

GREENHOUSE GAS–AIR POLLUTION INTERACTIONS AND SYNERGIES

GAINS

POTENTIALS AND COSTS
FOR MITIGATION OF
NON-CO₂ GREENHOUSE GASES
IN THE EUROPEAN UNION

METHODOLOGY

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This report documents the specific methodology of IIASA's GAINS model on methane, nitrous oxide and fluorinated gases that has been used for estimating baseline emissions and mitigation efforts across the EU-27 countries.

More details are available at <http://gains.iiasa.ac.at>.

Further information on GAINS:

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The views and opinions expressed herein do not necessarily represent the positions of IIASA or its collaborating and supporting organizations.

Executive summary

This report documents the approaches taken to estimate non-CO₂ greenhouse gases, i.e., methane, nitrous oxide and the fluorinated gases in the GAINS model <http://gains.iiasa.ac.at/> as used to assess baseline emissions, costs and potentials of greenhouse gas mitigation in the EU-27 countries. Results estimated using the methodology described here have been presented in a separate report (Höglund-Isaksson et al., 2010).

The methodology described here refers to a specific emission scenario developed in December 2009, which is consistent with projections on the economic development in EU Member States adopted by DG Economic and Financial Affairs in 2009 and used by the PRIMES and CAPRI models to generate future scenarios for the energy and agricultural sectors, respectively. An earlier draft of this report provided detailed background information to a set of activity data and baseline emission estimates that were sent to EU Member States in September 2009 as part of a review process organized by DG Environment. In the present version of the report, methodological changes in response to comments received from Member States have been included.

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1 Introduction

This report presents results of estimations of baseline emissions and mitigation cost curves for emissions of non-CO₂ greenhouse gases in the European Union (EU-27). It addresses the non-CO₂ greenhouse gases included in the Kyoto Protocol, i.e., methane (CH₄), nitrous oxide (N₂O), and the three groups of fluorinated gases hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF₆). This report complements the results report “Potentials and costs for mitigation of non-CO₂ greenhouse gas emissions in the European Union until 2030 -Results” (Höglund-Isaksson et al., 2010). An earlier version of this report was sent on review to EU Member States Sep, 18, 2009 as part of a review process organized by DG Environment, European Commission. Feedback from Member States or other experts on activity levels, emissions or methodology has been regarded in the current versions of the methodology and results reports.

Detailed information on activity data, emission factors, implementation of control technology, and control costs is available via the on-line version of the GAINS model at <http://gains.iiasa.ac.at/>. See Box 1 for instructions how to extract data.

Box 1: How to extract data from the GAINS-online model

1. Go to <http://gains.iiasa.ac.at/>
2. Click on GAINS Online, and the “Europe” box.
3. Log in to the model (you need to register first if you are a new user).
4. Choose the tab of interest, e.g., “Activity Data” or “Emissions” for display of data.
5. Choose the pollutant (CH₄, N₂O or FGAS) on the left menu bar.
6. Choose mode of data display in the left column, e.g., by sector.
7. A menu bar will appear to the right. Choose the scenario group name “PRIMES_09” and the scenario “PRIMES_BL2009_14jan10”.

The general features of the methodology of GAINS in relation non-CO₂ GHG have been described in previous reports (Höglund-Isaksson et al., 2009; Höglund-Isaksson and Mechler, 2005; Winiwarer, 2005; Tohka, 2005). The overall framework, in which the GAINS model operates, has been described by Amann et al. (2008a) and the respective reports mentioned therein. This particular reports builds on previous work done on non-CO₂ GHGs using GAINS for the Climate & Energy Package in 2008 (see http://ec.europa.eu/environment/climat/climate_action.htm for background documentation).

While the overall principles of the GAINS approach will be discussed in Section 2 of the report, Sections 3-8 (energy – industry – agriculture – waste) cover the important technical sectors related to estimation of baseline emissions of non-CO₂ greenhouse gases in the GAINS model.

2 Methodology

2.1 General GAINS approach

The GAINS model uses information on external drivers (activities) to estimate the release of trace substances into the atmosphere for past and future periods, on the level of administrative regions. Both air pollutants (SO₂, NO_x, NMVOC, NH₃, CO, PM) and greenhouse gases (CO₂, CH₄, N₂O and F-gases) are covered. Measures to mitigate emissions are defined and may affect one or several of the gases covered, and the amount of emission reduction (or: the “abated” emission factor) is determined. Also, the costs for each of the measures (by cost category: investment costs, operation/maintenance costs, savings) is presented. With assumption on the future implementation of such abatement measures, and on the environmental targets to be achieved, scenarios of a future development can be assessed and cost-optimized solutions can be developed. For the purpose of this project, the regions considered in GAINS include the 27 Member States of the European Union and the time frame covered is 2005 to 2030.

2.2 Sources of input

The basis for assessing the future development in GAINS is provided by external projections of economic development from DG-ECFIN (2009) and implied activity levels in terms of energy consumption, transport demand, industrial production and agricultural activities. For this project, energy activity and agricultural activity levels were provided as model inputs from the PRIMES (2009) and CAPRI (2009) models, respectively. Also activity levels for some industrial processes closely linked to energy use, e.g., fuel production and primary aluminium production, were provided as results from the PRIMES model. Activity types not resulting from the PRIMES or CAPRI models include e.g., amounts of solid waste and wastewater generated, adipic and nitric acid production, and several F-gas sources. For these activities, we use information from several different sources including EUROSTAT, national sources and data submitted by Member States in the “Common Reporting Format” (CRF) tables to the UNFCCC.

For emission calculations, the GAINS methodology follows the IPCC guidelines as closely as permitted by available information. By applying the same methodology to all EU-27 countries, the GAINS model maintains methodological consistency across countries. The results have been compared to the 2005 emission levels reported by countries for year 2005 in the UNFCCC CRF tables (UNFCCC, 2009). For some activities, like enteric fermentation in livestock or coal mining, implied emission factors used in the national submissions to the UNFCCC are more frequently based on empirical measurements and likely to more accurately reflect the country-specific circumstances than default regional emission factors available from the IPCC guidelines. In these cases, we have applied the implied emission factors reported to the UNFCCC rather than IPCC default factors. For N₂O emissions from soils, most EU Member States follow the methodology described in the IPCC 1997 guidelines for calculating reported emissions. The exceptions are Germany and Poland, who in their 2009

submissions apply the revised IPCC methodology from 2006. As the two methodologies produce substantive differences in results, GAINS emission estimates are adjusted accordingly for these two countries.

Any discrepancy still remaining between the national data (UNFCCC 2009) and the GAINS database was matched for 2005 using a source category “Other” (OTHER_CH4 and OTHER_N2O, respectively). These “other” emissions, that reflect sources presented to UNFCCC that are not included in GAINS or that account for discrepancies in emission estimates that are due to differences in the methodology used by individual Member States and the consistent methodology applied in GAINS to all Member States, are kept constant over time, as it reflects the part of emissions that can not reasonably be assigned. Thus this sector helps understand how well the two datasets match (see Section 9 on evaluation, which also covers the uncertainty associated with the emission estimates).

2.3 Control of baseline emissions due to current legislation

Baseline emission estimates assume mitigation technology adoption in compliance with adopted EU-wide directives as well as implemented national legislation affecting emissions of non-CO₂ greenhouse gases. EU-wide directives assumed to affect emissions of non-CO₂ greenhouse gases are:

- Landfill Directive (1999/31/EC), the Waste Directive (2006/12/EC) and the Waste Management Framework Directive (2008/98/EC): All EU-27 countries are assumed to meet the required diversion of biodegradable waste away from landfills corresponding to 25 percent in 2006, 50 percent in 2009 and 65 percent in 2016 of the 1995 amounts landfilled. All landfill sites should by 2009 be equipped with gas recovery equipment. Countries with a heavy reliance on landfills have been granted a four years grace period for compliance (i.e. Greece, Ireland, Italy, Spain, Portugal, United Kingdom, Cyprus, Estonia, Hungary, Slovenia, Poland, and Slovakia). The EU waste hierarchy is followed to the extent that recycling and composting are preferred to incineration and deposition on landfills. Waste incineration is not assumed to increase above currently implemented levels, unless information from national experts state otherwise.
- Nitrate Directive (1991/676/EEC), Common Agricultural Policy (CAP) Reform (2006/144/EC), the CAP “Health Check” and the “Set aside” regulation (73/2009): Assumptions on agricultural policies in the activity projections produced by the CAPRI model comprise the effects of the “Health Check” of the CAP, the abolition of the “Set aside” and the milk quota regulations, as well as, the impacts of the Nitrate Directive. In addition, agricultural premiums are considered largely decoupled from production levels and the WTO December 2008 Falconer proposal on trade with agricultural products is assumed implemented.
- F-gas Directive (2006/842/EC) and Motor vehicles Directive (2006/40/EC): The F-gas Directive stipulates that by 2010 end-of-life recollection of refrigeration and air-

conditioning equipment should be in place as well as adoption of good practice measures involving leakage control and improved components of refrigeration and air-conditioning equipment in use. From 2011, the use of HFC-134a in mobile air conditioners should be replaced by a cooling agent with GWP of less than 150 in all new vehicles placed on the market. In addition, the F-gas Directive stipulates an increased use of alternative blowing agents for one component foams, use of alternative propellants for aerosols, leakage control and end-of-life recollection and recycling of high-and mid voltage switches, SF₆ replaced by SO₂ in magnesium production and casting, and a ban of use of SF₆ in soundproof windows, sports equipment etc..

- ETS: Baseline emission estimates assume adoption of mitigation technologies within the sectors included in the EU emissions trading system (ETS) to the extent that marginal mitigation costs are lower than the established carbon price in the market for emission permits. Non-CO₂ sector sources included in the ETS are production of adipic and glyoxal/glyoxylic acid, nitric acid, and primary aluminium. Expected future carbon price levels in the ETS permit market were adopted as results from the PRIMES model (December 2009) and correspond to 13.6 Euro/t CO₂ in 2010, 18.7 Euro/t CO₂ in 2015, 23.4 Euro/t CO₂ in 2020, 30 Euro/ton CO₂ in 2025, and 36.6 Euro/ton CO₂ in 2030 (in Euro 2005 prices). ETS sector technologies assumed adopted in baseline emissions are catalytic reduction in nitric acid production (from 2015 onwards), catalytic reduction in adipic acid production (adopted voluntarily from 2000 onwards in all countries, except Italy where adoption starts from 2010 onwards), twin reduction system in adipic acid production (technology assumed readily available from 2020 onwards), and retrofitting of vertical stud Söderberg (VSS) technology in primary aluminium production (from 2015 onwards).
- Voluntary agreement to reduce PFC emissions in the semiconductor industry is assumed to have attained considerable reductions by 2005 (ESIA, 2006). The effect of the control in place in 2005 is assumed to continue into the future.
- Other relevant EU-wide legislation indirectly affecting non-CO₂ GHG concerns regulations on transport-related emissions and the Biofuels Directive (2009/28/EC). Production of biofuels in EU-27 are assumed to develop as projected by PRIMES (see Amann et al., 2010).
- National legislation affecting emissions of non-CO₂ GHG includes complete bans on depositing biodegradable waste on landfills in Denmark, Germany and Sweden and national legislation controlling emissions of nitrogen compounds (NO_x, NH₃) indirectly affecting non-CO₂ GHG emissions.

3 Energy

3.1 Combustion in power plants

CH₄ emissions from energy use have two sources; combustion and fugitive emissions. Fugitive emissions are accounted for whenever gas is used as fuel, while combustion emissions of CH₄ arise from combustion of any type of fuel. N₂O is formed as a combustion by-product, similar to NO_x. Activity data for combustion emissions from power plants is taken from PRIMES (2009) and emission factors from IPCC (2006). Emission factors are differentiated by fuel type and emissions of CH₄ or N₂O in country *i* in year *t* are calculated as:

$$E_{it} = \sum_s A_{sit} * ef_{si}$$

where A_{sit} is the amount of fuel *s* consumed in country *i* in year *t*,
 ef_{si} is the emission factor for fuel type *s* in country *i*.

No specific mitigation options have been identified for CH₄ or N₂O emissions from power plants. However, the use of fluidized bed combustion and abatement of NO_x (selective non-catalytic reduction of flue gas) affects emission factors for N₂O.

Fluidized bed combustion (FBC) is a technology that allows for an extended contact of solid fuels with air oxygen, minimizing the need to crush or even pulverize fuels, while at the same time hampering particle formation. Also, combustion temperatures are kept below the optimum for formation of NO_x. Lower NO_x emissions are accompanied with strong increases in N₂O emissions. The technology is used in the GAINS sectors PP_EX_OTH and PP_NEW.

Fluidized bed combustion requires advanced methods to properly regulate combustion air flow and fuel intake to achieve a stable fluidized bed. The GAINS database contains expert estimates of the shares of FBC, including their future development, in combustion of solid fuels for European countries. This data has been made available within country consultations previously, but has received very little attention.

Table 1: Activity sources for CH₄ and N₂O combustion emissions from power plants.

GAINS sector code	Fuels	Description	Unit
PP_EX_WB	Various fuels	Power heat plants: Existing wet bottom boilers	PJ
PP_EX_OTH		Power heat plants: Existing other	PJ
PP_IGCC		Power plants - integrated gasification combined cycle	PJ
PP_NEW		Power heat plants: New	PJ
Activity data sources:		(PRIMES 2009)	
Emission factor sources (CH ₄ , N ₂ O):		(IPCC 2006; de Soete 1993)	

Methods have been developed and implemented in pilot plants which allow minimizing N₂O formation (in GAINS summarized as “combustion modification in fluidized bed combustion”). Data presented by Winiwarter (2005) indicate that 80% of N₂O can be removed (Hendriks *et al.*, 2001). Also cost data was taken from this source. No discrimination has been made for applicability in different countries (considered to be 100%) or in abatement costs, as the technology is understood to be generally commercially available.

Table 2: Technologies in GAINS for mitigation of N₂O emissions from fluidized bed combustion

GAINS technology code	Description
FBC_CM	Combustion modification in fluidized bed combustion
Sources:	(Hendriks et al. 2001)

3.2 Combustion in residential and commercial sectors

CH₄ emissions from combustion in residential and commercial sectors are calculated using activity data from PRIMES (2009) and emission factors from IPCC (2006) and applying the methodology described for power plants in the previous subsection. Complementary information on emission factors in the residential sector for different types of fuels and boilers is taken from various sources (Delmas 1994; Johansson 2004; Kjällstrand and Olsson 2004; Leckner et al. 2004; Olsson and Kjällstrand 2006). For N₂O, the variation in emission factors is limited to fuel type without differentiation by GAINS sector. No specific mitigation options have been identified for CH₄ or N₂O emissions from boilers in the residential and commercial sectors.

Table 3: Activity sources for CH₄ combustion emissions from residential and commercial sectors.

GAINS sector code	Fuels	Description	Unit
DOM	Various fuels	Domestic (residential, commercial and agricultural)	PJ
DOM_FPLACE		Domestic combustion: fireplaces	PJ
DOM_MB_A		Domestic combustion: Medium boiler (<50MW) –automatic feeding	PJ
DOM_MB_M		Domestic combustion: Medium boiler (<1MW) –manual feeding	PJ
DOM_PIT		Domestic combustion: pit burning	PJ
DOM_SHB_A		Domestic combustion: single house boiler –automatic feeding	PJ
DOM_SHB_M		Domestic combustion: single house boiler –manual feeding	PJ
DOM_STOVE_C		Domestic combustion: cooking stove	PJ
DOM_STOVE_H		Domestic combustion: heating stove	PJ
Activity data sources:		(PRIMES 2009)	
Emission factor sources:		(Delmas 1994; Johansson, Leckner et al. 2004; Kjällstrand and Olsson 2004; IPCC 2006; Olsson and Kjällstrand 2006; de Soete 1993)	

3.3 Combustion in industry

CH₄ emissions from combustion in industry boilers are calculated using activity data from PRIMES (2009) and emission factors from IPCC (2006) and applying the methodology described for power plants in the subsection above. No CH₄-specific mitigation options have been identified for these activities. N₂O emission factors are affected by adoption of fluidized bed technology and NO_x abatement in the same way as described for emissions from power plants, and also the identical abatement technology (“combustion modification in FBC”) is available (Table 2).

