International Institute for
Applied Systems Analysis
IIASA www.iiasa.ac.at

Potentials and Costs for Mitigation of Non-CO2 Greenhouse Gases in Annex 1 Countries: Version 2.0

Hoeglund-Isaksson, L., Winiwarter, W. and Tohka, A.

IIASA Interim Report
November 2009

Hoeglund-Isaksson, L., Winiwarter, W. and Tohka, A. (2009) Potentials and Costs for Mitigation of Non-CO2 Greenhouse Gases in Annex 1 Countries: Version 2.0. IIASA Interim Report. IR-09-044
http://pure.iiasa.ac.at/9111/

International Institute for
Applied Systems Analysis
Schlossplatz 1
A-2361 Laxenburg, Austria

Tel: +43 2236 807 342
Fax: +43 2236 71313
E-mail: publications@iiasa.ac.at
Web: www.iiasa.ac.at

Interim Report IR-09-044

Potentials and costs for mitigation of non-CO_2 greenhouse gases in Annex I countries

Version 2.0

Lena Höglund-Isaksson
Wilfried Winiwarter
Antti Tohka

Approved by

Markus Amann
Program Leader, APD

November 6, 2009

This report documents the specific methodology of IIASA's GAINS model on methane, nitrous oxide and fluorinated gases that has been used for comparing mitigation efforts across Annex I Parties.

More details are available through the following information resources that are available at http://gains.iiasa.ac.at.

- An interactive **GAINS GHG mitigation efforts calculator** that allows online-comparison of mitigation efforts across Annex I Parties. Free access is provided at http://gains.iiasa.ac.at/MEC.
- Access to all input data employed for the calculations for all countries via the on-line version of the GAINS model at http://gains.iiasa.ac.at.

The following report documents the basic methodology of IIASA's GAINS model that has been used for comparing mitigation efforts across Annex I Parties:

- Potential and costs for greenhouse ghas mitigation in Annex I countries. M. Amann et al., 2008

Other reports to document specific methodology details are:

- Estimating CO_2 mitigation potentials and costs from energy use and industrial sources. J. Cofala, P. Purohit, P.Rafaj. Z. Klimont, 2008
- Mitigation potentials from transportation in Annex I countries. J. Borken *et al.*, 2008
- Estimating GHG mitigation potentials from LULUCF in Annex I countries. H. Boettcher *et al.*, 2008

Further information:

Markus Amann
Atmospheric Pollution and Economic Development Programme
International Institute for
Applied Systems Analysis (IIASA)
Schlossplatz 1
A-2361 Laxenburg
Austria

Tel: +43 2236 807 432
Email: amann@iiasa.ac.at
Web: http://gains.iiasa.ac.at

Executive summary

This report documents the approaches taken to include greenhouse gases other than CO_2 (methane, nitrous oxide, and the fluorinated gases explicitly mentioned in the Kyoto protocol) in the GAINS model as used to assess costs and potential of greenhouse gas mitigation in the “Annex I” countries to the Kyoto protocol. Annex I countries are those signatories to the protocol which agreed to legally binding emission reductions. The implementation greatly benefited from international statistical data sources, but also from the data submission to UNFCCC by the individual countries.

For each source sector and greenhouse gas considered, the methods to derive the emissions under uncontrolled and controlled conditions are presented, as well as the method to estimate the costs of control measures, if applicable. While methane and nitrous oxide emissions frequently occur in the identical sectors, emission of fluorinated gases occur separately. This reports documents the basic features of the methodology, and presents a general evaluation of data quality in terms of comparing national data with GAINS results, considering the respective national circumstances. Actual input data for calculations is available via the on-line version of the GAINS model at http://gains.iiasa.ac.at/.

About the authors

Lena Höglund-Isaksson and Wilfried Winiwarter work at the Atmospheric Pollution and Economic Development programme (led by Markus Amann) of the International Institute for Applied Systems Analysis.

Antti Tohka is with the Finnish Environment Institute (SYKE) in Helsinki.

Acknowledgements

The authors want to express their gratitude to the International Institute for Applied Systems Analysis (IIASA) for providing financial resources that enabled development of the methodology and an initial implementation for 36 Annex I Parties.

Table of contents

1 Introduction

Climate change impacts can be reduced, delayed or avoided by mitigation of greenhouse gases (GHGs). Mitigation efforts and investments over the next two to three decades will have a large impact on opportunities to achieve lower stabilisation levels of greenhouse gas emissions. It will be a formidable challenge to negotiating Parties to arrive at a generally accepted scheme for sharing efforts among Annex I countries that achieves the necessary emission reductions.

The International Institute for Applied Systems Analysis (IIASA) has developed a scientific tool to support the current negotiations. Known as GAINS (Greenhouse gas – Air pollution Interactions and Synergies), the tool not only helps negotiators identify the most cost effective way to reduce GHG emissions, but also allows negotiators to compare mitigation efforts among Parties.

GAINS estimates emission reduction potentials and costs for a range of greenhouse gases and air pollutants and quantifies the resulting impacts on air quality and total greenhouse gas emissions considering the physical and economic interactions between different control measures. As a principle, the analysis employs only such input data that are available in the public domain and that appear credible and consistent in an international perspective. While the IIASA team collaborated with national experts to validate important input data and assumptions for individual countries, constraints on time and financial resources did not allow for an extensive validation of all input data.

