioning equipment. PFC emissions in the aluminium industry will decrease autonomously. Regarding SF<sub>6</sub>, a monitoring system should be developed for high voltage equipment. For HFCs, PFCs and SF<sub>6</sub>, alternatives should be developed all types of applications. This will allow legislation to ban their use at a later stage. In the meantime, chain management options (recycling, more efficient use) can reduce emissions. On the long term, agricultural N<sub>2</sub>O emissions and agricultural CH<sub>4</sub> emissions will remain. Fundamental research should focus on solutions for both emission types. Options like biological nitrogen fixation or new protein sources may pose viable alternatives. New emission sources like N<sub>2</sub>O from transportation deserve also more attention.

The emission reduction that will be achieved depends to some extent on the national emission calculation method that is applied. Some emissions are still uncertain, with uncertainty levels well above Kyoto protocol emission abatement goals. This creates loopholes for individual countries that can undermine the credibility of the Kyoto protocol.

Finally Western European conclusions cannot be translated directly to other regions because local emission sources, costs and trends may significantly differ. However, the Western European case suggests that further analysis is warranted.

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