Table 4: Activity sources for CH₄ combustion emissions from industry

GAINS sector code	Fuels	Description	Unit
CON_COMB	Various fuels	Fuel conversion: combustion	PJ
IN_BO		Industry: combustion in boilers	PJ
IN_OC		Industry: other combustion	PJ
Activity data sources:		(PRIMES 2009)	
Emission factor sources (CH ₄ , N ₂ O):		(IPCC 2006)	

3.4 Transport – combustion and fugitive emissions from fuel use

CH₄ emissions from mobile sources arise from fuel combustion and as fugitive emissions when using gas as transport fuel. Activity data is adopted from PRIMES (2009). Emission factors depend on several factors like fuel, technology and operating characteristics. GAINS uses default emission factors as specified by IPCC (2006). As IPCC specifies default emission factors per km travelled, these have been converted to emissions per energy unit consumed using vehicle specific conversion factors from the GAINS database. For passenger cars and light duty vehicles, emission factors are specified by fuel and vehicle type and by the emission control standard of the vehicles. For other means of transportation, emission factors are specified only by types of fuel and vehicle, while no default factors by emission control standard are available. No CH₄ or N₂O specific mitigation options are identified for these activities. However, emissions of N₂O are known to strongly depend on NO_x abatement applied to vehicle exhaust. In general, NO_x abatement (as in catalytic converters or SCR-technology applied in diesel vehicles) leads to increased N₂O emissions. This fact is covered by applying differentiated N₂O emission factors following the categories of the EURO standard.

Table 5: Activity sources for CH₄ combustion emissions from transport.

GAINS sector code	Fuels	Description	Unit	
TRA_RD_LD4C	Various fuels	Cars: 4-stroke	PJ	
TRA_RD_LD4T		Light duty vehicles: 4-stroke (trucks)	PJ	
TRA_RD_HDB		Heavy duty buses	PJ	
TRA_RD_HDT		Heavy duty trucks	PJ	
TRA_RD_LD2		Motorcycles: 2-stroke, mopeds (also cars)	PJ	
TRA_RD_M4		Motorcycles: 4-stroke	PJ	
TRA_OT		Other transport	PJ	
TRA_OT_AGR		Other transport: agriculture	PJ	
TRA_OT_AIR		Other transport: air traffic	PJ	
TRA_OT_CNS		Other transport: construction machinery	PJ	
TRA_OT_INW		Other transport: inland waterways	PJ	
TRA_OT_LB		Other transport: other off-road 4-stroke	PJ	
TRA_OT_LD2		Other transport: off-road 2-stroke	PJ	
TRA_OT_RAI		Other transport: rail	PJ	
TRA_OTS_L		Other transport: ships –large vessels	PJ	
TRA_OTS_M		Other transport: ships –medium vessels	PJ	
Activity data sources:		(PRIMES 2009)		
Emission factor sources (CH ₄):		(IPCC 2006)		
Emission factor sources (N ₂ O):		(IPCC 2006; RICARDO 2003; Jimenez et al. 2000)		

3.5 Fugitive emissions from coal mining

Formation of coal produces CH₄, which is released to the atmosphere when coal is mined. IPCC identifies three sources of CH₄ emissions from coal mining: liberation of CH₄ during breakage of coal in the coal mine, post-mining emissions during handling, processing and transportation of mined coal, and emissions from abandoned coal mines (IPCC 2006). Emission factors for mining emissions are defined for underground and surface mining and increase with mine depth. Activity data in GAINS are specified as amounts of hard and brown coal mined. As emission factors from coal mining are site-specific and require detailed country-specific information, we use implied emission factors reported by countries to the UNFCCC for year 2005 (UNFCCC 2009). Emissions from abandoned coal mines are included to the extent they are reported to the UNFCCC. These are accounted for under the sector for other CH₄ emissions (see Section 9.1) and not under coal mining sectors. CH₄ emissions from coal mining in country *i* in year *t* are calculated as the sum of emissions from the two types of coal *s*:

$$E_{it} = \sum_s \sum_m ef_{is}^{IPCC} * \gamma_{i:UN2005} * A_{its} * (1 - remeff_{sm}) * Appl_{itsm}$$

where ef_{is}^{IPCC} is the default IPCC emission factor for coal mining,
 A_{its} is the amount of coal type *s* mined in country *i* in year *t*,
 $\gamma_{i:UN2005}$ is a factor correcting for the discrepancy between IPCC default emission factors and the implied emission factors reported by countries for year 2005 to UNFCCC,
 $remeff_{sm}$ is the removal efficiency of technology *m*, and
 $Appl_{itsm}$ is the application rate of technology *m* to coal type *s*.

Table 6: Activity sources for fugitive CH₄ emissions from coal mining.

GAINS sector code	GAINS fuel code	Description	Unit
MINE_BC	NOF	Mining of brown coal	Mt coal
MINE_HC	NOF	Mining of hard coal	Mt coal
Activity data sources:		PRIMES 2009	
Emission factor sources:		(IPCC 2006; UNFCCC 2008)	

About 30 percent of CH₄ emissions from coal mining is recovered and flared for security reasons (AEAT 1998). Options considered in GAINS as CH₄ mitigation options are defined as measures that extend gas recovery over the security level. This includes extended recovery and flaring of gas or that the recovered gas is utilized for energy purposes. Costs for these options were taken from AEAT (AEAT 1998; AEAT 2001) and specified for each technology *m* as:

$$C_{itm} = I_m * \left[\frac{(1+r)^{LT} * r}{(1+r)^{LT} - 1} \right] + M_m - p_{it}^{gas} * R_m$$

where I_m is the investment cost per unit of coal mined,
 r is the discount rate on investments,
 LT is the lifetime of investments,
 M_m is the operation and maintenance cost per unit of coal mined,
 p_{it}^{gas} is the gas price, and
 R_m is the amount of gas recovered per unit of coal mined.

Table 7: Technologies in GAINS for control of CH₄ emissions from coal mining.

GAINS technology code	Description
CH ₄ _REC	Recovery of mine gas above a 30 percent level assumed for security reasons and with flaring of gas
CH ₄ _USE	Recovery of mine gas above a 30 percent level assumed for security reasons and with utilization of gas for energy purposes
Sources:	(AEAT 1998; AEAT 2001)

3.6 Fugitive emissions from oil and gas operations

3.6.1 OIL AND GAS PRODUCTION AND PROCESSING

Extraction of crude oil and natural gas gives rise to fugitive CH₄ emissions. These are often referred to as associated gas. The fraction of associated gas to the energy content of oil and gas produced typically range in the order of 1 to 10 percent with lower fractions for gas production than for oil production (Cedigaz 2001; UNFCCC 2008). Most associated gas is flared off with very low CH₄ emissions. However, a fraction of the associated gas is vented either because flaring devices have not been applied fully to all outlets of associated gas or it occurs during maintenance of the flaring devices. IPCC (IPCC 2006) does not provide default estimates of the fraction of associated gas vented. We therefore assume default venting fractions of associated gas at five percent from gas production and ten percent from oil production. Activity data for oil and gas extraction and oil refinery were taken from PRIMES (2009). Emissions from oil (or gas) production are calculated as:

$$E_{it} = \sum_m A_{it} * [a_i * (ef_{venting} * s_{venting} + ef_{flaring} * (1 - s_{venting}))] * (1 - remeff_m) * Appl_{itm}$$

where A_{it} is the amount of oil (or gas) extracted in country i in year t ,
 a_i is the fraction of associated gas expressed as energy content of oil (or gas) produced,
 $ef_{venting}$ is the IPCC default emission factor for vented gas,
 $ef_{flaring}$ is the IPCC default emission factor for flared gas,

$S_{venting}$ is the assumed fraction of associated gas vented,
 $rem_{eff,m}$ is the removal efficiency of control technology m , and
 $Appl_{itm}$ is the application of control technology m .

Emission factors are adjusted to implied emission factors for oil and gas production reported to UNFCCC for 2005 (UNFCCC 2008). Discrepancies in implied emission factors are accounted for by adjusting the associated gas fractions.

The IPCC guidelines provide emission factors for oil transportation based on the amount of oil transported, while emission factors for refining and storage are based on the amount of oil refined. Since it was not possible to find data on the amount of oil transported by tanker, trucks or rails by region, GAINS assumes that the amount transported corresponds to the amount of oil refined. Thus, emission factors reported by IPCC for oil transported and refined have been added up. Fugitive CH₄ emissions from oil transportation, storage and refining are estimated as:

$$E_{it} = \sum_m A_{it} * ef_i * (1 - rem_{eff,m}) * Appl_{itm}$$

where A_{it} is the amount of oil refined,
 ef_i is the sum IPCC default emission factors for oil transportation, storage and refinery,
 $rem_{eff,m}$ is the removal efficiency of control technology m , and
 $Appl_{itm}$ is the application of control technology m .

Table 8: Activity sources for fugitive CH₄ emissions from oil and gas production.

GAINS sector code	GAINS fuel code	Description	Unit
PROD	GAS	Gas produced	PJ
PROD	CRU	Oil produced	PJ
PR_REF	CRU	Oil refined	PJ
Activity data sources:		PRIMES (2009)	
Emission factor sources:		(Cedigaz 2001; IPCC 2006; UNFCCC 2008)	

CH₄ emissions of associated gas from oil and gas production as well as oil refinery can be controlled by extending current flaring to reduce the venting of gas. AEAT (AEAT 1998) provides cost data for flaring based on Dutch off-shore installations. Woodhill (Woodhill 1994) estimates the capital costs of on-shore installations at 40 percent of the capital cost of off-shore installations. GAINS applies off-shore costs to installations in the Netherlands, the UK, Norway and Denmark and on-shore installation costs in all other countries. Costs per activity unit for control technology m in country i in year t are specified as:

$$C_{itm} = \left[I_m * \left[\frac{(1+r)^{LT} * i}{(1+r)^{LT} - 1} \right] + M_m \right] * \eta_i$$

where I_m is the investment cost per activity unit,
 r is the discount rate on investments,
 LT is the lifetime of investments,
 M_m is the operation and maintenance cost per activity unit, and
 η_i is a factor adjusting costs to on-shore or off-shore installations,

Table 9: Technologies considered in GAINS for the control of fugitive CH₄ emissions from gas and oil production.

GAINS technology code	Description
FLA_PROD	Flaring instead of venting of associated gas
FLA_REF	Flaring of refinery gases
Sources:	(AEAT 1998)

3.6.2 FUGITIVE EMISSIONS FROM GAS TRANSMISSION

Loss of natural gas during long-distance transmission of gas is an important source of CH₄ emissions. Activity data used is PJ gas transmitted. Data for 2005 was taken from UNFCCC (2008) CRF tables when available and complemented with information from national sources (Energy 2003; SPP 2007; TAG 2007). Projections for 2010 to 2030 follow the growth in total consumption of natural gas in respective country (PRIMES 2009) IPCC guidelines (IPCC 2006) report default emission factors for fugitive emissions for transmission, processing, and storage of natural gas. Adding up these emission factors, overall fugitive emissions of CH₄ make up 0.07 to 0.15 percent of gas transported with the low end value for developed countries and the high end value for transitional and developing countries. For EU-27, emission factors are adjusted to match implied emission factors reported by countries to the UNFCCC for year 2005 (UNFCCC 2008).

$$E_{it} = \sum_m ef_i^{IPCC} * A_{it} * \gamma_{i;UN2005} * (1 - remeff_m) * Appl_{itm}$$

where ef_i^{IPCC} is the default IPCC emission factor for gas transmission emissions in country i ,
 A_{it} is the amount of gas transmitted through country i in year t ,
 $\gamma_{i;UN2005}$ is a factor correcting for the discrepancy between IPCC default emission factors and implied emission factors reported by countries for year 2005 to UNFCCC,
 $remeff_m$ is the removal efficiency of technology m , and
 $Appl_{itm}$ is the application rate of technology m in country i in year t .

Table 10: Activity sources for fugitive CH₄ emissions from gas transmission.

GAINS sector code	GAINS activity code	Description	Unit
TRANS	GAS	Amount of gas transmitted through long-distance pipelines	PJ gas transmitted
Activity data sources:		(SPP 2007; TAG 2007; UNFCCC 2008, 2009; PRIMES 2009)	
Emission factor sources:		(IPCC 2006; UNFCCC 2008)	

CH₄ emissions from gas transmission pipelines arise for several reasons, e.g., compressor seals are not tight, valves are poorly controlled, or natural gas is flushed during start-ups. Hendriks et al. (Hendriks, de Jager et al. 1998) calculate costs for a set of measures to reduce emissions at compressor stations. These include no flushing at start-up, electrical start-up, and inspection and maintenance programs to secure compressor seals and valves. Control costs per PJ gas transported are calculated as:

$$C_{itm} = I_m * \left[\frac{(1+r)^{LT} * r}{(1+r)^{LT} - 1} \right] + M_m - p_{it}^{gas} * R_m$$

where I_m is the investment cost per activity unit,
 r is the discount rate on investments,
 LT is the lifetime of investments,
 M_m is the operation and maintenance cost per activity unit, and
 p_{it}^{gas} is the gas price, and
 R_m is the amount of gas recovered per unit of gas transported.

Table 11: Technologies in GAINS for mitigation of fugitive CH₄ emissions from gas transmission

GAINS technology code	Description
COMPRESS	Set of measures to reduce emissions at compressor stations
Sources:	(AEAT 1998; Hendriks, de Jager et al. 1998)

3.6.3 FUGITIVE EMISSIONS FROM GAS DISTRIBUTION NETWORKS

Fugitive CH₄ emissions from distribution of natural gas to end users are estimated using default IPCC (IPCC 2006) emission factors. Activity data is amount of gas consumed and taken from PRIMES (2009).

$$E_{it} = \sum_m ef_i^{IPCC} * A_{it} * (1 - remeff_m) * Appl_{itm}$$

where ef_i^{IPCC} is the default IPCC emission factor for gas distribution emissions in country i ,

A_{it} is the amount of gas consumed in country i in year t ,
 $rem_{eff,m}$ is the removal efficiency of technology m , and
 $App_{i,t,m}$ is the application rate of technology m in country i in year t .

Methane emissions from consumer distribution networks can be reduced by replacing old town gas distribution networks made from grey cast iron by polyethylene (PE) or polyvinylchloride (PVC) networks. This option typically reduces almost all fugitive emissions from this source. An alternative option is to increase the control frequency of gas distribution networks. For this option, GAINS assumes a doubling of the control frequency from every fourth to every second year. Costs for these options are provided by AEAT (AEAT 1998) and calculated similarly to control costs for emissions from gas transmission (Section 3.6.2).

Table 12: Activity sources for fugitive CH₄ emissions from gas distribution networks.

GAINS sector code	GAINS activity code	Description	Unit
CON_COMB	GAS	Fuel conversion –fugitive emissions from distribution networks	PJ gas consumed
IN_BO	GAS	Industry boilers –fugitive emissions from distribution networks	PJ gas consumed
IN_OC	GAS	Industry other combustion –fugitive emissions from distribution networks	PJ gas consumed
PP_EX_WB	GAS	Power plants existing wet bottom boilers – fugitive emissions from distribution networks	PJ gas consumed
PP_EX_OTH	GAS	Power plants existing other –fugitive emissions from distribution networks	PJ gas consumed
PP_NEW	GAS	Power plants new –fugitive emissions from distribution networks	PJ gas consumed
DOM	GAS	Domestic –fugitive emissions from distribution networks	PJ gas consumed
NONEN	GAS	Nonenergy use of fuel –fugitive emissions from distribution networks	PJ gas consumed
Activity data sources:		PRIMES 2009	
Emission factor sources:		(IPCC 2006; UNFCCC 2008)	

Table 13: Technologies considered in GAINS for mitigation of fugitive CH₄ emissions from gas distribution networks.

GAINS technology code	Description
REPL_NET	Replacement of grey cast iron gas networks with polyethylene (PE) or polyvinylchloride (PVC) networks
CONT_NET	Doubling of leak control frequency of consumer networks from every fourth to every second year
Sources:	(AEAT 1998; Hendriks, de Jager et al. 1998)

4 Industrial Processes

4.1 Adipic acid production

The industrial process generating adipic acid (a compound required in the Nylon® production) involves treating the raw material with concentrated nitric acid, at which large quantities of N₂O are released. Typically, for each ton of product 300 kg of N₂O are formed, making the process an important contributor to overall N₂O emissions, although the amount of production is fairly low compared to production of standard chemicals.

Adipic acid production occurs in only a handful of countries, and since only very few production plants are involved, the CRF tables usually list production data as “confidential”. Therefore, we supplement activity data with information from EPA (2006) on production capacity and future development by country.

The small number of producers also allows observing general structural changes efficiently. Industry have made voluntary agreements after a cost-efficient method had been developed to take advantage of the high N₂O concentrations in plume and convert these back into nitric acid (with 95% efficiency). Most plants had been retrofitted by 2000, with the exception of Italy where this modification started to be fully operative from 2006 only.

As the instrumentation as such is able to reduce 99.9 percent of the emissions, and the remaining emissions still reported are mainly caused by operational shutdown, a pilot plant in Krefeld, Germany, recently installed a backup abatement device. This backup device is expected to reduce 80 percent of the remaining emissions (LANXESS, 2008), such that total abatement of 99 percent can be achieved, allowing for some system failure still. Costs for the installations have been estimated to be identical to the original system, but the marginal cost (considering the much smaller reductions) is of course considerably higher. The option termed “twin reduction technology” will presumably not be available in 2015, but with the expected carbon price level of the ETS system (see Section 2.3), we assume full implementation of this option from 2020 onwards.