In brief, the methodology (i) adopts exogenous projections of future economic activities as a starting point, (ii) develops a corresponding baseline projection of greenhouse gas emissions for 2020 with information derived from the national GHG inventories that have been reported by Parties to the UNFCCC for 2005, (iii) estimates, with a bottom-up approach, for each economic sector in each country the potential emission reductions that could be achieved in 2020 through application of the available mitigation measures, and (iv) quantifies the associated costs that would emerge for these measures under the specific national conditions. The approach includes all six gases that are included in the Kyoto protocol (i.e., CO_2, CH_4, N_2O, HFCs, PFCs, SF_6) and covers all anthropogenic sources that are included in the emission reporting of Annex I countries to UNFCCC (i.e., Energy, Industrial Processes, Agriculture, Waste, and from LULUCF).

This report describes how the non-CO_2 greenhouse gases methane (CH_4), nitrous oxide (N_2O) and the fluorinated gases as specifically dealt with in the Kyoto protocol (F-gases) are covered in the GAINS. Specifically, the extension of the GAINS model to cover all Annex I countries (industrialized countries as listed in Annex I of the Kyoto protocol) is treated. The methodology is based on previous descriptions of GAINS in relation to these gases (Höglund-Isaksson and Mechler, 2005; Winiwarter, 2005; Tohka, 2005), and extends on coverage of all Annex I countries. The overall framework, in which the GAINS model operates, has been described by Amann et al. (2008a) and the respective reports mentioned therein.

In the present report, we will not cover general details of the model methodology in terms of assessing abatement measures and their related costs. Instead we will refer to the respective literature. The state of model development, the specific circumstances for implementation of the Annex I countries and an assessment of the non-CO_2 greenhouse gases with respect to CO_2 are the topics of this report.

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. The specific sections will be followed by an evaluation of the robustness of the data presented, also in reflection to CO_2 and in connection with integrating climate measures to air pollution (Section 9).

2 Methodology

2.1 General 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 (SO_2, NO_x, NMVOC, NH_3, CO, PM) and greenhouse gases (CO_2, CH_4, N_2O and F-gases) are covered. Measures to mitigate emissions are defined, which may affect one or several of the gases covered, and the amount of emission reduction (or: the new "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. GAINS covers a period of 40 years (1990 – 2030, in five-year intervals).

For the purpose of this project, the regions considered in GAINS include the Annex I Parties as administrative regions, i.e., the 27 Member States of the European Union, six additional European countries (Belarus, Croatia, Norway, Switzerland, Turkey and Ukraine), as well as Australia, Canada, Japan, New Zealand, Russia, and the United States of America.

2.2 Sources of input

The basis for assessing the future development in GAINS is provided by external projections of economic development and implied activity levels in terms of energy consumption, transport demand, industrial production and agricultural activities. Main sources that provide such information are the World Energy Outlook of the International Energy Agency (IEA, 2008) for energy data, and the Food and Agriculture Organization (FAO, 2003) on agriculture-related developments. A number of further sources have been used, which will be reported specifically in the respective sections.

We were also able to draw on country-specific information, as it has been compiled by UNFCCC (2008). National data submitted in the "Common Reporting Format", the CRF tables, have been used to draw on a considerable number of present and past data on activities, surrogate parameters and implied emission factors. As CRF tables are compulsory for all Annex- countries, and as they are subject to several stages of review by UNFCCC, they may be considered mostly reliable.

A considerable wealth of information was also available in the GAINS database (Amann et al., 2007, 2008b). For EU-27, many of the activity numbers, emission factors and general parameters in GAINS have been developed together with national experts during consultations for the revision of the National Emission Ceilings Directive, or for the European Climate Change Programme. Consultations were also held with Norway and Switzerland. Thus, in 2005 the match between information in CRF and GAINS was considered to be close. For other European countries, we took advantage of the implied emission factors provided by Parties in their CRFs. With assumptions on the current (2005) degree of implementation of abatement measures, emission factors of unabated sources as well as abated sources were scaled to match the CRF–implied emission factor for the current situation. The proportional spread, i.e., an emission reduction due to a certain measure, was maintained this way. In the case of countries outside Europe, we took additional advantage of the activity numbers presented, supplementing or supporting other data sources.

Any discrepancy still remaining between the national data (UNFCCC 2008) 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, 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 on evaluation).

3 Energy

3.1 Combustion in power plants

CH_4 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 CH_4 arise from combustion of any type of fuel. N_2O is formed as a combustion by-product, similar to NO_x. Activity data for combustion emissions from power plants is taken from IEA (2008) and emission factors from IPCC (2006). Emission factors are differentiated by fuel type and emissions of CH_4 or N_2O 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 CH_4 or N_2O emissions from power plants. However, the use of fluidized bed combustion and abatement of NO_x (selective non-catalytic reduction of flue gas) affect emission factors for N_2O.

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 N_2O 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. Traditionally the technology has been favoured in some European countries and in Japan. The GAINS database contains estimates of the shares of FBC in combustion of solid fuels for European countries. Data for Japan are extracted from the CRF tables. The share of FBC is considered negligible in Annex I countries outside Europe and Japan and hence, no abatement is considered in these countries.