In this sector, we also cover emissions from Glyoxal/glyoxylic acid production as the underlying chemical process is similar. Glyoxal production employing the nitric acid pathway (thus causing N₂O emissions) is reported from one plant in EU27 only (in France).

4.2 Nitric acid production

The oxidation of ammonia to nitric acid is one of the large scale industrial processes. Nitric acid is needed both for the production of fertilizer and of explosives. Most EU countries accommodate nitric acid production, often in several installations, but several countries keep activity data confidential. Thus, data listed by EPA (2006) proved helpful to supplement the information provided by countries in the CRF tables. Future production development has been scaled according to the value added in chemical industry, consistent with PRIMES (2009).

Table 14: Activity sources for N₂O emissions from adipic or nitric acid production.

GAINS sector code	GAINS activity code	Description	Unit
PR_ADIP	NOF	Adipic acid production	Mt product
PR_NIAC	NOF	Nitric acid production	Mt product
Activity data sources:		(EPA 2006; UNFCCC 2009)	
Emission factor sources:		(IPCC 2006; UNFCCC 2009)	

As a by-product in the oxidation, nitrous oxide is formed. While the amount lost is by far smaller than with adipic acid production, the sheer amount of production makes this an important emission source. In nitric acid production the concentration of the released gas is considerably smaller, making it more difficult to reclaim. Still, industrial scale production has been proven successful in applying catalytic reduction also to nitric acid production. The use of information from a demonstration plant in Linz, Austria, allows for reasonable estimates of the additional costs incurred. For Austria and Belgium, where specific plans for implementation before 2010 were made available (Muik, pers. Information; Grobben, pers. information), we estimate that a certain share of the capacity is controlled. In Germany (due to the implementation of an air quality standard “TA Luft”) and the Netherlands (opt-in to the ETS scheme as of 2010), we assume full implementation of this option from 2010, for the rest of the EU-27 from 2015. The marginal cost of using catalytic reduction to control emissions from nitric acid production is estimated at less than the expected carbon price in the ETS market (see Section 2.3), thus full adoption of this option seems reasonable in all Member States as soon as nitric acid production becomes included in the ETS scheme.

Table 15: Technologies in GAINS for control of N₂O emissions from adipic or nitric acid production.

GAINS technology code	Description
CR	Catalytic or thermal reduction (to be used in connection with the production of adipic acid or nitric acid)
TWIN_RED	Twin reduction technology (applicable for adipic acid production)
Sources:	(de Soete 1993; de Beer 2001; Kuiper 2001; LANXESS, 2008)

4.3 Aluminum production

Primary aluminium production has been identified as a major anthropogenic source of emissions of two perfluorocarbon (PFC) emissions, namely CF₄ and C₂F₆. These are both gases with very high greenhouse warming potentials, 6500 and 9200 times that of CO₂ over a 100 year time horizon. During normal operating conditions, an electrolytic cell used to produce aluminium does not generate measurable amounts of PFC. Instead, PFC is

produced during brief upset conditions known as “anode effects”. These conditions occur when the level of aluminium oxide drops too low and the electrolytic bath itself begins to undergo electrolysis. Since the aluminium oxide level in the electrolytic bath cannot be directly measured, surrogates such as electrical resistance or voltage are most often used in modern facilities to ensure that the aluminium in the electrolytic bath is maintained at the correct level.

GAINS uses the volume of primary aluminium production as the activity for calculating emissions from this source. Three different types of activities are distinguished based on the technology used; point-feeder prebake (PFPB), Side-worked prebake (SWPB), and Vertical stud Söderberg (VSS) technology. Primary aluminium production data is provided as results from the PRIMES model (2009) and shares of different aluminium production technologies were adopted from the aluminium industry website (<http://www.aluminium.net/>) and from the national communications to the UNFCCC (2008). The latter source is also used for final verification of emissions. Emission factors depend on the production technology and on a number of site-specific conditions and are taken from Harnisch and Hendricks (2000).

Table 16: Activity sources for F-gas emissions from primary aluminum production.

GAINS sector code	GAINS activity code	Description	Unit
ALU_PFPB	NOF	Primary aluminium production with point feeder prebake technology	Mt aluminium
ALU_SWPB	NOF	Primary aluminium production with sideworked prebake technology	Mt aluminium
ALU_VSS	NOF	Primary aluminium production with vertical stud Söderberg technology	Mt aluminium
Activity data sources:		(IEA 2008), aluminium industry website (http://www.aluminium.net/)	
Emission factor sources:		(Harnisch and Hendricks 2000), UNFCCC (2008)	

Table 17 presents mitigation measures for PFC emissions in the primary aluminium production sector considered in GAINS. Conversion of SWPB or VSS to PFPB technology is assumed to remove over 90 percent of emissions, while retrofitting of the two technologies removes about a quarter of emissions (Harnisch and Hendricks, 2000). Also data on mitigation costs was taken from this source. The marginal cost of retrofitting VSS technology is estimated at less than the expected carbon price in 2015 in the ETS market (see Section 2.3) and full adoption of this option is assumed from this year onwards in all Member States.

Table 17: Technologies in GAINS for control of F-gas emissions from primary aluminium production.

GAINS technology code	Description
CONVSWPB	Conversion SWPB to PFPB

RETSWPB	SWPB retrofitting
CONVSS	Conversion VSS to PFPB
RETVSS	VSS retrofitting
Sources:	(Harnisch, Sue Wing et al. 1998; Harnisch and Hendriks 2000)

4.4 Sources of SF₆ emissions

Sulphur hexafluoride (SF₆) emissions arise from high- and mid-voltage switches, magnesium production and casting and a variety of other applications, like soundproof windows or sports equipment. SF₆ has a very high greenhouse warming potential of 23900 times that of CO₂ over a 100 year time horizon.

SF₆ is a manufactured gas used mainly as electrical insulator in the transmission and distribution equipment of electric systems. The use of SF₆ increased between the 1970s and 1990s as SF₆ equipment gradually replaced older oil and compressed air systems. Suitable alternatives to SF₆ do not exist for these applications as oil and compressed air systems suffer from safety and reliability problems (AEAT, 2003). Most of the SF₆ is stored in gas-insulated switchgears for high and mid-voltage electric networks. Emissions depend on the age of the gas insulated switchgear (GIS) since older models leak more than newer, as well as on the size of the transmission network and recycling practices of old equipment. Although specialized methods for the estimation of SF₆ emissions from electrical equipment have been developed (Schaefer et al., 2002), implementation of these methods would need significant information on transmission network length, age and size of utilities, which is not readily available for the EU countries. The activity unit used in GAINS for this sector are emissions of SF₆ reported to the UNFCCC (2008) and country reports from the German Federal Environment Agency (Schwarz and Leisewitz, 1999), VTT Energy in Finland (Oinonen and Soimakallio, 2001), AEAT (2003), Poulsen (2001), and USEPA (2008). Projections follow growth in value added for manufacturing industry sector. It is important to note that in some Eastern European countries, other insulation gases/methods are still in use.

Casting and production of primary and secondary magnesium are well known sources of SF₆ emissions. SF₆ is used as a shielding gas in magnesium foundries to protect the molten magnesium from re-oxidising. Activity data on historic volumes of processed magnesium is taken from the World Mineral Statistics (Taylor et al., 2003) and from national communications to the UNFCCC (2008). Projections follow growth in value added for manufacturing industry sector. An emission factor of one kg SF₆ per ton processed metal is based on the average emission factor published in Schwartz and Leisewitz (1999) and Oinonen and Soimakallio (2001).

Some European countries used significant amounts of SF₆ in tires and soundproof windows as well as in the semiconductor industry. Other smaller quantities have been used by sports equipment manufacturers in tennis balls and sport shoes. Activity data for these other sources of SF₆ emissions are taken from emissions reported by countries to the UNFCCC (2008)

complemented by information from national reports (Schwarz and Leisewitz, 1999, Oinonen and Soimakallio, 2001; AEAT, 2003; Poulsen, 2001). From 2006, the F-gas Directive bans the use of SF₆ in sports equipment, tyres and soundproof windows. As soundproof windows have a longer life-time, it is assumed that the stock of SF₆ found in soundproof windows in 2005 will be successively phased-out over a period of 25 years. The available stock of SF₆ in soundproof windows in 2005 in EU countries is estimated at 288 t SF₆ in Austria, 132 t SF₆ in Belgium, 86 t SF₆ in Denmark, 1764 t SF₆ in Germany, 1.78 t SF₆ in Slovenia, and 11.1 t SF₆ in Sweden. With an assumed leakage/refill rate of 1 percent per year for windows still in use and a linear phase-out of emissions, annual emissions from this source until 2030 (when phase-out is completed) are estimated as:

$$E_t^{SF_6} = \frac{Stock_{2005}}{25} + Stock_t * 0.01,$$

where the first term represents the end-of-life emissions from soundproof windows scrapped in year t and the latter term represents the emission leakage from windows still in use.

Table 18: Activity sources for F-gas emissions from SF₆ sources.

GAINS sector code	GAINS activity code	Description	Unit
GIS	NOF	High and mid-voltage switches	t SF ₆
MAGNPR	NOF	Magnesium production and casting	t Mg processed
WIND_B	NOF	Soundproof windows	t SF ₆
SF6_OTH	NOF	Other use of SF ₆ , e.g., sports equipment	t SF ₆
Activity data sources:		Taylor et al. (2003), UNFCCC (2008) Schwarz and Leisewitz (1999), Oinonen and Soimakallio (2001), AEAT (2003), Poulsen (2001)	
Emission sources:	factor	(IPCC 1997)	

SF₆ emissions from high- and mid voltage switches can be reduced through good practice measures, i.e., leakage control and end-of-life recollection and recycling of old switchgears. SF₆ emissions in magnesium production and casting can be substituted by using sulphur dioxide (SO₂) as alternative gas. Other SF₆ uses in tires, windows and sports equipment can be phased-out or banned. Cost data is taken from Harnisch and Hendriks (2000), Oinonen and Soimakallio (2001), and Harnisch and Schwarz (2003). In baseline, EU-27 countries are assumed to meet the targets set out in the F-gas Directive, which came into force in July 2006. The Directive regulates the use of both SF₆ and HFC. Emissions from high and mid voltage switches should be controlled through better leakage control and end-of-life recollection and recycling. SO₂ should replace SF₆ use in magnesium production and casting and other SF₆ use in e.g., windows and sports equipment, is banned.

Table 19: Technologies in GAINS for control of F-gas emissions from SF₆ sources.

GAINS technology code	Description
GP_GIS	Good practice: leakage control and end-of-life recollection and recycling
ALT_MAGN	Alternative protection gas SO ₂ for use in magnesium production and casting
ALT_WIND	Ban of use in windows
ALT_SF	Ban of use
Sources:	Harnisch and Hendriks (2000), Oinonen and Soimakallio (2001), Harnisch and Schwarz (2003)

4.5 Semiconductor industry

The semiconductor industry uses several PFC compounds, e.g., CF₄, C₂F₆, C₃F₈, c-C₄F₈, as well as HFC-23, SF₆ and nitrogen trifluoride (NF₃) in two production processes: plasma etching thin films and plasma cleaning of chemical vapour deposition (CVD) tool chambers. Data on F-gas use in semiconductor industry is often confidential, since the industry is characterized by one or a few companies in each country and any data on F-gas use can easily be converted into production volumes. The activity data used by GAINS is the volume of PFC emissions reported by countries for this sector to the UNFCCC (2008) complemented by information from national reports (Schwarz and Leisewitz, 1999, Oinonen and Soimakallio, 2001; AEAT, 2003; Poulsen, 2001; USEPA (2001b)). Projections follow growth in value added for manufacturing industry sector.

Table 20: Activity sources for F-gas emissions from semiconductor industry.

GAINS sector code	GAINS activity code	Description	Unit
SEMICOND	NOF	Semiconductor manufacture	t PFC
Activity data sources:		Harnisch and Hendriks (2000), UNFCCC (2008)	
Emission factor sources:		(IPCC 1997)	

Use of nitrogen trifluoride (NF₃) as substitute for PFC is the only mitigation option identified for the reduction of PFC emissions in the semiconductor industry. This option is assumed to completely remove PFC emissions in CVD chambers. The European semiconductor manufacturers have made voluntary commitments to reduce PFC emissions from this source (ESIA, 2006). We assume that the reduction attained by the industry in 2005 will continue into the future. This corresponds to an application of control to 86 percent of the production from 2010 onwards. Costs for switching to NF₃ use were taken from Harnisch et al. 2000, Harnisch and Hendriks, 2000 and Oinonen and Soimakallio, 2001.

Table 21: Technologies considered in GAINS for control of F-gas emissions from the semiconductor industry

GAINS technology code	Description
ALT_SOLV	Use of alternative solvent: NF ₃
Sources:	Harnisch and Hendriks (2000), Harnisch et al. (2000); Oinonen and Soimakallio (2001)

4.6 Use of HFC in industrial processes

Hydrofluorocarbons (HFCs) are used in industrial applications for production of chlorodifluoromethane (HCFC-22) and for refrigeration mainly in the food and agricultural sectors. HCFC-22 is a gas used for refrigeration and air-conditioning systems, in foam manufacturing as a blend component of blowing agents, and in the manufacturing of synthetic polymers. HFC-23 is a by-product of the HCFC-22 production process and has a greenhouse warming potential of 11700 over a 100 year time horizon (IPCC, 1997). As an ozone depleting substance, the use of HCFC-22 is being phased out in most developed countries following the commitments made in the Montreal Protocol, which entered into force in 1989. The protocol stipulates that developed countries stabilize consumption levels in 1989 for CFCs and in 1996 for HCFCs. CFCs should be completely phased-out in 1996 and HCFCs in 2030. Developing countries have to stabilize the CFCs consumption in 1990 and HCFCs in 2016 and stop using CFCs in 2010 and HCFCs in 2040. Activity data used in GAINS for estimating HFC emissions from HCFC-22 production are reported production levels for historic years (Harnisch and Hendriks, 2000; AEAT, 2003; Schwarz and Leisewitz, 1999; Kokorin and Nakhutin, 2000) coupled with UNEP's phase out schedule for CFC and HCFC products for future years (UNEP, 1997). After phase-out completion, projections follow growth in value added for manufacturing industry sector. Emission factors are taken from Harnisch and Hendriks, 2000; AEAT, 2003.

For any type of cooling purposes, CFC and HCFC gases were used in the past. With the phase-out of these ozone-depleting gases following the Montreal Protocol, the gases are replaced by corresponding HFC compounds. For industrial refrigeration, the GAINS activity data is amount of HFC emissions from refrigerators in use and from scrapped refrigerators. Increase in HFC emissions from industrial refrigeration follows the phase-out of CFCs and HCFCs. Depending on the life-time of the equipment, a saturation year is reached when the market growth in HFC use does no longer depend on the CFC phase-out. After the saturation year, the growth rate in future HFC emissions follows the growth in value added for manufacturing industry sector. Activity data for the year 2000 has been compiled from various sources (UNFCCC, 2008; Harnisch and Hendriks, 2000; AEAT, 2003; Schwarz and Leisewitz, 1999). Estimates of the average charge size of different appliances are based on IPCC (1997), Pedersen (1998) and Oinonen and Soimakallio (2001).

Activity levels are split into emissions banked in equipment and those originating from scrapped equipment. Banked emissions refer to emissions released during the life-time of the appliance and include direct leakage and leakage during regular refill of the cooling agent.

The size of these emissions depends on the average annual stock of refrigerants in a particular application as a function of past sales of refrigerants and the scrapping rate of the application.

Table 22: Activity sources for HFC use in industry

GAINS sector code	GAINS activity code	Description	Unit
IND_B	NOF	Industrial refrigeration –emissions banked in equipment	t HFC
IND_S	NOF	Industrial refrigeration –emissions from scrapped equipment	t HFC
HCFC-22	NOF	Production of HCFC-22	t HCFC22 produced
Activity data sources:		(UNFCCC, 2008; Harnisch and Hendriks, 2000; AEAT, 2003; Schwarz and Leisewitz, 1999)	
Emission factor sources:		(IPCC 1997)	

Table 23 presents options for control of HFC use in industry. HFC-23 emissions from HCFC-22 production can be almost eliminated by post combustion during which HFC-23 is oxidized to carbon dioxide, hydrogen fluoride (HF) and water. HFC emissions from industrial refrigeration can be reduced through good practice options like component improvements, leakage control, and end-of-life recollection of the refrigerant. Emissions from refrigeration can be almost entirely eliminated through process modifications where a secondary loop system replaces the ordinary system and in some cases uses alternative refrigerants. These systems require significantly lower charging of refrigerant, have lower leakage rates, and allow for the use of flammable or toxic refrigerants. A drawback is that the secondary loop system reduces the energy efficiency of the appliance.