Table 1: Activity sources for CH_4 and N_2O 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:		(IEA 2008)	
Emission factor sources (CH_4, N_2O):		(IPCC 2006; de Soete 1993)	

Methods have been developed and implemented in pilot plants which allow minimizing N_2O formation (in GAINS summarized as "combustion modification in fluidized bed combustion"). Data presented by Winiwarter (2005) indicate that 80% of N_2O can be removed (Hendriks *et al.,* 2001). Obviously, abatement is limited to countries where data on FBC is included in the GAINS database. 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 N_2O 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

CH_4 emissions from combustion in residential and commercial sectors are calculated using activity data from IEA (2008) 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 N_2O, the variation in emission factors is limited to fuel type without differentiation by GAINS sector. No specific mitigation options have been identified for CH_4 or N_2O emissions from boilers in the residential and commercial sectors.

Table 3: Activity sources for CH_4 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:	(IEA 2008)	
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

CH_4 emissions from combustion in industry boilers are calculated using activity data from IEA (2008) and emission factors from IPCC (2006) and applying the methodology described for power plants in the subsection above. No CH_4-specific mitigation options have been identified for these activities. N_2O 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 CH_4 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:		(IEA 2008)	
Emission factor sources (CH_4, N_2O):		(IPCC 2006)	

3.4 Transport – combustion and fugitive emissions from fuel use

CH_4 emissions from mobile sources arise from fuel combustion and as fugitive emissions when using gas as transport fuel. Activity data is adopted from IEA (2008). Emission factors depend on several factors like fuel, technology and operating characteristics. GAINS uses default emission factors as specified by IPCC (2006). 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 standards were available. No CH_4 or N_2O specific mitigation options are identified for these activities. However, emissions of N_2O 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 N_2O emissions. This fact is covered by applying differentiated N_2O emission factors following the categories of the EURO standard.

Table 5: Activity sources for CH_4 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:		(IEA 2008)	
Emission factor sources (CH_4):		(IPCC 2006)	
Emission factor sources (N_2O):		(IPCC 2006; RICARDO 2003; Jimenez et al. 2000)	

3.5 Fugitive emissions from coal mining

Formation of coal produces CH_4, which is released to the atmosphere when coal is mined. IPCC identifies three sources of CH_4 emissions from coal mining: liberation of CH_4 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 Annex-I countries to the UNFCCC for year 2005 (UNFCCC 2008). 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 CH_4 emissions (see Section 9.1) and not under coal mining sectors. CH_4 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 CH_4 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:		IEA 2008	
Emission factor sources:		(IPCC 2006; UNFCCC 2008)	

About 30 percent of CH_4 emissions from coal mining is recovered and flared for security reasons (AEAT 1998). Options considered in GAINS as CH_4 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 CH_4 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 CH_4 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 CH_4 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 IEA (IEA 2008). Emissions from oil (or gas) production are calculated as:

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

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,

$remeff_m$ is the removal efficiency of control technology m, and

$Appl_{itm}$ is the application of control technology m.

For Annex I countries, 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. This means, e.g., that the associated gas fractions for Norway amount to 0.2 percent of gas produced and 0.4 percent of oil produced, while the corresponding fractions for Russia are 6 percent for both oil and gas production.

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 CH_4 emissions from oil transportation, storage and refining are estimated as:

$$E_{it} = \sum_{m} A_{it} * ef_i * (1 - remeff_m) * Appl_{itm}$$

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

Table 8: Activity sources for fugitive CH_4 emissions from oil and gas production.

GAINS sector code	GAINS fuel code	Description	Unit
PROD	GAS	Gas produced	PJ
PROD	CRU	Oil produced	PJ
REF	CRU	Oil refined	PJ
Activity data sources:		(IEA 2008), Russian Federation Ministry of Energy (Energy 2003)	
Emission factor sources:		(Cedigaz 2001; IPCC 2006; UNFCCC 2008)	

CH_4 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 CH_4 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 TRANSPORTATION

Losses of natural gas during transmission and distribution to final users are important sources of CH_4 emissions. 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 CH_4 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 Annex I countries, emission factors are adjusted to match implied emission factors reported by countries to the UNFCCC for year 2005 (UNFCCC 2008). The reported implied emission factors suggest considerably higher losses from gas transportation for some countries, e.g., 3 percent for Russia and 0.55 percent for the United States.

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

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 CH_4 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:		(Energy 2003; SPP 2007; TAG 2007; UNFCCC 2008)	
Emission factor sources:		(IPCC 2006; UNFCCC 2008)	

CH_4 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		
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 CH_4 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 CH_4 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 IEA (IEA 2008).

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

where		
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*,
	$remeff_m$	is the removal efficiency of technology *m*, and
	$Appl_{itm}$	is the application rate of technology *m* in country *i* in year *t*.

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 transportation (Section 3.6.2) .

Table 12: Activity sources for fugitive CH_4 emissions from gas transmission and distribution

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:		(IEA 2008)	
Emission factor sources:		(IPCC 2006; UNFCCC 2008)	

Table 13: Technologies considered in GAINS for mitigation of fugitive CH_4 emissions from gas transmission and distribution.

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 to generate adipic acid (a compound required in the Nylon® production) involves treating the raw material with concentrated nitric acid, at which large quantities of N_2O are released. Typically, for each ton of product 300 kg of N_2O are formed, making the process an important contributor to overall N_2O emissions, although the amount of production is fairly low compared to production of standard chemicals.

Adipic acid production is relevant for a handful of countries only, 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 N_2O concentrations in plume and convert these back into nitric acid (with 95% efficiency). Most plants had been retrofitted by 2000, only a few installations (part of the Ukraine and all of the Italian capacity) still seem to be on the old methodology, according to data these countries provide in their CRF tables. We understand that the implementation in Italy will follow shortly, in Ukraine we did not consider any change.

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. The majority of Annex I countries accommodate nitric acid production, often in several installations, and there is no reason for keeping data confidential. Still, data listed by EPA (2006) proved helpful to check the information provided by countries in the CRF tables and to fill in missing countries (specifically, Ukraine). In the case of Australia, national data in the CRF tables is considered confidential, however, the environmental reports of the involved companies contain the necessary data and are available on the internet.

Table 14: Activity sources for N_2O 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 2008)	
Emission factor sources:		(IPCC 2006; UNFCCC 2008)	

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 (Grobben, pers. information), we estimate that 50 percent of the capacity is controlled. But as there is no legal requirement to control, no additional implementations are adopted in the baseline scenario.

Table 15: Technologies in GAINS for control of N_2O emissions from adipic or nitric acid production.

GAINS technology code	Description
CR	Catalytic reduction (to be used in connection with the production of adipic acid or nitric acid)
Sources:	(de Soete 1993; de Beer 2001; Kuiper 2001)

4.3 Aluminum production

Primary aluminium production has been identified as a major anthropogenic source of emissions of two perflourocarbon (PFC) emissions, namely CF_4 and C_2F_6. These are both gases with very high greenhouse warming potentials, 6500 and 9200 times that of CO_2 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 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 taken from IEA (2008) and shares of different aluminium production technologies used in the Annex_I countries are 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 Hendriks 2000)	

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).

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

4.4 Sources of SF_6 emissions

Sulphur hexafluoride (SF_6) emissions arise from high- and mid-voltage switches, magnesium production and casting and a variety of other applications, like soundproof windows or sports equipment. SF_6 has a very high greenhouse warming potential of 23900 times that of CO_2 over a 100 year time horizon.

SF_6 is a manufactured gas used mainly as electrical insulator in the transmission and distribution equipment of electric systems. The use of SF_6 increased between the 1970s and 1990s as SF_6 equipment gradually replaced older oil and compressed air systems. Suitable alternatives to SF_6 do not exist for these applications as oil and compressed air systems suffer from safety and reliability problems (AEAT, 2003). Most of the SF_6 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 specialised methods for the estimation of SF_6 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 Annex-I countries. The activity unit used in GAINS for this sector are emissions of SF_6 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). It is important to note that in some Easter European countries, other insulation gases/methods are still in use.

Casting and production of primary and secondary magnesium are well known sources of SF_6 emissions. SF_6 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 was taken from the World Mineral Statistics (Taylor et al., 2003) and from national communications to the UNFCCC (2008). An emission factor of one kg SF_6 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 SF_6 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 SF_6 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).

Table 18: Activity sources for F-gas emissions from high voltage switches.

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 SF_6
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 and Leisewitz (1999), Oinonen and Soimakallio (2001), AEAT (2003), Poulsen (2001)	
Emission factor sources:		(IPCC 1997)	

SF_6 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. SF_6 emissions in magnesium production and casting can be substituted by using sulphur dioxide (SO_2) as alternative gas. Other SF_6 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). 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 SF_6 and HFC. Emissions from high and mid voltage switches should be controlled through better leakage control and end-of-life recollection and recycling. SO_2 should replace SF_6 use in magnesium production and casting and other SF_6 use in e.g., windows and sports equipment, is banned.

Table 19: Technologies in GAINS for control of F-gas emissions from high voltage switches.

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., CF_4, C_2F_6, C_3F_8, c-C_4F_8, as well as HFC-23, SF_6 and nitrogen triflouride (NF_3) 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 difficult to obtain, since the industry is characterized by one or a few companies in each countries and use data is sensitive since it 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)).

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 (NF_3) 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 a ten percent reduction relative the 1995 base year. Costs for switching to NF_3 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). 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 industry sector growth rates. 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 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 HFC
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 N_2O 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 N_2O used will eventually be emitted to the atmosphere. In both cases, N_2O 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 N_2O_USE).

Methods to reduce application of N_2O 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 N_2O. 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 N_2O emissions from direct application (sector N_2O_USE).

GAINS technology code	Description
REDUCE	Apply nitrous oxide in combination with other (liquid) aneasthetics
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, 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 (see Section ??), 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 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-specfic 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 Lesisewitz, 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, CO_2 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), Schwartz 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 CO_2 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 CO_2 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:

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

where S is the size of the vehicle stock, LT is the vehicle lifetime, η 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 the various sources used to construct the vehicle stock are referred to in Kleefelt-Borken et al. (2008). 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 CO_2 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. All HFC in mobile air conditioners is assumed 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

CH_4 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 CH_4 during digestion, while it is lower in pseudo-ruminants with three compartment stomachs like horses, mules, and asses and monogastric animals like swine.