The F-gas Directive, adopted by the EU-27 countries, stipulates leakage control and adoption of improved components in all cooling and air-conditioning appliances.

Table 23: Technologies in GAINS for control of HFC use in industry

GAINS technology code	Description
GP_INDB	Good practice: leakage control and improved components
PM_INDB	Process modifications including alternative refrigerants
GP_INDS	Good practice: end-of-life recollection
PM_INDS	Process modifications including alternative refrigerants
INC	Incineration: post combustion of HFC-23 emitted from production of HCFC-22
Sources:	USEPA, 2001a; Pedersen (1998), Kaapola (1989)

4.7 Anaesthetics

The specific properties of N₂O are taken advantage of in medicine as an anaesthetic gas, in the food industry as an unreactive propellant, and in specific combustion engine applications providing additional oxygen to the combustion process. At least for the first two applications, virtually all of the N₂O used will eventually be emitted to the atmosphere. In both cases, N₂O enters the human body, where it remains only for a short time and is not metabolised. Based on a handful of assessment to support national emission inventories, Winiwarter (2005) extracted an emission factor by population of a country (i.e., GAINS sector N₂O_USE).

Methods to reduce application of N₂O have been derived in hospitals, mostly due to concerns about workplace security for hospital personnel. Medical research allows to supplement or even to fully replace the use of N₂O. While supplement is a process that can be observed in practice already following national sale statistics, data on replacement are highly speculative.

Table 24: Technologies in GAINS for mitigation of N₂O emissions from direct application (sector N₂O_USE).

GAINS technology code	Description
REDUCE	Apply nitrous oxide in combination with other (liquid) anaesthetics
REPLACE	Replace nitrous oxide by alternative; suggested alternative is Xe
Sources:	(Spakman et al. 2003; Nakata et al. 1999)

5 Residential and commercial non-energy sources

5.1 Residential and commercial refrigeration

For residential and commercial refrigeration, the estimation of HFC emissions are similar to industrial refrigeration, as described in Section 4.6. Activity data for the year 2000 was compiled from various sources (UNFCCC, 2008; Harnisch and Hendriks, 2000; AEAT, 2003; Schwarz and Leisewitz, 1999). Future emissions follow the phase-out of CFCs and HCFCs as stipulated in the Montreal Protocol. Upon completion of the phase-out, a saturation year is reached after which emissions follow the growth rate of the commercial sector or the development of the number of households. Residential refrigeration only generates HFC emissions from scrapped refrigerators, since these appliances have minimal leakage during their life-time and do not need to be refilled.

Table 25: Activity sources for HFC use in residential and commercial refrigeration

GAINS sector code	GAINS activity code	Description	Unit
COMM_B	NOF	Commercial refrigeration –emissions banked in equipment	t HFC
COMM_S	NOF	Commercial refrigeration –emissions from scrapped equipment	t HFC
DOM_S	NOF	Residential small hermetic refrigerators –emissions from scrapped equipment	t HFC
Activity data sources:		UNFCCC (2008), AEAT (2003), Oinonen and Soimakallio (2001), Harnisch and Hendriks (2000), Harnisch and Schwarz (2003), Schwartz and Leisewitz (1999), Poulsen (2001)	
Emission factor sources:		(IPCC 1997)	

Similar to industrial refrigeration, HFC emissions from residential and commercial refrigeration can be controlled through good practice options like component improvements, leakage control, and end-of-life recollection of the refrigerant, or through process modifications like a secondary loop system (see Section 4.6). Assuming adoption of the F-gas Directive in all EU-27 countries, HFC emissions from residential and commercial refrigeration will be controlled through better leakage control and improved components.

Table 26: Technologies in GAINS for control of HFC use in residential and commercial refrigeration

GAINS technology code	Description
GP_COMMB	Good practice: leakage control and improved components
PM_COMMB	Process modifications including alternative refrigerants
GP_COMMS	Good practice: end-of-life recollection
PM_COMMS	Process modifications including alternative refrigerants
GP_DOMS	Good practice: end-of-life recollection
Sources:	USEPA (2001a), Pedersen (1998), Kaapola (1989) Harnisch and Hendriks (2000), Oinonen and Soimakallio (2001), AEAT (2003) Harnisch and Schwarz (2003), Schwartz and Leisewitz (1999), Oinonen and Soimakallio (2001), AEAT (2003), Poulsen (2001)

5.2 Stationary air conditioning

HFC emissions from stationary air conditioning are estimated in a similar way as HFC emissions from the industrial, residential and commercial sectors (as described in Sections 4.6 and 5.1). Activity data for the year 2000 is compiled from various sources (UNFCCC, 2008; Harnisch and Hendriks, 2000; AEAT, 2003; Schwarz and Leisewitz, 1999) and future emissions follow the phase-out of CFCs and HCFCs until a saturation year is reached, after which emissions follow the growth rate of the commercial sector.

Table 27: Activity sources for HFC use in stationary air conditioning

GAINS sector code	GAINS activity code	Description	Unit
AIRCON_B	NOF	Stationary air conditioning using water chilling – emissions banked in equipment	t HFC
AIRCON_S	NOF	Stationary air conditioning using water chilling – emissions from scrapped equipment	t HFC
Activity data sources:		UNFCCC (2008), AEAT (2003), Oinonen and Soimakallio (2001), Harnisch and Hendriks (2000), Harnisch and Schwarz (2003), Schwartz and Leisewitz (1999), Poulsen (2001)	
Emission factor sources:		(IPCC 1997)	

Similar to industrial refrigeration, HFC emissions from stationary air conditioning can be controlled through good practice options like component improvements, leakage control, and end-of-life recollection of the refrigerant, or through process modifications like a secondary loop system (see Section 4.6). Just like HFC emissions from refrigeration, HFC emissions from stationary air conditioning in the EU are assumed regulated by the F-gas Directive through better leakage control and improved components.

Table 28: Technologies in GAINS for control of HFC use in stationary air conditioning

GAINS technology code	Description
GP_STATB	Good practice: leakage control and improved components
PM_STATB	Process modifications including alternative refrigerants
GP_STATS	Good practice: end-of-life recollection
PM_STATS	Process modifications including alternative refrigerants
Sources:	Devotta et al. (2004), Heijnes et al. (1999), USEPA (2001a), Pedersen (1998), Kaapola (1989) Harnisch and Hendriks (2000), Oinonen and Soimakallio (2001), AEAT (2003) Harnisch and Schwarz (2003), Schwartz and Leisewitz (1999), Oinonen and Soimakallio (2001), AEAT (2003), Poulsen (2001)

5.3 Foams

The main application of polyurethane one component (OC) foams is to fill cavities and joints when installing inner fixtures in housing constructions. OC foams blowing agents are typically gaseous and function as both blowing agent and propellant for the foam. They volatilise upon application, except for small residues that remain for at most one year in the hardened foam (Schwarz and Leisewitz, 1999). There are country-specific variations in the composition of the HFC blend inside the can. Emissions rather than production units are therefore used as activity unit. Activity forecasts are taken from national communications to the UNFCCC (2008) as well as Harnisch and Schwarz (2003), Schwarz and Leisewitz (1999), Oinonen and Soimakallio (2001) and AEAT (2003). Future activity levels are assumed to follow average growth in GDP.

Other foams refer to a group of about ten different foam products based on polyurethane (PU) foam (e.g., PU appliances, PU/PIR/Phen laminates, PU disc panel, PU blocks, PU spray, PU pipe) and extruded polystyrene (XPS). The activity unit used in GAINS is amount of HFC emissions and historical activity levels are taken from national communications to the UNFCCC (2008). Future growth in activity is based on insights from more detailed studies (Schwarz and Leisewitz, 1999; AEAT 2003) and take into account the average market growth rate of these products, the ratio between hydrocarbons and HFCs in foam cells, differences in product life times (15 to 50 years), as well as differences in production, lifetime and disposal emissions.

Table 29: Activity sources for HFC use in foams and foam products

GAINS sector code	GAINS activity code	Description	Unit
OC	NOF	Use of one component foams	t HFC
OF	NOF	Use of other foams	t HFC
Activity data sources:		UNFCCC (2008), AEAT (2003), Oinonen and Soimakallio (2001), Harnisch and Hendriks (2000), Harnisch and Schwarz (2003), Schwartz and Leisewitz (1999), Poulsen (2001)	
Emission factor sources:		(IPCC 1997)	

For one component foams, HFC emissions can be controlled by switching to alternative blowing agents, i.e., switching R-134a for R-152a or hydrocarbons. For other foam products, CO₂ is an alternative to extruded polystyrene (XPS). The F-gas Directive stipulates for the EU-27 countries, that alternative blowing agents to HFCs should be used in foams.

Table 30: Technologies in GAINS for control of HFC use in foams and foam products

GAINS technology code	Description
ALT_OC	Alternative blowing agent in one component foams: different kinds
ALT_OF	Alternative blowing agent in other foams: different kinds
Sources:	AEAT (2003) Schwartz and Leisewitz (1999)

5.4 Aerosols

HFC emissions from aerosols are mainly released from aerosol propellant cans and metered dose inhalers that are used for medical purposes, e.g., asthma treatment. In these applications, HFC is used as propellant and vaporizes immediately. The activity unit is amount of HFC emissions. Historical emission estimates are taken from national communications to the UNFCCC (2008) complemented by information from national sources (Harnisch and Schwarz, 2003 ; Schwarz and Leisewitz, 1999 ; Oinonen and Soimakallio, 2001 ; AEAT, 2003 ; Poulsen, 2001). Future growth in HFC emissions from aerosols is assumed to follow the average GDP growth rate.

Table 31: Activity sources for HFC use in aerosols

GAINS sector code	GAINS activity code	Description	Unit
AERO	NOF	Aerosols	t HFC
Activity data sources:		UNFCCC (2008), AEAT (2003), Oinonen and Soimakallio (2001), Harnisch and Hendriks (2000), Harnisch and Schwarz (2003), Schwartz and Leisewitz (1999), Poulsen (2001)	
Emission factor sources:		(IPCC 1997)	

HFC emissions from use of aerosols could be controlled by replacing HFC with an alternative propellant, e.g., switching from HFC-134a to HFC-152a, which is a propellant with considerably lower greenhouse warming potential. The F-gas Directive stipulates for EU-27 that alternative propellants to HFCs should be used in aerosols.

Table 32: Technologies in GAINS for control of HFC use in aerosols

GAINS technology code	Description
ALT_PROP	Alternative propellant for aerosols
Sources:	USEPA (2001a), Pedersen (1998), Kaapola (1989) Harnisch and Hendriks (2000), Oinonen and Soimakallio (2001), AEAT (2003) Harnisch and Schwarz (2003), Schwartz and Leisewitz (1999), Poulsen (2001)

6 Transport non-energy sources

6.1 Refrigerated transport

HFC emissions from refrigerated transport are estimated in a similar way as the emissions from industrial, residential and commercial sectors (as described in Sections 4.6 and 5.1). Activity data for the year 2000 is compiled from various sources (UNFCCC, 2008; Harnisch and Hendriks, 2000; AEAT, 2003; Schwarz and Leisewitz, 1999). Due to the short equipment lifetime of refrigerated transport, no saturation year is assumed for this source. Instead, we assume a stabilization of the use of HFCs in refrigerated transport after year 2000.

Table 33: Activity sources for HFC use in refrigerated transport

GAINS sector code	GAINS activity code	Description	Unit
TRA_REFB	NOF	Refrigerated transport –emissions banked in equipment	t HFC
TRA_REFS	NOF	Refrigerated transport –emissions from scrapped equipment	t HFC
Activity data sources:		UNFCCC (2008), AEAT (2003), Oinonen and Soimakallio (2001), Harnisch and Hendriks (2000), Harnisch and Schwarz (2003), Schwarz and Leisewitz (1999), Poulsen (2001)	
Emission factor sources:		(IPCC 1997)	

HFC emissions from refrigerated transport can be reduced through good practice options. Emissions banked in equipment can be reduced through better leakage control or improved components, while emissions from scrapped equipment can be controlled through end-of-life recollection. Alternatively, pressurized CO₂ can substitute HFC as cooling agent, which would entirely remove HFC emissions. GAINS assumes a 50 percent maximum applicability of this option, due to that the open CO₂ system needs frequent refill and is therefore assumed unsuitable for long-distance transports.

Table 34: Technologies in GAINS for control of HFC use in refrigerated transport

GAINS technology code	Description
ALT_TRAB	Alternative refrigerant: use of open CO ₂ refrigerant system
GP_TRAB	Good practice: leakage control and improved components
ALT_TRAS	Alternative refrigerant: use of open CO ₂ refrigerant system
GP_TRAS	Good practice: end-of-life recollection
Sources:	Heijnes et al. (1999), Jyrkonen (2004), USEPA (2001a), Pedersen (1998), Harnisch and Hendriks (2000), Oinonen and Soimakallio (2001), AEAT (2003) Harnisch and Schwarz (2003), Schwartz and Leisewitz (1999), Poulsen (2001)

6.2 Mobile air conditioning

Emissions from mobile air conditioning are caused by leakage and losses during the replacement of the refrigerant, during the lifetime of the vehicle, as well as at the end of the vehicle life.

The use of HFC refrigerants in new vehicles in country i in year t was calculated using the formula:

$$U_{it} = \frac{1}{LT} * m * P_{it} * S_{it},$$

where S is the size of the vehicle stock, LT is the vehicle lifetime, m is the average charge of HFC per car (in kg/car), and P is the penetration of HFC-based air-conditioners in the vehicle stock. Vehicle stock data is taken from the GAINS database and was derived from the fuel use in the transport sector as estimated by PRIMES (2009). Current and future estimates of the penetration of air-conditioned cars in the car stock are taken from AEAT (2003), Oinonen and Soimakallio (2001) and national communications to the UNFCCC (2008). The vehicle lifetime is assumed to 12 years and the average charge of refrigerant per vehicle is assumed to 0.67 kg HFC-134a per vehicle. The air conditioner is refilled in case of leakage and the amount of HFC is the same at the end of the vehicle lifetime as it was when the vehicle was new. Emissions come from leakage from banked emissions and at the end-of-life. A leakage rate of 8.2 percent is assumed for banked emissions (Schwarz, 2001, Schwarz and Harnisch, 2003, Oinonen and Soimakallio, 2001).

Table 35: Activity sources for HFC use in mobile air conditioning

GAINS sector code	GAINS activity code	Description	Unit
MAC_B	NOF	Mobile air conditioning –emissions banked in equipment	t HFC
MAC_S	NOF	Mobile air conditioning –emissions from scrapped equipment	t HFC
Activity data sources:		UNFCCC (2008), AEAT (2003), Oinonen and Soimakallio (2001), Schwarz (2001), Schwarz and Harnisch (2003)	
Emission factor sources:		(IPCC 1997)	

Options to control HFC emissions from mobile air conditioning include good practice measures, i.e. leakage control and/ or modified components and end-of-life recollection. It is also possible to use pressurized CO₂ or HFC-152a as alternative refrigerants to HFC-134a. HFC-152a has a considerably lower (about ten times) greenhouse warming potential than HFC-134a. For EU-27 countries, the F-gas Directive requires a phase out of the use of HFC-134a in mobile air conditioning. From 2011 onwards, the use of HFC-134a is banned in all new cars and fully phased out in EU-27 by 2025.

Table 36: Technologies in GAINS for control of HFC use in mobile air conditioning

GAINS technology code	Description
ALT_MACB	Alternative refrigerant: HFC-134a replaced by pressurized CO ₂ (replacing emissions banked in equipment)
GP_MACB	Good practice: leakage control and improved components
ALT_MACS	Alternative refrigerant: HFC-134a replaced by pressurized CO ₂ (replacing emissions from scrapped equipment)
GP_MACS	Good practice: end-of-life recollection
Sources:	Heijnes et al. (1999), USEPA (2001a), Pedersen (1998), Harnisch and Hendriks (2000), Oinonen and Soimakallio (2001), AEAT (2003), Harnisch and Schwarz (2003), Schwartz and Leisewitz (1999)

7 Agriculture

7.1 Livestock – enteric fermentation

CH₄ emissions from livestock emerge primarily from enteric fermentation during the digestive process in the stomachs of ruminants. Ruminants with four compartment stomachs like cows, cattle, sheep, goats, buffalo, and camels have the highest formation of CH₄ during digestion, while it is lower in pseudo-ruminants with three compartment stomachs like horses, mules, and asses and monogastric animals like swine.