CH_4 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.,

$$ef_{it;cow}^{NOC} = ef_{i}^{animal} + ef_{i}^{milk} * \left(x_{it} - 3000\right)$$

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 for Australia, Canada, Japan, New Zealand, Russia, and the US are national statistics reported to FAO (FAOSTAT 2008) for historical years and projections based on FAO regional long term projections (FAO 2003). For the European countries, agricultural activity data with projections have been communicated between IIASA and national experts through bilateral communications that took place as part of the revision process of the NEC directive (Amann, Asman et al. 2007). Projections should reflect national agricultural policies and must include all necessary measures to comply with the Kyoto targets on greenhouse gases.

Regional default emission factors are taken from IPCC (IPCC 2006) (Tables 10.10 and 10.11, Vol.4). For Annex I countries, adjustments are made to country-specific factors by using implied emission factors reported to UNFCCC for year 2005 (UNFCCC 2008).

Table 37: Activity sources in GAINS for CH_4 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
	BS	Buffaloes	M heads
	CM	Camels	M heads
Activity data sources:		National statistics and communications with IIASA, (FAO 2003; FAOSTAT 2008)	
Emission factor sources:		(IPCC 2006; UNFCCC 2008)	

Recent research shows that CH_4 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 CH_4 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 CH_4 emissions per unit of milk or meat produced. With general increases in feed levels, CH_4 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 CH_4 in the rumen. As it is difficult to draw accurate conclusions about the effects on CH_4 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

CH_4 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 and applying European rates to non-European Annex I countries with similar agricultural structure.

Currently, GAINS does not include any mitigation options that reduce CH_4 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 CH_4 diet *m* is specified as:

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

where g_s	is the fraction of conventional diet replaced by low CH_4 diet,
$f_{is;1}$	is the cost per animal for low CH_4 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 CH_4 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 CH_4 diet in comparison to a conventional diet depend on the relative prices of the different feeds used. The focus of comparative studies of CH_4 low feeds is typically on effectiveness in CH_4 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. As a general assumption, we assume no additional costs per animal for change of feed but a small positive net effect on milk or meat production of one percent after controlling for reductions in livestock size.

Table 38: Technologies in GAINS for control of CH_4 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, replacement of roughage for concentrates, 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)			

7.2 Livestock - Manure management

CH_4 emissions from livestock also arise when the organic content in manure decomposes. CH_4 release occurs under anaerobic conditions, while the formation of N_2O requires oxygen. Manure management practices and temperature are important factors for the formation of CH_4 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 Annex I countries, default emission factors are adjusted to country-specific factors using implied emission factors reported to UNFCCC for year 2005 (UNFCCC 2008).

CH_4 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 CH_4 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.,

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

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 Annex I countries, adjustments are made to country-specific factors by using implied emission factors reported to UNFCCC for year 2005 (UNFCCC 2008).

Emissions of N_2O 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). 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 CH_4 and N_2O 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:		National statistics and communications with IIASA, (FAO 2003; FAOSTAT 2008)	
Emission factor sources (CH_4):		(Brink 2003; IPCC 2006; UNFCCC 2008)	
Emission factor sources (N_2O):		(IPCC 2006; UNFCCC 2008)	

CH_4 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 CH_4 reduction option in areas with intensive pig farming specified as areas with more than 200 pigs per square kilometre. Among Annex I 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 GAINS[1]. European farm-scale fractions are taken from AEAT (AEAT 1998) and EUROSTAT (EUROSTAT 2008). European fractions are applied to non-European Annex I countries with similar agricultural structure. 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. Farm scale costs were taken from the same source and based on costs for a German plant handling 9 kt manure per year.

For N_2O emissions from manure management, no specific mitigation options are identified in GAINS.

---

[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 Annex I countries, this option is assumed not applicable in these countries.

Table 40: Technologies in GAINS for control of CH_4 emissions from animal manure

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_BEEF	OL	
		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)			

7.3 Rice cultivation

CH_4 emissions from rice cultivation result from anaerobic decomposition of organic material in rice fields. CH_4 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 CH_4 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 CH_4.

CH_4 emissions from rice cultivation in a country *i* in year *t* are calculated as:

$$E_{it} = \sum_{s} \sum_{m} \left\lfloor ef_s * h_i * \beta_s * \gamma_{i;UN2005} * V_{is} * n_{it} * *(1 - remeff_{sm}) * Appl_{itsm} \right\rfloor,$$

where ef_s	is the IPCC (2006) default emission factor for CH_4 emissions from rice cultivated under water regime *s* during the growing season,
h_i	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
$Appl_{itsm}$	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 CH_4 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 CH_4 emissions to varying extents. By careful selection of low CH_4 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 CH_4 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 Annex-I countries, the potential reduction in CH_4 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 CH_4 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, CH_4 can be reduced because bacteria which produce CH_4 compete for the same substrate as the sulphate reducing bacteria (Denier van der Gon, van Bodegom et al. 2001). This option reduces CH_4 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 of 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:

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

where L_m is the additional worktime needed as fraction of a workyear,
w_{it} is the average annual wage for agricultural workers,
$(p_1\text{-}p_0)$ 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,
$(y_1\text{-}y_0)$ 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 CH_4 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 N_2O as a side product. Soil processes are by far the most important source of N_2O.

Despite a considerable amount of on-going research, there are still important gaps in knowledge about N_2O release from soils. Especially, the amount of N_2O 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 N_2O 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. The amount of animal manure is taken from animal numbers and nitrogen excretion rates, all data are available in the national reports (UNFCCC, 2008). 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 N_2O 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 N_2O 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:		(FAO 2003; FAOSTAT 2008; UNFCCC 2008)	
Emission factor sources:		(IPCC 2006; UNFCCC 2008)	

Emissions of N_2O are also affected by measures to abate ammonia emissions from soil. Specifically, injection techniques for manure (deep injection) remove manure from the surface but are expected to increase N_2O formation (Brink et al., 2001). This is considered in GAINS by using an increased emission factor.

An implied emission factor is derived from the activity and emission data reported by countries to the UNFCCC (2008). 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. It is of interest to note that emission factors used by Australia, and partly also by Canada, are significantly lower (up to a factor of 2) than IPCC's default emission factor (IPCC, 2006).

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 European 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 N_2O 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
PRECFARM	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, only that 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 N_2O 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

CH_4 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 provided by 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.

Amounts of municipal and industrial solid waste generated in different European countries between 1985 and 2003 were taken from EUROSTAT (EUROSTAT 2005). This data was used to econometrically estimate elasticities 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 municipal waste per capita is assumed determined by per capita GDP and the urbanization rate (UN 2005). Generation of industrial waste was estimated on industry level and related to the production value or the value added of the industry (UNIDO 2006; Groningen 2008). Projections for production value and value added follow industry forecasts by IEA (IEA 2008). These forecasts, together with the estimated elasticities, were the basis for projections of future waste generation by industry. For non-European Annex-I countries Australia, Canada, Japan, New Zealand and the United States, no systematic data on generated waste amounts could be found. Instead, for municipal solid waste, waste generation rates were taken from IPCC (2006) using the default value given for 1996 for the years 1990 and 1995 and the value given for year 2000 for this year and projecting future years using the elasticity estimated for Europe. For industrial waste, average waste generation rates for Western Europe were assumed. For Russia and other non-EU countries in Eastern Europe, average waste generation rates for Eastern Europe were adopted. Waste amounts were then verified with data reported by countries to the UNFCCC for year 2005 (UNFCCC 2008).

CH_4 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 CH_4 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).

CH_4 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 $A_{i;(t-y_s);s}$ are amount of waste type (or industry sector) *s* deposited to landfills in year $t\text{-}y_s$, where y_s is the average lag in CH_4 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*.

Table 46: Activity sources in GAINS for CH_4 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)	
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:

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

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,
	$CS_{sm}^{\mathrm{Re}cycled}$	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 47: Technologies in GAINS for control of CH_4 emissions from municipal 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_FLA	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_FLA	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_FLA	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_FLA	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_FLA	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 48, ctd.: Technologies in GAINS for control of CH_4 emissions from municipal solid waste.

GAINS technology code	Description
INW_TEX_INC	Waste from textile industry incinerated
INW_TEX_SWD_FLA	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_FLA	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 CO_2 and molecular nitrogen, but during the process also CH_4 and N_2O are released. CH_4 is formed whenever wastewater with high organic content is handled under anaerobic conditions. N_2O 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 CH_4 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, CH_4 formation is unlikely, however, with less well managed systems the occurrence of anaerobic conditions increase as well as CH_4 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. CH_4 emissions from domestic wastewater in country *i* and year *t* are in GAINS estimated as:

$$E_{it} = \sum_{s}\sum_{m} A_{its} * ef_s * \left(1 - remeff_{sm}\right) * Appl_{itsm}$$

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

$Appl_{itsm}$ 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, CH_4 formation in the uncontrolled case are likely to be very limited. CH_4 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 from (IPCC 2006).

Table 49: Activity sources in GAINS for CH_4 and N_2O 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 CH_4 emissions. There are, however, several different ways of treating wastewater, which have different implications for CH_4 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 CH_4. With well managed aerobic or anaerobic treatment, the CH_4 formation is effectively mitigated and CH_4 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 as part of 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. For investment costs we use cost estimates for sewage treatment in Denmark and the Netherlands in 1976-98 (Andersen 2005). 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 50: Technologies in GAINS for control of CH_4 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 N_2O release can be accomplished without compromising the desired decomposition of the organic substrate.

Table 51: Technology in GAINS for control of N_2O emissions from domestic wastewater handling.

GAINS technology code	Description
OPTIM	Process optimization to increase the N_2/N_2O 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 CH_4 formation under anaerobic conditions, if not handled through well managed treatment systems. Industry sectors identified in GAINS as potential sources for wastewater CH_4 emissions are food, beverages and tobacco, pulp- and paper, and organic chemical industry. CH_4 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 follow industry forecasts by IEA (IEA 2008). These forecasts, together with the estimated elasticities, were the basis for projections of future wastewater generation in industry. For non-European Annex-I countries Australia, Canada, Japan, New Zealand and the United States, average wastewater generation rates for Western Europe were assumed, while averages for Eastern Europe were used for Russia. Wastewater amounts were then verified with data reported by countries to the UNFCCC for year 2005 (UNFCCC 2008).

Table 52: Activity sources in GAINS for CH_4 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)	
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 m^3 wastewater treated (see Section 8.2).

Table 53: Technologies in GAINS for control of CH_4 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-CO_2 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, which is the most recent year. In consequence, total national emissions in GAINS correspond exactly to emissions in the national submissions (UNFCCC, 2008).