CH₄ emissions from enteric fermentation for a certain animal type s in country i and year t are calculated as:

$$E_{its} = \sum_m \left[ef_{is}^{NOC} * n_{its} * \gamma_{i:UN2005} * (1 - remeff_{sm}) * Appl_{itsm} \right],$$

where ef_{is}^{NOC} is the no control emission factor for animal type s in country i ,
 n_{its} is the number of animals of type m in country i and year t ,
 $\gamma_{i:UN2005}$ is a factor correcting for the discrepancy between IPCC (IPCC 2006) default region emission factors and implied emission factors reported by countries for year 2005 to UNFCCC (UNFCCC 2008),
 $remeff_{sm}$ is the removal efficiency of technology m when applied to animal type s , and
 $Appl_{itsm}$ is the application rate of technology m to animal type s in country i and year t .

For dairy cows, enteric fermentation emissions per animal are affected by the milk productivity of the cow. This effect is particularly accentuated for highly productive milk cows. To capture this, the no control emission factor for dairy cows is specified as the sum of a fixed emission factor per animal for cows producing up to 3000 kg per head per year and an additional term describing the emission factor per milk yield for milk production exceeding the productivity level 3000 kg per animal per year, i.e.,

$$ef_{it;cow}^{NOC} = ef_i^{animal} + ef_i^{milk} * (x_{it} - 3000)$$

where ef_i^{animal} is the default emission factor for cows in country i producing 3000 kg milk per year,
 ef_i^{milk} is the emission factor per kt milk produced above the threshold level 3000 kg milk per animal per year, and
 x_{it} is the average milk yield per animal in country i and year t .

The agricultural activity data with projections have been derived from the CAPRI model (2009) (<http://www.capri-model.org/>). Animal numbers have been calibrated to activity levels reported by Member States to EUROSTAT (2009) and FAOSTAT (2009) for year 2005. Future activity levels are derived using trends as estimated by the CAPRI model (2009). Splits

between solid and liquid manure management are based on communications between IIASA and National experts as part of the Clean Air for Europe (CAFE) and NEC Directive revision processes. Regional default emission factors are taken from IPCC (IPCC 2006) (Tables 10.10 and 10.11, Vol.4) and adjusted to country-specific circumstances by using implied emission factors reported to UNFCCC for year 2005 (UNFCCC 2009).

Table 37: Activity sources in GAINS for CH₄ emissions from enteric fermentation.

GAINS sector code	GAINS activity code	Description	Unit
AGR_COWS	DL_F	Dairy cows, liquid manure management	M heads
	DS	Dairy cows, solid manure management	M heads
COWS_3000_MILK	DL_F	Milk produced over threshold 3000 kg milk per head	kt milk
	DS	Milk produced over threshold 3000 kg milk per head	Mt milk
AGR_BEEF	OL_F	Non-dairy cattle, liquid manure management	M heads
	OS	Non-dairy cattle, solid manure management	M heads
AGR_PIG	PL	Pigs, liquid manure management	M heads
	PS	Pigs, solid manure management	M heads
AGR_OTANI	SH	Sheep and goat	M heads
	HO	Horses	M heads
Activity data sources:		EUROSTAT (2009), CAPRI model (2009), National communications, FAO (2009)	
Emission factor sources:		(IPCC 2006; UNFCCC 2008, 2009)	

Recent research shows that CH₄ emissions from enteric fermentation in cows and non-dairy cattle can be reduced through various types of changes in animal diets (Gerbens 1998; ECCP 2003; Boadi, Benchaar et al. 2004). Although extensive research has been performed on these control options in recent years, the effects on CH₄ emissions when applied on a large scale outside controlled farm environments remain uncertain. Comparability of results also suffers from inaccuracy and large variation in the measurement techniques used (Farooq Iqbal, Cheng et al. 2008). Still, we conclude from literature that diet options have negative, although limited, effects on CH₄ emissions per unit of milk or meat produced. With general increases in feed levels, CH₄ emission reductions come from increased productivity per animal coupled with reductions in livestock sizes. Switching to more concentrate in the feed and increasing the fat content of the feed also increase animal productivity as more of the energy in the feed is diverted to production of milk or meat instead of converted to CH₄ in the rumen. As it is difficult to draw accurate conclusions about the effects on CH₄ emissions from individual diet change options, we combine all options into a single mixed option and assume that when applied to animals on a large scale such options can attain a reduction in CH₄ emissions of almost ten percent. As all feed changes require control over what the animals eat, they are only assumed applicable to animals kept in stables. Abated emission factors

have been adjusted to country-specific data on average number of housing days per year for cows and cattle. These are taken from (Klimont and Brink 2003) for the European countries.

Currently, GAINS does not include any mitigation options that reduce CH₄ emissions from grazing livestock. Such options would include, e.g., immunization and genetic selection of animals (Boadi, Benchaar et al. 2004; Farooq Iqbal, Cheng et al. 2008). Although these options have shown promising in recent research, we consider large scale application too uncertain within the timeframe of the GAINS model.

Since diet changes are only assumed applicable to animals currently fed indoor in stables, no costs for investments in new equipment are assumed. The cost per animal s in country i of changing a conventional diet to a low CH₄ diet m is specified as:

$$C_{is} = \left[g_s * (f_{is;1} - f_{is;0}) - p_{is}^{product} * (M_{is;1} - M_{is;0}) \right] * [1 - d_s^{livestock}],$$

where g_s is the fraction of conventional diet replaced by low CH₄ diet,
 $f_{is;1}$ is the cost per animal for low CH₄ diet,
 $f_{is;0}$ is the cost per animal for current diet,
 $p_{is}^{product}$ is the price per unit of product (i.e., milk or meat) produced,
 $M_{is;1}$ is the product produced per animal with low CH₄ diet,
 $M_{is;0}$ is the product produced per animal with conventional diet, and
 $d_s^{livestock}$ is the relative reduction in livestock size.

Additional costs for a low CH₄ diet in comparison to a conventional diet depend on the relative prices of the different feeds used. The focus of comparative studies of CH₄ low feeds is typically on effectiveness in CH₄ reductions with only sporadic mentioning of costs. Gerbens (1998) indicates that additional costs are close to zero for replacing 25 percent of a structural carbohydrates diet with non-structural carbohydrates, but that the change has some effects on animal productivity. Ecofys (2009) calculates the costs of replacing 6% of a conventional diet with soy oil. We assume this translates into a replacement of 40 kg fodder for oil per animal per year and that soy oil cost 0.49 Euro/kg. With an additional average cost of 0.14 Euro/kg fodder replaced by soy oil, we estimate the cost to 5.52 Euro per animal per year. In addition, we follow Gerbens (1998) and assume a small positive net effect on milk or meat production of 0.25 percent after controlling for reductions in livestock size.

Table 38: Technologies in GAINS for control of CH₄ emissions from enteric fermentation.

GAINS technology code	Description	Activities applied to		Application limitations
FEED	Mix of feed changes for CH ₄ reducing purposes (includes e.g., increased feed intake, change to more fat and non-structural carbohydrates in diet)	AGR_COWS	DL_F, DS	Only applicable to housed animals
		COWS_3000_MILK	DL_F, DS	Only applicable to housed animals
		AGR_BEEF	OL_F, OS	Only applicable to housed animals
Sources:	(Gerbens 1998; Brink 2003; ECCP 2003; Klimont and Brink 2003; Boadi, Benchaar et al. 2004; Farooq Iqbal, Cheng et al. 2008; Ecofys 2009)			

7.2 Livestock - Manure management

CH₄ emissions from livestock also arise when the organic content in manure decomposes. CH₄ release occurs under anaerobic conditions, while the formation of N₂O requires oxygen. Manure management practices and temperature are important factors for the formation of CH₄ from manure. Default regional emission factors from IPCC (IPCC 2006) are specified for different climate zones and adjusted to the effects from liquid or solid manure management practices (Brink 2003). For EU-27 countries, default emission factors are adjusted to country-specific factors using implied emission factors reported to UNFCCC for year 2005 (UNFCCC 2008, 2009).

CH₄ emissions from manure management for a certain animal type *s* and manure management practice *h* in country *i* and year *t* are calculated as:

$$E_{itsh} = \sum_m \left[ef_{ish}^{NOC} * n_{itsh} * \gamma_{i:UN2005} * (1 - remeff_{shm}) * Appl_{itshm} \right],$$

- where ef_{ish}^{NOC} is the default no control emission factor for animal type *s* with (liquid or solid) management practice *h* in the climate zone for country *i*,
- n_{itsh} is the number of animals of type *s* with management practice *h* in country *i* and year *t*,
- $\gamma_{i:UN2005}$ is a factor correcting for the discrepancy between IPCC default region emission factors and implied emission factors reported by countries for year 2005 to UNFCCC,
- $remeff_{shm}$ is the removal efficiency of technology *m* when applied to animal type *s* and management practice *h*, and
- $Appl_{itshm}$ is the application rate of technology *m* to animal type *s* with management practice *h* in country *i* and year *t*.

Just like for CH₄ emissions from enteric fermentation, manure emissions per animal are affected by milk productivity, in particular for highly productive cows. To capture this, the no

control emission factor for dairy cows is specified as the sum of a fixed emission factor per animal for cows producing up to 3000 kg per head per year and an additional term describing the emission factor per milk yield for milk productivity rates exceeding 3000 kg per animal per year, i.e.,

$$ef_{it;cow}^{NOC} = ef_i^{animal} + ef_i^{milk} * (x_{it} - 3000)$$

where ef_i^{animal} is the default emission factor for cows in country i producing 3000 kg milk per year,
 ef_i^{milk} is the emission factor per kt milk produced above the threshold level 3000 kg milk per animal per year, and
 x_{it} is the average milk yield per animal in country i and year t .

Activity data sources used are the same as described for enteric fermentation (Section 7.1). Regional default emission factors by climate zone are taken from IPCC (IPCC 2006). For EU-27 countries, adjustments are made to country-specific factors by using implied emission factors reported to UNFCCC for year 2005 (UNFCCC 2008, 2009).

Emissions of N₂O are calculated as a fraction of the total nitrogen excretion, where the size of the fraction depends on the type of manure management. Both animal number and nitrogen excretion rates required for this calculation are elements of the national submissions to UNFCCC (UNFCCC 2008, 2009). Increased nitrogen excretion associated with high milk yields (above 3000 kg/hd) is considered at a rate of 14.5 kg additional N excreted per 1000 kg milk produced (this figure was empirically derived based on data from several European countries; Klimont, pers. communication).

Table 39: Activity sources in GAINS for CH₄ and N₂O emissions from manure management.

GAINS sector code	GAINS activity code	Description	Unit
AGR_COWS	DL	Dairy cows, liquid manure management	M heads
	DS	Dairy cows, solid manure management	M heads
COWS_3000_MILK	DL	Milk produced over threshold 3000 kg milk per head	kt milk
	DS	Milk produced over threshold 3000 kg milk per head	Mt milk
AGR_BEEF	OL	Non-dairy cattle, liquid manure management	M heads
	OS	Non-dairy cattle, solid manure management	M heads
AGR_PIG	PL	Pigs, liquid manure management	M heads
	PS	Pigs, solid manure management	M heads
AGR_POULT	LH	Laying hens	M heads
	OP	Other poultry	M heads
AGR_OTANI	SH	Sheep and goat	M heads
	HO	Horses	M heads
	BS	Buffaloes	M heads
	CM	Camels	M heads
Activity data sources:		EUROSTAT (2009), CAPRI model (2009), National communications, FAO (2009)	
Emission factor sources (CH ₄):		(Brink 2003; IPCC 2006; UNFCCC 2008)	
Emission factor sources (N ₂ O):		(IPCC 2006; UNFCCC 2009)	

CH₄ emissions from liquid management of manure from cows, non-dairy cattle and pigs can be reduced by treating the manure in anaerobic digesters (AD). AD plants produce biogas, which can be utilized as heat or electricity and thereby potentially substitute fossil fuel use. Three scales of AD installations for treatment of manure are considered in GAINS. The largest scale are the community size AD plants, which is assumed to receive manure from several farms in the vicinity of the plant. Transportation of manure for long distances is costly and increase emissions of both methane and carbon dioxide. This option is therefore only assumed applicable as a CH₄ reduction option in areas with intensive pig farming specified as areas with more than 200 pigs per square kilometre. Among EU-27 countries, only Belgium, Denmark, the Netherlands and Malta meet this requirement. For other countries, farm scale AD is the option assumed feasible for handling manure. Application of farm scale AD is limited to relatively large farms, i.e., farms with a minimum size of 100 dairy cows, 200 beef cattle or 1000 pigs. The option is assumed infeasible to smaller farms because of too high costs. Thus, for small farms in areas with low intensity in livestock farming, no option for

digestion of manure is considered in GAINS¹. European farm-scale fractions are taken from AEAT (AEAT 1998) and EUROSTAT (EUROSTAT 2008). The application limitation of farm scale AD is integrated in the calculation by adjusting the removal efficiency of the technology with a large farm factor.

Annual unit costs (per activity unit) are calculated as the sum of annualized investment costs, labour costs, other operation and maintenance costs, and cost-savings from utilizing recovered biogas as heat or electricity.

$$C_{itm} = I_m * \left[\frac{(1+r)^{LT} * i}{(1+r)^{LT} - 1} \right] + L_m * w_{it} - p_{it}^{gas} * R_m ,$$

Where I_m is the investment cost per animal,
 r is the discount rate on investments,
 LT is the lifetime of investments,
 L_m is the additional worktime needed as fraction of a workyear,
 w_{it} is the average annual wage for agricultural workers,
 p_{it}^{gas} is the gas price per PJ in country i in year t , and
 R_m is the energy content in PJ of biogas recovered per animal.

Costs for community scale AD were taken from AEAT (AEAT 1998) based on a Danish plant handling 200 kt manure per year. Costs for farm scale AD were taken from ECOFYS (2009). The reported costs refer to smaller application scales of 100 cows or 100 pigs. As GAINS assumes applicability only to farms with at least 100 cows, 200 non-dairy cattles or 1000 pigs, investment costs have been adjusted to account for the larger scales for non-dairy cattle and pig farms.

For N₂O emissions from manure management, no specific mitigation options are identified in GAINS.

Table 40: Technologies in GAINS for control of CH₄ emissions from animal manure

¹ A small scale AD option has been introduced in GAINS to include household size digesters common in some developing countries. These digest manure and other organic waste material from farm households and produce biogas to be utilized e.g., for cooking stoves. Such digesters are cheap to install but labor intensive to operate effectively. Costs for Household scale AD plant are based on a survey of 192 digesters installed in Vietnam (An, Preston et al. 1997). Because of relatively high labor/energy cost ratios in EU-27 countries, this option is assumed not applicable.

GAINS technology code	Description	Activities applied to		Application limitations
COMM_AD	Community scale anaerobic digester	AGR_COWS	DL	Only applicable to areas with intensive pig farming (as defined in text)
		COWS_3000_MILK	DL	
		AGR_BEEF	OL	
		AGR_PIG	PL	
FARM_AD	Farm scale anaerobic digester	AGR_COWS	DL	Only applicable to large farms (as defined in text)
		COWS_3000_MILK	DL	
		AGR_PIG	PL	
HOUS_AD	Household scale anaerobic digester	AGR_COWS	DL	Only applicable to some developing countries and not to any Annex I country
		COWS_3000_MILK	DL	
		AGR_BEEF	OL	
		AGR_PIG	PL	
Sources:	(An, Preston et al. 1997; AEAT 1998; ECCP 2003; IEA-Bioenergy 2007; ECOFYS 2009)			

7.3 Rice cultivation

CH₄ emissions from rice cultivation result from anaerobic decomposition of organic material in rice fields. CH₄ is released into the atmosphere mainly by diffusive transport through rice plants during the growing season. Emissions depend on the season, soil characteristics, soil texture, use of organic matter and fertilizer, climate, as well as agricultural practices. The emission calculation methodology used follows the IPCC guidelines (IPCC 2006) and adopt IPCC default emission factors unless country-specific factors have been reported to UNFCCC (UNFCCC 2008). The IPCC method is based on the annual harvested area with scaling factors for different water regimes. In GAINS, the rice cultivated area is divided into three activities depending on the water regime used:

- Continuously flooded: fields have standing water throughout the growing season and may only dry out for harvest.
- Intermittently flooded: fields have at least one aeration period of more than three days during the growing season and emit about 50-60 percent of CH₄ emissions per hectare from continuously flooded fields.
- Upland rice: fields are never flooded for a significant period of time and are not assumed to emit CH₄.

CH₄ emissions from rice cultivation in a country *i* in year *t* are calculated as:

$$E_{it} = \sum_s \sum_m [ef_s * h_i * \beta_s * \gamma_{i,UN2005} * V_{is} * n_{it} * (1 - remeff_{sm}) * Appl_{ism}]$$

where ef_s is the IPCC (2006) default emission factor for CH₄ emissions from

h_i	rice cultivated under water regime s during the growing season, is the duration of the growing season expressed as fraction of days in a year,
β_s	is an emission scaling factor for water regime s (=1 for continuously flooding, =0.5 for intermittently flooded, and =0 for upland rice).
$\gamma_{i;2005}$	is a factor correcting for differences in IPCC default emission factor and implied emission factors reported by countries to UNFCCC for year 2005,
V_{is}	is the fraction of rice cultivated land under water regime s , and
n_{it}	is the area of land used for rice cultivation in country i in year t .
$remeff_{sm}$	is the removal efficiency of technology m , and
$AppI_{itsm}$	is the application of technology m for rice cultivated under water regime s in country i in year t .