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 perfectly adequate.

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 different activity levels are used for the UNFCCC calculations than what countries report to other databases, e.g., IEA or FAO. 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 CH_4 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 presents in detail the reasons for discrepancies in GAINS estimates vs. CH_4 and N_2O emissions, respectively, reported to the UNFCCC for year 2005. 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 an inventory’s quality.

Table 54: “Other CH_4” emissions: explanations for divergence between GAINS estimates and CH_4 emissions reported to UNFCCC for year 2005 (UNFCCC 2008).

Country	GAINS divergence from UNFCCC	Explanations for divergences in GAINS vs emissions reported to UNFCCC for year 2005
Austria	-4.6%	Emissions from managed waste disposal on land reported to UNFCCC are higher than GAINS estimate for comparable control.
Australia	-11.1%	Emissions from prescribed burning of savannahs (291 kt CH_4 in 2005) not included in GAINS. Discrepancies in cow, cattle and rice cultivation activities between data reported to UNFCCC and FAO (used in GAINS) for year 2005. Discrepancy in coal mining activity between data reported to UNFCCC and IEA (used in GAINS) for year 2005.
Belarus	-6.7%	Emissions from waste disposal on land reported to UNFCCC are higher than GAINS estimate for comparable control.
Belgium	+3.3%	Discrepancies in cow and cattle activities between data reported to UNFCCC and data communicated between national experts and IIASA (used in GAINS) for year 2005.
Bulgaria	-30.5%	Emissions from managed waste disposal on land reported to UNFCCC are higher than GAINS estimate for comparable control.
Canada	-8.5%	Emissions from managed waste disposal on land reported to UNFCCC are higher than GAINS estimate for comparable control and discrepancies in oil and gas production activities between data reported to UNFCCC and IEA (used in GAINS) for year 2005.
Croatia	+2.7%	Emissions from managed waste disposal on land reported to UNFCCC are lower than GAINS estimate for comparable control.
Cyprus	n.a.	No reporting to UNFCCC
Czech Rep.	-3.0%	Discrepancy in coal mining activity between data reported to UNFCCC and IEA (used in GAINS) for year 2005.
Denmark	-0.3%	No major divergences
Estonia	+4.7%	Emissions from managed waste disposal on land reported to UNFCCC are lower than GAINS estimate for comparable control.

Finland	-8.7%	Discrepancy in cattle numbers between data reported to UNFCCC and data communicated between national experts and IIASA (used in GAINS) for year 2005.
France	-2.1%	Discrepancy in pig numbers between data reported to UNFCCC and data communicated between national experts and IIASA (used in GAINS) for year 2005.
Germany	-2.8%	Discrepancies in cow and non-dairy cattle numbers between data reported to UNFCCC and data communicated between national experts and IIASA (used in GAINS) for year 2005. Emissions from managed waste disposal on land reported to UNFCCC are higher than GAINS estimate for comparable control. Emissions from abandoned coal mines (3 kt in 2005).
Greece	-3.0%	Emissions from managed waste disposal on land reported to UNFCCC are higher than GAINS estimate for comparable control.
Hungary	-13.9%	CH_4 emissions from thermal baths (22 kt CH_4 in 2005) not accounted for in GAINS. Emissions from managed waste disposal on land reported to UNFCCC are higher than GAINS estimate for comparable control.
Ireland	-0.7%	No major divergences
Italy	-7.6%	Emissions from managed waste disposal on land reported to UNFCCC are higher than GAINS estimate for comparable control. CH_4 emissions from rabbits and deer (4 kt CH_4 in 2005) not accounted for in GAINS.
Japan	-3.8%	Discrepancies in cow and non-dairy cattle numbers between data reported to UNFCCC and data reported to FAO (used in GAINS) for year 2005. GAINS estimates of CH_4 emissions from gas transmission and distribution higher than reported to UNFCCC for year 2005.
Latvia	-9.9%	GAINS estimates of CH_4 emissions from gas transmission and distribution lower than reported to UNFCCC for year 2005.
Lithuania	+6.7%	Emissions from managed waste disposal on land reported to UNFCCC are lower than GAINS estimate for comparable control.
Luxembourg	+5.7%	Discrepancies in cow and non-dairy cattle numbers between data reported to UNFCCC and data communicated between national experts and IIASA (used in GAINS) for year 2005.
Malta	n.a.	No reporting to UNFCCC
Netherlands	-7.5%	Emissions from managed waste disposal on land reported to UNFCCC are higher than GAINS estimate for comparable control.
Norway	-8.4%	Discrepancies in oil refinery activity between data reported to UNFCCC and data reported to IEA (used in GAINS) for year 2005. Emissions from reindeers (3 kt CH_4 in 2005) not accounted for in GAINS.