Activity data for rice cultivation is measured in million hectares of land and is taken from FAO (FAOSTAT 2008) with projections based on (FAO 2003).

Table 41: Activity sources in GAINS for CH₄ emissions from rice cultivation.

GAINS sector code	GAINS activity code	Description	Unit
RICE_FLOOD	AREA	Continuously flooded rice cultivation area	M ha
RICE_INTER	AREA	Intermittently flooded rice cultivation area	M ha
RICE_UPLAND	AREA	Upland rice cultivation area	M ha
Activity data sources:		(FAO 2003; FAOSTAT 2008)	
Emission factor sources:		(IPCC 2006; UNFCCC 2008)	

Different rice hybrids affect CH₄ emissions to varying extents. By careful selection of low CH₄ producing hybrids, emissions can be ten percent lower, while simultaneously increasing crop yield (ADB 1998). The Asian Development Bank (ADB 1998) estimates that Chinese rice yields may increase by as much as 10 to 20 percent from switching to low CH₄ rice hybrids. In other parts of the world, where high yield rice hybrids are already in extensive use, potentials for additional yield increases are likely to be lower. For EU-27, the potential reduction in CH₄ emissions from switching to alternative rice hybrids is assumed ten percent with a three percent increase in crop yield.

Introducing intermittent aeration of continuously flooded rice fields reduces CH₄ emissions, but is also likely to increase weed growth in the fields (Barrett, Moser et al. 2004; Ferrero and Nguyen 2004). This increases labour costs for weeding and drainage and affects the crop yield negatively.

By applying sulphate-containing substrates to rice fields, CH₄ can be reduced because bacteria which produce CH₄ compete for the same substrate as the sulphate reducing bacteria (Denier van der Gon, van Bodegom et al. 2001). This option reduces CH₄ on all types of rice fields but has particular interest for continuously flooded rice fields in dry areas, where increased aeration is not an option because of shortage of water to re-flood fields after drainage. Costs associated with this option are the costs of acquiring sulphate containing fertilizers like e.g., ammonium sulphate.

Annual unit costs (per activity unit) are calculated as the sum of increased labour costs, additional costs for hybrid grains or sulphate amendments, and costs or cost-savings from changes in yield productivity:

$$C_{im} = L_m * w_{it} + (p_1 - p_0) * T_m + g_{sulphate} * S_m + (y_1 - y_0) * p_{rice} ,$$

where L_m is the additional worktime needed as fraction of a workyear,
 w_{it} is the average annual wage for agricultural workers,
 $(p_1 - p_0)$ is the additional price for hybrid rice compared with conventional rice per ton grain,
 T_m is the amount of rice grains per hectare,
 $g_{sulphate}$ is the price of sulphate amendments per ton,
 S_m is the amount of sulphate amendment applied per hectare,
 $(y_1 - y_0)$ is the change in yield productivity in tons per hectare, and
 p_{rice} is the producer price of rice.

Table 42: Technologies in GAINS for control of CH₄ emissions from rice cultivation

GAINS technology code	Description	Application limitations
ALT_RICE	Alternative low methane generating rice hybrids	Applicable to all water regimes
INTER_RICE	Aeration of continuously flooded rice fields	Only applicable to continuously flooded rice fields (RICE_FLOOD)
SULF_RICE	Sulphate containing amendments	Applicable to all water regimes
COMB1_RICE	Combination of alternative rice hybrids and sulphate containing amendments	Applicable to all water regimes
COMB2_RICE	Combination of alternative rice hybrids, sulphate containing amendments, and aeration	Only applicable to continuously flooded rice fields (RICE_FLOOD)
Sources:	(ADB 1998; Denier van der Gon, van Bodegom et al. 2001; Barrett, Moser et al. 2004; Ferrero and Nguyen 2004; IRRI 2007)	

7.4 Agricultural and grassland soils

Microbial processes in soil convert ammonia into nitrate (nitrification) and further to molecular nitrogen (denitrification). The processes occur in soil under aerobic and anaerobic conditions, respectively, and both release N₂O as a side product. Soil processes are by far the most important source of N₂O.

Despite a considerable amount of on-going research, there are still important gaps in knowledge about N₂O release from soils. Especially, the amount of N₂O formed and converted while still in the soil (during diffusion to the surface) seems difficult to assess, but is needed to obtain the overall release rate in a process based approach. Chamber measurements on top of the soil yield highly variable results. As a consequence, uncertainty associated with the emission figures has been estimated as an order of magnitude, when emissions are related to the input of nitrogen (IPCC 2006). Despite of contributing only a minor fraction to overall greenhouse gas emissions, soil N₂O emissions are typically responsible for the major part of uncertainty in a national greenhouse gas inventory (Winiwarter and Rypdal, 2001).

Nitrous oxide emissions are typically assessed as a fraction of the nitrogen deposited on soils. Nitrogen input in GAINS is derived from nitrogen contained in mineral fertilizer, animal manure and crop residue left on the field. Mineral fertilizer data has been derived from the International Fertilizer Association (IFA) and the European Fertilizer Manufacturers Association (EFMA); animal numbers come from the CAPRI model and the respective estimate of nitrogen excretion of GAINS acquired in interaction with country experts; amount of N contained in crop residues, has been estimated from harvest data originating in the Food and Agriculture Organization's statistical database (FAOSTAT), using IPCC factors for nitrogen contents and share of crop left on field. National data on nitrogen input as crop residues and from N-fixing crops (UNFCCC, 2009), where available, were used to replenish this information. The amount of animal manure is taken from animal numbers and nitrogen excretion rates, all data are available in the national reports (UNFCCC, 2009). While the national reports account separately for manure applied on fields (taking into account evaporative losses prior to application), this is not done in GAINS. Instead, these losses (and consequential redeposition on soils, to be considered as "indirect emissions" according to IPCC, 2006) are lumped into an overall N₂O release fraction. Thus, GAINS does not separate direct and indirect emissions, but it also does not need to account for atmospheric deposition as an input.

Table 43: Activity sources in GAINS for N₂O emissions from soils.

GAINS sector code	GAINS activity code	Description	Unit
GRASSLAND	N_INPUT	Nitrogen (fertilizer) applied to grassland	kt N
AGR_ARABLE_TEMP	N_INPUT	Nitrogen (fertilizer) applied to agricultural land in temperate climate	kt N
AGR_ARABE_SUBB	N_INPUT	Nitrogen (fertilizer) applied to agricultural land in subboreal climate (exposed to frost-thaw cycles)	kt N
Activity data sources:		(IFA (2009); EFMA (2009); CAPRI model (2009); FAO 2003; FAOSTAT 2008; UNFCCC 2009)	
Emission factor sources:		(IPCC 2006; UNFCCC 2009)	

An implied emission factor is derived from the activity and emission data reported by countries to the UNFCCC (2008, 2009). We use this factor to adapt the general GAINS

emission factor to a country-specific situation, considering the estimated amount of deep injection of manure. The resulting emission factors (also for abatement options, see below) are scaled such that the respective techniques have the same order and follow the same improvements as in the standard situation.

All abatement measures focus on reducing the input of nitrogen, specifically fertilizer nitrogen, to soil. In reality this is a change in activity numbers. The technical implementation in GAINS, however, requires that each emission factor is targeted, respectively. While a considerable number of individual measures can be discerned, we distinguish four principal groups of options with similar technical and economic features. This is supported by data provided in the literature (de Jager *et al.*, 1996; Hendriks *et al.*, 1998; Bates, 2001; Gibson, 2001; Gale and Freund, 2002).

- ***Reduced application of fertilizer***

This group includes a set of relatively simple “good practice” options to reduce fertilizer consumption. Generally, it is safe to assume that the amount of fertilizer applied is considerably larger than what is required for optimum plant growth. Any measure for a more effective distribution of fertilizer, which results in a lower overall consumption, is beneficial. A good overview of available options has been compiled by de Jager *et al.* (1996). Among these options are maintenance of fertilizer spreader, fertilizer free zones on edges of fields (to reduce loss into ditches), row application, or fertilizer need analysis (soil testing) to account for nitrogen already available in soil or applied otherwise (manure, atmospheric deposition). Set-aside agricultural policy also falls into this category. Some of these options overlap.

- ***Optimized timing of fertilizer application***

Timing of fertilizer application is normally optimized to fit the internal work procedures of a farmer, not the needs of plants. A reduced availability of nitrogen in soil would reduce emissions and leaching and allow a further decrease in nitrogen application (Hendriks *et al.*, 1998). This group includes the application of slow-release fertilizers (e.g., coated fertilizers; Gale and Freund, 2002) or the use of catch crops to shorten the fallow period and subsequently use them as green manure (Bates, 2001). Procedural changes in manure application also include an increased frequency of slurry spreading and the ban of manure application during off-season (while increasing storage capabilities of slurry tanks) to decrease surplus nitrogen in soils.

- ***Nitrification inhibitors***

This option represents the use of agro-chemistry to reduce nitrogen requirements. Application of nitrification inhibitors suppresses the conversion of ammonium to nitrate. As nitrogen in the form of ammonium is less prone to leaching than nitrate, nitrification inhibitors allow for a significantly more efficient application of fertilizers. However, inhibitors are substances that affect the soil microflora (Freibauer, 2001) and may exhibit possible unintentional side effects, which could make them undesirable. The high proven efficiency of this option is decreased as the effect of the inhibitor is temporally limited to a few months.

- **Precision farming**

The aim of precision farming is to provide a plant with exactly the amount of nitrogen that it needs using the latest available technology to allow variable N-input according to specific plant needs. Ideally, this would make surplus nitrogen application unnecessary and avoid the release of excess nitrogen compounds to the environment. Precision farming requires high-tech equipment in combination with detailed soil analysis to assess specifically the plants' needs.

In the EU countries, legal requirements have been set primarily to protect groundwater and surface water from nitrogen loads. We expect that these requirements lead to the implementation of “fertilizer reduction” measures in the current legislation scenario. Further options are not considered to occur in the baseline.

Table 44: Technologies in GAINS for control of N₂O emissions from soil processes.

GAINS technology code	Description
FERT_RED	Set of “good practice” measures to reduce fertilizer input
FERTTIME	Adjusting fertilizer addition to the periods of agricultural demand
NITR_INH	Application of agrochemicals such as nitrification inhibitors
PREC_FARM	Optimization of agricultural nitrogen efficiency by “precision farming”
Sources:	(AEAT 1998; Hendriks, de Jager et al. 1998)

7.5 Organic soils

Soil processes in organic soils do not differ from those in other soils, but the larger amount of carbon available provides “feed” for micro-organisms which become more productive. Organic soils (histosols) are thus treated separately in national greenhouse gas inventories (IPCC, 2006). Thus the area of histosols used for agricultural purposes (HISTOSOL, presented in Mha area) is taken from the national submissions to the UNFCCC (UNFCCC 2008).

As emissions are large compared to other soils, and the overall area of organic soils under cultivation is fairly low in all countries, the obvious abatement option is to stop utilizing these soils for agricultural purposes. This option has been implemented in GAINS, even if studies on abandoned Finnish histosols (Maljanen *et al.*, 2004) indicate that banning cultivation may in reality not return the emission situation to the natural background.

Table 45: Technologies in GAINS for control of N₂O emissions from organic soils.

GAINS technology code	Description
FALLOW	Abandonment of agricultural use of organic soils
Sources:	(IPCC, 2000)

8 Waste

8.1 Biodegradable solid waste

CH₄ from municipal and industrial solid waste is generated when biodegradable matter is digested under anaerobic conditions in landfills. The amounts of waste that end up in landfills depend on the initial amounts of waste generated and the amounts of waste that are diverted away from landfills through different types of waste treatment options. The activity data is defined as the total amount of waste generated before waste is diverted to different treatments or to land disposal. Waste amounts are first split by municipal and industrial solid wastes and then by waste composition for municipal solid waste and by manufacturing industry sub-sector for industrial solid waste. The splits are made to fit the structure of the emission factors for different waste types that are possible to calculate from default factors derived from the IPCC guidelines (IPCC 2006). In the IPCC methodology, emission factors vary with the degradable organic carbon content (DOC) of the waste and the management standard of landfills, i.e.,

$$ef_s = DOCm_s * DOCf * MCF * F * 16/12 * (1 - OX), \quad \text{Equation 5}$$

where

$DOCm_i$	Fraction of Decomposable Organic Carbon (DOC) in waste type/sector s ,
$DOCf$	Fraction of DOC that can decompose (default used is 0.5),
MCF_i	Methane Correction Factor correcting for aerobic decomposition and vary with the management standard of the landfills (default used for EU-27 is 0.8),
F	Fraction of CH ₄ in generated landfill gas (default used is 0.5),
$16/12$	Molecular weight ratio CH ₄ /C,
OX	Oxidation factor correcting for increased oxidation from covering of landfills (default used for EU-27 is 0.1), and

Amounts of municipal solid waste (MSW) and industrial solid waste generated in different European countries between 1985 and 2003 were taken from EUROSTAT (EUROSTAT 2005) together with waste type fractions for MSW and fractions for the type of manufacturing industry generating the waste for the industrial solid waste. This data was used to econometrically obtain elasticity estimates for waste generation (Höglund-Isaksson 2007), which were then used to extend the data on waste amounts for the entire period 1970-2030. In the elasticity estimations, the generation of MSW per capita is assumed determined by per capita GDP and the urbanization rate (UN 2005). The basis for the extension of the municipal solid waste was MSW per capita reported by EU Member States to EUROSTAT (2009) for the year 2005.

Generation of industrial waste was estimated on industry level and related to the value added of the industry (UNIDO 2006; Groningen 2008). For EU-27, projections for value added

follow industry forecasts consistent with the economic forecasts used by the PRIMES model (2009). The economic forecasts, together with the elasticity estimates, were the basis for projections of future waste generation by type of industry. The average amount of industrial waste per value added in a certain industry sub-sector may vary considerably between countries, e.g., due to variations in the technology used and the water content of the generated waste. To calculate emissions, the amount of waste is multiplied by a default industry-specific IPCC emission factor with a fixed fraction of degradable organic carbon (DOC) for all countries. We assume the IPCC default factor is developed based on an average waste generation observed across several countries. The IPCC emission factor is therefore related to a cross-country average waste generation rate per value added rather than the actual reported country-specific waste generation rates. We divide the sample into EU-15 and EU-10 (i.e., the ten Member States joining the union in 2005) and derive average waste generation rates per value added for these two country groups as basis for emission calculations. Elasticity estimates and basis for future projections are presented in Table 46.

CH₄ from waste deposited on landfills is formed and released with a time delay of up to several decades. IPCC (IPCC 2006) recommends the use of a First-order-decay model taking up to fifty years disposal into account. The GAINS model structure does not allow for implementation of a full First-order-decay model. Instead, a simplified structure is used, where the delay between waste disposal and CH₄ release is accounted for as a lag in the activity data of 10 years for fast degrading organic waste like food waste and 20 years for more slowly degrading waste like paper, wood and textile. The lags correspond to approximate average half-life values for the corresponding waste types (IPCC 2006).

CH₄ emissions from municipal (or industrial) solid waste in country *i* in year *t* are estimated as the sum of emissions from a certain waste type *s* (or industry sector) summed over emissions from waste diverted to waste treatment option *m* :

$$E_{it} = \sum_s \sum_m A_{i;(t-y_s),s} * ef_s * (1 - remeff_{sm}) * Appl_{itsm}$$

where $A_{i;(t-y_s),s}$ is amount of waste type (or industry sector) *s* deposited to landfills in year *t*-*y_s*, where *y_s* is the average lag in CH₄ release assumed for waste type (or industry sector) *s*,
 ef_s is the IPCC default emission factor for waste type (or industry sector) *s* deposited in a landfill without recovery of landfill gas,
 $remeff_{sm}$ is the removal efficiency of waste treatment option *m*, and
 $Appl_{itsm}$ is the application of waste treatment option *m* to waste type (or industry sector) *s* in country *i* in year *t*.

Waste amounts were also verified with data reported by countries to the UNFCCC for year 2005 (UNFCCC 2008). The emission factor for waste from the pulp and paper industry has been reduced ten times as the industry is assumed to operate closed production processes in all EU countries.

Table 46: Basis for solid waste generation and elasticity estimates used for future generation of solid waste

Sector	Basis for future projections	Elasticity estimates Source: Estimations by Höglund-Isaksson (2007) based on data from EUROSTAT (2005)	Fraction Degradable organic carbon (DOC), IPCC (2006)
Municipal solid waste	Country-specific MSW per capita reported to EUROSTAT (2009) for year 2005	Relative change in MSW per capita to GDP per capita: 0.48 Relative change in MSW per capita to urbanization rate: -0.17	Food: 0.15 Paper: 0.40 Wood: 0.43
Food, beverages, tobacco industry	Waste amount per value added in 2000 (EUROSTAT, 2005): EU-15: 390 ton/MEuro EU-10: 724 ton/MEuro	Relative change in solid waste to value added: 0.81	0.15
Pulp and paper industry	EU-15: 271 ton/MEuro EU-10: 542 ton/MEuro	1.03	0.40
Textile, footwear, leather industry	EU-15: 105 ton/Meuro EU-10: 154 ton/Meuro	0.74	0.24
Wood and wood products industry	EU-15: 963 ton/Meuro EU-10: 1544 ton/Meuro	0.33	0.43
Rubber and plastics industry	EU-15: 86 ton/Meuro EU-10: 106 ton/Meuro	0.67	0
Other manufacturing industry	EU-15: 244 ton/Meuro EU-10: 1331 ton/Meuro	0.70	0

Table 47: Activity sources in GAINS for CH₄ emissions from municipal and industrial solid waste

GAINS sector code	GAINS activity code	Description	Unit
MSW_FOOD	10YR_BP	Food waste in MSW generated 10 years before period	Mt waste
MSW_PAP	20YR_BP	Paper waste in MSW generated 20 years before period	Mt waste
MSW_PLA	20YR_BP	Plastic waste in MSW generated 20 years before period	Mt waste
MSW_WOOD	20YR_BP	Wood waste in MSW generated 20 years before period	Mt waste
MSW_OTH	20YR_BP	Other waste in MSW generated 20 years before period	Mt waste
INW_FOOD	10YR_BP	Waste generated by the food, beverages and tobacco industry 10 years before period	Mt waste
INW_PAP	20YR_BP	Waste generated by the paper, pulp and printing industry 20 years before period	Mt waste

INW_RUB	20YR_BP	Waste generated by the plastics and rubber industry 20 years before period	Mt waste
INW_TEX	20YR_BP	Waste generated by the textile and leather industry 20 years before period	Mt waste
INW_WOOD	20YR_BP	Waste generated by the wood and wood products industry 20 years before period	Mt waste
INW_OTH	20YR_BP	Waste generated by other manufacturing industry 20 years before period	Mt waste
Activity data sources:		(EUROSTAT 2005; UN 2005; UNIDO 2006; Höglund-Isaksson 2007; Groningen 2008) PRIMES (2009)	
Emission factor sources:		(IPCC 2006; UNFCCC 2008)	

Options available for control of methane emissions from waste include both waste diversion options and the option of equipping landfills with gas recovery, where the recovered gas is flared or utilized for energy purposes. Waste diversion options include waste incineration, treatment of food waste in anaerobic digesters or composts, or recycling of paper or wood waste.

The no control option for waste is defined as disposal of waste to landfills without gas recovery. Although disposal of waste to a solid waste disposal (SWD) without gas recovery is costly, these costs are paid for other reasons than methane prevention and methane abatement costs are therefore taken to be zero in the no control case.

Costs for controlling methane from solid waste were estimated as:

$$C_{itsm} = I_{sm} * \left[\frac{(1+r)^{LT} * r}{(1+r)^{LT} - 1} \right] + L_{sm} * w_{it} + M_{sm} + S_{sm} - (CS_{sm}^{Recycled} + CS_{sm}^{Landfill}) - p_{it}^{gas} * R_{sm}$$

where I_{sm} is the investment cost per Mt waste when technology m is installed to control emissions from waste type (or industry sector) s ,

r is the discount rate on investments,

LT is the lifetime of investments,

L_{sm} is the additional worktime needed as fraction of a workyear,

w_{it} is the average annual wage for skilled workers in country i in year t ,

M_{sm} is the operation and maintenance cost,

S_{sm} is the waste separation cost when separation is necessary,

$CS_{sm}^{Recycled}$ is a cost saving in form of income from sales of recycled products (e.g., recycled paper, wood particle boards or quality compost),

$CS_{sm}^{Landfill}$ is the opportunity cost of avoiding landfilling, i.e., a cost saving from diverting waste away from landfills,

p_{it}^{gas} is the gas price per PJ in country i in year t , and

R_m is the energy content in PJ of biogas recovered per Mt waste generated.

Table 48: Technologies in GAINS for control of CH₄ emissions from solid waste.

GAINS technology code	Description
MSW_FOOD_AD	Municipal food waste separated and treated in anaerobic digester with biogas recovery and utilization for energy purposes
MSW_FOOD_HSC	Municipal food waste separated and treated in household compost
MSW_FOOD_INC	Municipal food waste incinerated
MSW_FOOD_LSC	Municipal food waste separated and treated in large-scale compost
MSW_FOOD_SWD_FL A	Municipal food waste deposited to landfill equipped with gas recovery
MSW_FOOD_SWD_USE	Municipal food waste deposited to landfill equipped with gas recovery and utilizing the gas for energy purposes
MSW_PAP_REC	Municipal paper waste separated and recycled
MSW_PAP_INC	Municipal paper waste incinerated
MSW_PAP_SWD_FL A	Municipal paper waste deposited to landfill equipped with gas recovery
MSW_PAP_SWD_USE	Municipal paper waste deposited to landfill equipped with gas recovery and utilizing the gas for energy purposes
MSW_WOOD_INC	Municipal wood waste incinerated
MSW_WOOD_SWD_FL A	Municipal wood waste deposited to landfill equipped with gas recovery
MSW_WOOD_SWD_USE	Municipal wood waste deposited to landfill equipped with gas recovery and utilizing the gas for energy purposes
INW_FOOD_AD	Waste from food industry treated in anaerobic digester with biogas recovery and utilization for energy purposes
INW_FOOD_COM	Waste from food industry treated in large-scale compost
INW_FOOD_INC	Waste from food industry incinerated
INW_FOOD_SWD_FL A	Waste from food industry deposited to landfill equipped with gas recovery
INW_FOOD_SWD_USE	Waste from food industry deposited to landfill equipped with gas recovery and utilizing the gas for energy purposes
INW_PAP_REC	Waste from paper industry recycled
INW_PAP_INC	Waste from paper industry incinerated
INW_PAP_SWD_FL A	Waste from paper industry deposited to landfill equipped with gas recovery
INW_PAP_SWD_USE	Waste from paper industry deposited to landfill equipped with gas recovery and utilizing the gas for energy purposes

Table 49, ctd.: Technologies in GAINS for control of CH₄ emissions from solid waste.

GAINS technology code	Description
INW_TEX_INC	Waste from textile industry incinerated
INW_TEX_SWD_FL A	Waste from textile industry deposited to landfill equipped with gas recovery
INW_TEX_SWD_USE	Waste from textile industry deposited to landfill equipped with gas recovery and utilizing the gas for energy purposes
INW_WOOD_REC	Waste from wood industry recycled
INW_WOOD_INC	Waste from wood industry incinerated
INW_WOOD_SWD_FL A	Waste from wood industry deposited to landfill equipped with gas recovery
INW_WOOD_SWD_USE	Waste from wood industry deposited to landfill equipped with gas recovery and utilizing the gas for energy purposes
Sources:	(Sakai 1997; AEAT 1998; Bontoux 1999; Tanskanen 2000; AEAT 2001; EuropeanCommunities 2001; IPPC 2001; Persson 2003; IPCC 2006; SEA 2007)

8.2 Wastewater from the domestic sector

Wastewater treatment plants serve to decompose compounds containing nitrogen and carbon from the wastewater before discharge. Main gaseous products are CO₂ and molecular nitrogen, but during the process also CH₄ and N₂O are released. CH₄ is formed whenever wastewater with high organic content is handled under anaerobic conditions. N₂O formation is basically the same process as in soils (microbial nitrification and denitrification), occurring either in aerobic or anaerobic conditions.

In developed countries, domestic wastewater is conventionally treated in centralized aerobic treatment plants and lagoons. Implementation of anaerobic treatment in reactors and lagoons is on increase especially in Western Europe. Anaerobic treatment has advantages over aerobic treatment like lower costs, smaller volumes of excess sludge produced, and the possibility of recovering useful biogas (Lettinga 1995). During anaerobic treatment, the formation of CH₄ is extensive especially in warm climates with temperatures exceeding 15°C, which is the temperature needed for an active methanogenesis. With a well managed aerobic treatment, CH₄ formation is unlikely, however, with less well managed systems the occurrence of anaerobic conditions increase as well as CH₄ formation (IPCC 2006).

Domestic wastewater is in GAINS split into the two sectors centralized and decentralized collection of wastewater. Centralized collection systems refer primarily to wastewater from urban population and decentralized systems to wastewater from rural population. The activity unit is number of people living in areas with centralized or decentralized collection systems. Population numbers were taken from PRIMES (2009), the fractional split into centralized and

decentralized collection systems in 2005 was taken from EUROSTAT (2005) and change in the future following expected growth in urbanization rates as estimated by (UN, 2006). CH₄ emissions from domestic wastewater in country *i* and year *t* are in GAINS estimated as:

$$E_{it} = \sum_s \sum_m A_{its} * ef_s * (1 - remeff_{sm}) * Appl_{it sm}$$

where A_{its} is number of people in urban/rural areas or with wastewater collection system *s*,
 ef_s is the IPCC default uncontrolled emission factor,
 $remeff_{sm}$ is the removal efficiency of wastewater treatment system *m*, and
 $Appl_{it sm}$ is the application of wastewater treatment system *m*.

Uncontrolled emissions are defined as emissions when wastewater is emitted directly to a water body without prior collection and treatment. As anaerobic conditions are formed when large quantities of wastewater are collected and stored, CH₄ formation in the uncontrolled case are likely to be very limited. CH₄ emissions are likely to increase from any form of organized wastewater collection. Collection is however a prerequisite for treatment, which is important for combating water pollution from excessive nitrogen and phosphor. Uncontrolled emission factors were derived following the IPCC guidelines (IPCC 2006):

$$ef_s = BOD * B_0 * MCF_0,$$

where

ef_{ik} Emission factor specified for technology *k* in country *i* in kt CH₄/M people
 BOD Amount of BOD (biochemical oxygen demand) generated in kt BOD/M people (default factor used is 21.9 kt CH₄/M people).
 B_0 Maximum CH₄ producing capacity in kt CH₄/kt BOD (default used is 0.6).
 MCF_0 Methane Correction Fraction in uncontrolled case, i.e. fraction of BOD that will be converted to CH₄ in the uncontrolled case (default is 0.1)

Table 50: Activity sources in GAINS for CH₄ and N₂O emissions from domestic wastewater

GAINS sector code	GAINS activity code	Description	Unit
WW_DOM_CC	POP	Domestic wastewater –centralized collection	M people
WW_DOM_DC	POP	Domestic wastewater –decentralized collection	M people
Activity data sources:		(IMF 2006; UN 2006; Höglund-Isaksson 2007)	
Emission factor sources:		(IPCC 2006; UNFCCC 2008)	

There are no wastewater options available that primarily target CH₄ emissions. There are, however, several different ways of treating wastewater, which have different implications for

CH₄ emissions. When domestic wastewater is centrally collected and emitted to a water body with only mechanical treatment to remove larger solids, plenty of opportunities for anaerobic conditions are created, which promotes extensive formation of CH₄. With well managed aerobic or anaerobic treatment, the CH₄ formation is effectively mitigated and CH₄ emissions can be kept on a negligible level.

GAINS does not count costs for investments in sewage pipe networks as methane abatement costs. Such costs are usually justified by major improvements in public health, e.g., lower rates of waterborne diseases and infant mortality, and would probably never be considered primarily as a methane control strategy. In GAINS, only costs for various types of sewage treatment are included as methane mitigation costs. The cost of switching from no control to centralized collection with none or mechanical treatment involves a small operation and maintenance cost. Investments in aerobic or anaerobic treatment of the sewage are more costly. We use cost estimates for sewage treatment in Denmark and the Netherlands in 1976-98 (Andersen 2005) as basis for investment costs. Operation and maintenance costs were taken from a study of Spanish sewage treatment works (Hernandez-Sancho and Sala-Garrido 2008).

Anaerobic digestion of wastewater will generate biogas, which can be recovered and upgraded to meet requirements for gas used in gas networks or as vehicle fuel. Costs for upgrading the gas are balanced by revenues from external gas sales. Information on costs for upgrading were obtained from (Persson 2003) and based on a survey of costs from 17 upgrading facilities (twelve in Sweden, three in the Netherlands and two in France) and six different suppliers of upgrading techniques.

In rural areas, domestic wastewater can be collected and treated in latrines, septic tanks or similar anaerobic treatment. We use the cost for a septic treatment system serving four people on average (USEPA 1999).

Costs for different wastewater treatment systems m are defined as:

$$C_{itm} = I_m * \left[\frac{(1+r)^{LT} * r}{(1+r)^{LT} - 1} \right] + L_m * w_{it} + M_m - p_{it}^{gas} * R_m$$

where I_m is the investment cost per M people for technology m ,
 r is the discount rate on investments,
 LT is the lifetime of investments,
 L_m is the additional worktime needed as fraction of a workyear,
 w_{it} is the average annual wage for skilled workers in country i in year t ,
 M_m is the operation and maintenance cost,
 p_{it}^{gas} is the gas price per PJ in country i in year t , and
 R_m is the energy content in PJ of biogas recovered from wastewater per M people.

Table 51: Technologies in GAINS for control of CH₄ emissions from domestic wastewater handling.

GAINS technology code	Description
DOM_CC_1	Centralized collection of domestic wastewater with none or mechanical treatment
DOM_CC_23	Centralized collection of domestic wastewater with anaerobic treatment
DOM_CC_23U	Centralized collection of domestic wastewater with anaerobic treatment with gas recovery and utilization for energy purposes
DOM_CC_AER	Centralized collection of domestic wastewater with aerobic treatment
DOM_DC_TRM	Decentralized collection of domestic wastewater in septic tanks, latrines or other anaerobic treatment
Sources:	(Lettinga 1995; USEPA 1999; Persson 2003; Andersen 2005; IPCC 2006; Hernandez-Sancho and Sala-Garrido 2008)

Operating conditions in wastewater treatment plants (temperature, residence time, pH, ...) control the biochemical process. We assume that optimization of these parameters to reduce N₂O release can be accomplished without compromising the desired decomposition of the organic substrate.

Table 52: Technology in GAINS for control of N₂O emissions from domestic wastewater handling.

GAINS technology code	Description
OPTIM	Process optimization to increase the N ₂ /N ₂ O ration in effluent gases
Sources:	(Hendriks et al., 1998)

8.3 Wastewater from industrial sources

Similar to domestic wastewater, industrial wastewater with high organic content may create good opportunities for CH₄ formation under anaerobic conditions, if not handled through well managed treatment systems. Industry sectors identified in GAINS as potential sources for wastewater CH₄ emissions are food, beverages and tobacco, pulp- and paper, and organic chemical industry. CH₄ emissions from these sources in country *i* in year *t* are calculated as the sum of emissions from each industry *s* summed over the different wastewater treatment systems *m* applied:

$$E_{it} = \sum_s \sum_m A_{its} * ef_s * (1 - remeff_{sm}) * Appl_{itsm}$$

where A_{its} is amount of industry wastewater generated by industry sector s ,
 ef_s is the IPCC default uncontrolled emission factor for wastewater from industry sector s ,
 $remeff_{sm}$ is the removal efficiency of wastewater treatment system m , and
 $Appl_{itsm}$ is the application of wastewater treatment system m .

Industrial wastewater generation in different industries in the European countries between 1985 and 2003 were taken from EUROSTAT (EUROSTAT 2005). This data was used to econometrically estimate elasticities for industrial wastewater generation (Höglund-Isaksson 2007). Estimations were performed at industry sector level and by relating wastewater generation to industry production value or value added (UNIDO 2006; Groningen 2008). Projections for production value and value added in EU-27 follow industry forecasts by PRIMES (2009). These forecasts, together with the estimated elasticities, are the basis for projections of future wastewater generation in industry.

Just like for industrial solid waste, we derive average wastewater generation rates per value added for the two country-groups EU-15 and EU-10. The average wastewater generation rates are used to calculate wastewater amounts, which are multiplied by IPCC default emission factors by industry to calculate emissions. Estimated wastewater amounts were verified with data reported by countries to the UNFCCC for year 2005 (UNFCCC 2008). The emission factor for wastewater from the pulp and paper industry has been reduced ten times as the industry is assumed to operate closed production processes in all EU countries.

For industrial wastewater, default uncontrolled emission factors were derived following the IPCC guidelines (IPCC, 2006):

$$ef_s = COD_s * B_0 * MCF_0 * (1 - R_s),$$

where

COD_s Amount of COD (chemical oxygen demand) generated in kt COD/Mm³ per year in industry sector s .

B_0 Maximum CH₄ producing capacity in kt CH₄/kt COD. (default is 0.25)

MCF_0 Methane Correction Fraction in uncontrolled case, i.e. fraction of COD that will be converted to CH₄ in the uncontrolled case (default is 0.1)

R Removal of organic content from wastewater

T_k Control correction factor for technology k ($X=1$ in uncontrolled case)

Table 53: Basis for industrial wastewater generation and elasticity estimates used for projections of industrial wastewater amounts.

Industry sector	Basis for future projections	Elasticity estimates Source: Estimations by Höglund-Isaksson (2007) based on data from EUROSTAT (2005)	Organic content kt COD/Mm3 IPCC (2006)
Food, beverages, tobacco industry	Wastewater amount per value added in 2000 (EUROSTAT, 2005): EU-15: 5.7 m3/kEuro EU-10: 28 m3/kEuro	Relative change in wastewater to value added: 0.69	5.2
Pulp and paper industry	EU-15: 52.2 m3/kEuro EU-10: 76 m3/kEuro	0.20	9
Organic chemical industry	EU-15: 25.2 m3/kEuro EU-10: 82.6 m3/kEuro	0.04	3

Table 54: Activity sources in GAINS for CH₄ emissions from industrial wastewater

GAINS sector code	GAINS activity code	Description	Unit
IND_FOOD	NOF	Food, beverages and tobacco industry –wastewater generation	M m ³
IND_PAP	NOF	Paper and pulp industry –wastewater generation	M m ³
IND_OCH	NOF	Organic chemical industry –wastewater generation	M m ³
Activity data sources:		(EUROSTAT 2005; UNIDO 2006; Höglund-Isaksson 2007; Groningen 2008; UNFCCC 2008) PRIMES (2009)	
Emission factor sources:		(IPCC 2006)	

Industrial wastewater with high organic content can be treated in aerobic or anaerobic digesters. The latter can be equipped with biogas recovery. Costs for treating wastewater from these three industrial sectors are assumed comparable to treating domestic wastewater in terms of costs per m³ wastewater treated (see Section 8.2).

Table 55: Technologies in GAINS for control of CH₄ emissions from industrial wastewater

handling.

GAINS technology code	Description
IND_FOOD_AERO	Aerobic treatment
IND_FOOD_ANAE_NON	Anaerobic treatment in digester, reactor, deep lagoon without gas recovery
IND_FOOD_ANAE_USE	Anaerobic treatment in digester, reactor, deep lagoon with gas recovery and utilization for energy purposes
IND_PAP_AERO	Aerobic treatment
IND_PAP_ANAE_NON	Anaerobic treatment in digester, reactor, deep lagoon without gas recovery
IND_PAP_ANAE_USE	Anaerobic treatment in digester, reactor, deep lagoon with gas recovery and utilization for energy purposes
IND_OCH_AERO	Aerobic treatment
IND_OCH_ANAE_NON	Anaerobic treatment in digester, reactor, deep lagoon without gas recovery
IND_OCH_ANAE_USE	Anaerobic treatment in digester, reactor, deep lagoon with gas recovery and utilization for energy purposes
Sources:	(Lettinga 1995; USEPA 1999; Persson 2003; Andersen 2005; IPCC 2006; Hernandez-Sancho and Sala-Garrido 2008)

9 Evaluation of non-CO₂ greenhouse gas data in GAINS

9.1 Category “Other emissions”

The sectors “OTHER_CH4” and “OTHER_N2O” have been introduced to cover systematic differences between GAINS and the emissions reported to UNFCCC. These systematic differences were “corrected” on a sector level using data reported for 2005 in the April 2009 version of the UNFCCC CRF tables. Total national emissions in GAINS correspond therefore exactly to 2005 emissions in the national submissions (UNFCCC, 2009).

The emission discrepancies represent primarily emission sources that are not accounted for fully in GAINS. For such sources, GAINS is also not able to cover any potential abatement, nor provide appropriate projections. Coverage with a fully inactive sector seems therefore appropriate.

The discrepancies may however also result from differences in activity data used and calculation methodologies applied in GAINS and for estimates reported to UNFCCC. Activity data differences occur when there is inconsistency between activity levels used for the UNFCCC calculations than what is used in GAINS and consistent with activity levels in 2005 used in the PRIMES or CAPRI models, or reported to other databases, e.g., EUROSTAT. In GAINS, methodologies are applied consistently to all regions, while methodologies applied to UNFCCC estimates may vary considerably between countries. This is particularly apparent for CH₄ emissions from the waste and wastewater sectors, where IPCC calculation methodologies in the 1996 guidelines left much freedom in the choice of methodology to the reporting countries.

The following tables present in detail the reasons for discrepancies in GAINS estimates vs. CH₄ and N₂O emissions, respectively, reported to the UNFCCC for year 2005 (UNFCCC, April 2009). The magnitude of deviation allows for conclusions about the extent to which the GAINS model covers a national situation, or the situation considered adequate from a national perspective. A discrepancy often provides a reason for data comparison, which may result in overall improvements of the inventory quality.

Table 56: “Other CH₄” emissions: explanations for divergence between GAINS estimates and CH₄ emissions reported to UNFCCC for year 2005 (UNFCCC, Version July 2009).

Country	GAINS divergence from UNFCCC	Explanations for divergences in GAINS vs emissions reported to UNFCCC for year 2005
Austria	+2.1%	No major divergences
Belgium	+0.6%	No major divergences
Bulgaria	-30.6%	GAINS emissions from solid waste sectors in 2005 are considerably (54%) lower than the estimate reported to the UNFCCC.
Cyprus	n.a.	No reporting to UNFCCC
Czech Rep.	+0.3%	GAINS emissions from solid waste sectors in 2005 are 13% higher than the estimate reported to the UNFCCC. GAINS emissions from wastewater sectors in 2005 are 34% lower than the estimate reported to the UNFCCC.
Denmark	-4.4%	GAINS emissions from solid waste sectors in 2005 are 15% lower than the estimate reported to the UNFCCC. GAINS emissions from wastewater sectors in 2005 are almost twice as high as emissions reported to the UNFCCC. Denmark only reports emissions from domestic and commercial wastewater handling and no emissions from industrial wastewater handling.
Estonia	+6.6%	GAINS emissions from solid waste sectors in 2005 are 14% lower than the estimate reported to the UNFCCC. GAINS estimates emissions from wastewater sectors in 2005, while Estonia reports no CH ₄ emissions from this source to the UNFCCC.
Finland	+5.4%	GAINS emission estimate for the industrial wastewater sector in 2005 is considerably higher than what Finland reports to the UNFCCC. Finland reports 1.13 kt CH ₄ , while GAINS estimates 26 kt CH ₄ from this source.
France	+1.9%	GAINS estimates lower CH ₄ emissions in the Energy sector than reported to UNFCCC. This is primarily due to discrepancy in amount of biomass fuel used in 2005, which is lower in PRIMES 2009 than reported to UNFCCC (2009). GAINS also uses a lower emission factor for biomass fuels (on average 122 kg/TJ while the average implied emission factor reported to UNFCCC is 217 kg/TJ for France). GAINS emissions from solid waste sectors in 2005 are 62% higher than the estimate reported to the UNFCCC.

Germany	-3.0%	Germany reports -30 kt CH ₄ from “CH ₄ -consumption in agricultural soils”. This source is accounted for in GAINS in the OTHER_CH4 sector and it is noteworthy that no other EU-27 country reports CH ₄ emissions from this source. GAINS emissions from solid waste sectors in 2005 are 22% lower than the estimate reported to the UNFCCC. GAINS emissions from wastewater sectors in 2005 are considerably higher than the estimate reported to the UNFCCC. Germany does not report CH ₄ emissions from industrial wastewater handling, but only from domestic and commercial wastewater handling.
Greece	+4.6%	GAINS emissions from wastewater sectors in 2005 are 36% higher than the estimate reported to the UNFCCC.
Hungary	-3.9%	CH ₄ emissions from thermal baths (22 kt CH ₄ in 2005) not included as a separate sector GAINS, but accounted for in the OTHER_CH4 sector in GAINS. GAINS emissions from solid waste and wastewater sectors in 2005 are higher than the estimate reported to the UNFCCC.
Ireland	-4.3%	GAINS emissions from wastewater sectors in 2005 are about seven times higher than emissions reported to the UNFCCC. GAINS emissions from solid waste sectors in 2005 are 42% lower than the estimate reported to the UNFCCC.
Italy	-4.7%	GAINS uses a considerably lower leakage rate from gas distribution networks than the implied emission factor Italy reports to UNFCCC. Italy reports 1.72 kt CH ₄ from rabbits, which are not accounted for in GAINS.
Latvia	-7.0%	GAINS estimates lower emissions in the energy sector than reported to UNFCCC. This is primarily due to discrepancy in total amount of biomass fuel used in 2005 (50 PJ in PRIMES 2009 and 95 PJ reported to UNFCCC 2009). GAINS also uses a lower emission factor for biomass fuels (on average 137 kg/TJ while the average implied emission factor reported to UNFCCC is 253 kg/TJ for Latvia). GAINS emissions from solid waste sectors in 2005 are 31% lower than the estimate reported to the UNFCCC. GAINS emissions from wastewater sectors in 2005 are 41% higher than emissions reported to the UNFCCC.
Lithuania	+13.8%	GAINS emissions from solid waste sectors in 2005 are 27% higher than the estimate reported to the UNFCCC. CH ₄ emissions from industrial wastewater in 2005 were reported in the 2008 version of the CRF, but not in the 2009 version. In GAINS, emissions from this source are included.
Luxembourg	+3.6%	No major divergences

Malta	n.a.	No reporting to UNFCCC
Netherlands	-7.8%	<p>15 kt CH₄ emissions are reported to UNFCCC from industrial processes (styrene, ethylene, carbon black and methanol production). These processes are not accounted for as separate activities in GAINS and hence, emissions are accounted for in the OTHER_CH4 sector.</p> <p>GAINS emissions from solid waste sectors in 2005 are 13% lower than the estimate reported to the UNFCCC.</p>
Poland	+1.4%	<p>GAINS estimate lower emissions in the energy sector than reported to UNFCCC. This is primarily due to a discrepancy in total amount of biomass fuel used in 2005 (198 PJ in PRIMES 2009 and 339 PJ reported to UNFCCC 2009). GAINS also use a lower emission factor for biomass fuels (on average 144 kg/TJ, while the average implied emission factor reported to UNFCCC is 230 kg/TJ for Poland).</p> <p>19 kt CH₄ emissions are reported to UNFCCC from industrial processes (ammonia production). This process is not accounted for as a separate activity in GAINS and hence, emissions are accounted for in the OTHER_CH4 sector.</p>
Portugal	-3.0%	GAINS emissions from wastewater sectors in 2005 are 21% lower than emissions reported to the UNFCCC.
Romania	+3.3%	<p>GAINS estimate 20 Kt CH₄ emissions from burning of agricultural waste in 2005. No emissions from this source were reported to UNFCCC (2009).</p> <p>GAINS emissions from solid waste sectors in 2005 are 15% higher than the estimate reported to the UNFCCC.</p>
Slovakia	-5.6%	<p>GAINS emissions from solid waste sectors in 2005 are 8% lower than the estimate reported to the UNFCCC.</p> <p>GAINS emissions from wastewater sectors in 2005 are 30% higher than emissions reported to the UNFCCC.</p>
Slovenia	+9.8%	GAINS emissions from solid waste sectors in 2005 are 33% higher than the estimate reported to the UNFCCC.
Spain	+0.2%	<p>Spain reports venting 19 kt CH₄ from production of 1.13 PJ natural gas. The emission factor 16.7 kt CH₄/PJ is very high and suggests that the amount of vented gas exceeds 80% of gas produced (assuming 50 MJ/kg CH₄). GAINS uses an emission factor of 0.055 kt CH₄/PJ gas produced.</p> <p>GAINS emission factor for flooded rice cultivation is about twice as high as the emission factor used by Spain in the reporting to UNFCCC for 2005.</p>
Sweden	-8.7%	Sweden reports 5 kt CH ₄ emissions from reindeers to UNFCCC. As GAINS does not have reindeers as a separate category, these emissions are accounted for in the OTHER_CH4 sector.
United Kingdom	-1.5%	No major divergences

Table 57: “Other N₂O” emissions: explanations for divergence between GAINS estimates and emissions reported to UNFCCC for year 2005 (UNFCCC 2009). The relative difference is presented in % of the national data (negative numbers indicate GAINS emissions to be higher)

Country	GAINS divergence from UNFCCC	Explanations for divergences in GAINS vs emissions reported to UNFCCC for year 2005
Austria	+2.6%	o.k. - no major divergences
Belgium	-3.3%	o.k. - no major divergences
Bulgaria	+8.4%	GAINS estimates a higher share of fluidized bed combustion for solid fuels
Cyprus	n.a.	No reporting to UNFCCC
Czech Rep.	+30.1%	GAINS estimates a higher share of fluidized bed combustion for solid fuels
Denmark	+9.2%	Differences in estimates on agricultural N-input
Estonia	+27.1%	Differences in estimates on agricultural N-input
Finland	-4.6%	o.k. - no major divergences
France	-1.4%	o.k. - no major divergences
Germany	+18.9%	GAINS estimates a higher share of fluidized bed combustion for solid fuels; Differences in estimates on agricultural N-input
Greece	-18.4%	Differences in estimates on agricultural N-input
Hungary	-6.8%	Nitric acid production (emission factor)
Ireland	+16.6%	Differences in estimates on agricultural N-input, e.g. regarding losses of N-manure before application on fields

Italy	-4.7%	o.k. - no major divergences
Latvia	+8.4%	Differences in estimates on agricultural N-input
Lithuania	-15.9%	Nitric acid production (confidential)
Luxembourg	-9.0%	o.k. - no major divergences
Malta	n.a.	No reporting to UNFCCC; in reporting to EEA, agricultural input of nitrogen is incomplete
Netherlands	+2.5%	o.k. - no major divergences, but several sectoral differences
Poland	+18.1%	GAINS estimates a higher share of fluidized bed combustion for solid fuels; histosols
Portugal	-8.6%	Differences in estimates on agricultural N-input
Romania	-6.9%	Nitric acid production (emission factor)
Slovakia	+17.7%	Differences in estimates on agricultural N-input and on the impact of fluidized bed combustion
Slovenia	-5.0%	o.k. - no major divergences
Spain	-4.2%	o.k. - no major divergences
Sweden	-10.7%	Cultivation of mineral soils (sector employed by Sweden only)
United Kingdom	+20.9%	GAINS estimates a higher share of fluidized bed combustion for solid fuels

9.2 Uncertainties

It is not easy to correctly assess emissions of non-CO₂ greenhouse gases. They are per se harmless substances, such that detailed accounting of their release has not been needed traditionally. F-gases are released in quite small quantities, which are difficult to trace, and CH₄, as well as N₂O, are primarily produced by biological processes which tend to be irregular in behaviour and difficult for an exact quantitative assessment. Some of these gases are also stable in the atmosphere, thus any release provides only a small concentration gradient to background air, which is difficult to measure. It is therefore not surprising that non-CO₂ greenhouse gases are generally associated with high uncertainty. Despite its only minor contribution, N₂O from soil (direct emissions) has been shown to provide the highest contribution to the overall uncertainties of national greenhouse gas inventories (Winiwarter and Rypdal, 2001). A growing body of studies on the uncertainties of national inventories has become available. While CO₂ emissions are in general considered very reliable (normally 3% or less uncertainty at a 95% confidence interval), CH₄ emissions typically range near 15-20% and N₂O emissions 40-100%. Uncertainty of fluorinated gas emissions mostly has been estimated between 13 and 30% (see Winiwarter and Muik, 2010). Estimates vary by method, country-specific circumstances and may differ much more when specifically considering individual source sectors.

Seen in this perspective, it is almost surprising that the agreement between the GAINS model and the nationally submitted emission data presented in Table 56 and Table 57 is as good as shown. Of course, the agreement is only apparent: by choosing similar activity numbers, often reported to various international databases from the same national source, and the same emission factors, an agreement in model figures can be reached, even if these are distant from any “real” release rates. We should, however, emphasize that at this stage a set of comparable numbers between models as well as between countries proves more valuable, as it allows to compare data on the same level. Only if additional information on certain national circumstances is available that clearly allows for a data improvement, diverging approaches to assess emissions (or different emission factors) are really helpful. Often enough, such basic data is not available for non-CO₂ greenhouse gases.

Despite of the inherent uncertainties associated with the reported data on national emissions to which the GAINS model is adapted, this data is probably the most adequate data available for assessing emission reduction options. Nationally reported data reflect the best knowledge available in a country, and they refer to a commitment a country is willing to make.

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