New Zealand	-0.4%	Emissions from deer (38 kt CH_4 in 2005) not accounted for in GAINS. Emissions from wastewater reported to UNFCCC lower than GAINS estimate for comparable control.
Poland	-2.0%	Discrepancies in cow, non-dairy cattle and pig numbers between data reported to UNFCCC and data communicated between national experts and IIASA (used in GAINS) for year 2005.
Portugal	-6.9%	Discrepancy in emission factors for continuously flooded rice fields between UNFCCC and GAINS in year 2005. Emissions from managed waste disposal on land reported to UNFCCC are higher than GAINS estimate for comparable control.
Romania	-5.3%	Discrepancies in cow and non-dairy cattle numbers between data reported to UNFCCC and data communicated between national experts and IIASA (used in GAINS) for year 2005. Emissions from managed waste disposal on land reported to UNFCCC are higher than GAINS estimate for comparable control.
Russia	+1.9%	Discrepancy in coal mining activity between data reported to UNFCCC and IEA (used in GAINS) for year 2005. GAINS estimates of CH_4 emissions from gas transmission and distribution lower by 5% than reported to UNFCCC for year 2005.
Slovakia	-4.7%	Emissions from managed waste disposal on land reported to UNFCCC are higher than GAINS estimate for comparable control.
Slovenia	+5.5%	Discrepancies in cow, non-dairy cattle and pig numbers between data reported to UNFCCC and data communicated between national experts and IIASA (used in GAINS) for year 2005.
Spain	-3.7%	Discrepancy in non-dairy cattle numbers between data reported to UNFCCC and data communicated between national experts and IIASA (used in GAINS) for year 2005. Discrepancy in coal mining activity between data reported to UNFCCC and IEA (used in GAINS) for year 2005. Emissions from managed waste disposal on land reported to UNFCCC are higher than GAINS estimate for comparable control.
Sweden	-5.0%	Discrepancy in emission factors for biomass combustion in domestic sector between UNFCCC and GAINS in year 2005. CH_4 emissions form reindeers (5 kt CH_4 in 2005) not accounted for in GAINS.
Switzerland	+3.3%	No major divergences
Turkey	+1.9%	No emissions from domestic or industrial wastewater reported to UNFCCC for 2005 (but included in GAINS).
Ukraine	-9.1%	Emissions from managed waste disposal and wastewater reported to UNFCCC are lower than GAINS estimate for comparable control.

United Kingdom	-6.3%	Emissions from managed waste disposal and wastewater reported to UNFCCC are higher than GAINS estimate for comparable control. Emissions from livestock in Overseas Territories and Crown Dependencies (9.23 kt CH_4) not accounted for in GAINS.
United States	-4.6%	Discrepancies in cow, pig and horse numbers between data reported to UNFCCC and data reported to FAO (used in GAINS) for year 2005. Emissions from wastewater reported to UNFCCC are higher than GAINS estimates for comparable control.
All Annex_I	**-3.5%**	

Table 55: “Other N_2O” emissions: explanations for divergence between GAINS estimates and emissions reported to UNFCCC for year 2005 (UNFCCC 2008). The relative difference is presented in % of the national data (negative numbers indicate GAINS emissions to be higher)

Country	Fraction of divergence	Explanations for divergences in GAINS vs emissions reported to UNFCCC for year 2005
Austria	3.3%	o.k. - no major divergences
Australia	7.9%	National sectors not considered by GAINS: Prescribed savannah burning & LULUCF
Belarus	-54.0%	Error in manure N-excretion calculation (underestimate in the national submission to UNFCCC): factor 1000
Belgium	6.4%	Differences in estimates on agricultural N-input
Bulgaria	-13.2%	GAINS estimates a higher share of fluidized bed combustion for solid fuels
Canada	8.9%	National sector not considered by GAINS: LULUCF
Croatia	21.1%	Differences in estimates on agricultural N-input
Cyprus	n.a.	No reporting to UNFCCC
Czech Rep.	-26.8%	GAINS estimates a higher share of fluidized bed combustion for solid fuels
Denmark	-24.9%	Differences in estimates on agricultural N-input
Estonia	-64.5%	Differences in estimates on agricultural N-input
Finland	-11.1%	Differences in estimates on agricultural N-input
France	2.0%	o.k. - no major divergences
Germany	2.2%	o.k. - no major divergences
Greece	14.6%	Differences in estimates on agricultural N-input
Hungary	19.8%	Differences in nitric acid production

Ireland	-3.0%	o.k. - no major divergences
Italy	8.1%	Adipic acid production and nitric acid production: national data are higher than GAINS
Japan	7.2%	National sector not considered by GAINS: waste incineration with FBC
Latvia	-28.5%	Differences in estimates on agricultural N-input
Lithuania	16.6%	Nitric acid production; Differences in estimates on agricultural N-input
Luxembourg	29.1%	Different accounting of transport (Luxembourg has an extremely high share of fuel sale exports)
Malta	n.a.	No reporting to UNFCCC
Netherlands	-7.7%	GAINS estimates a higher share of fluidized bed combustion for solid fuels
Norway	-15.7%	Differences in estimates on agricultural N-input
New Zealand	3.6%	o.k. - no major divergences
Poland	-26.5%	Differences in N_2O from agricultural sources as Poland uses an emission factor different to most European countries; GAINS estimates a higher share of fluidized bed combustion for solid fuels
Portugal	-8.2%	Differences in estimates on agricultural N-input
Romania	24.2%	Differences in nitric acid production; differences in estimates on agricultural N-input
Russia	-14.9%	Differences in manure N-input (Russia considers unusually high losses of manure to the atmosphere)
Slovakia	20.5%	Differences in nitric acid production
Slovenia	-5.4%	o.k. - no major divergences
Spain	-4.5%	o.k. - no major divergences
Sweden	-5.3%	o.k. - no major divergences
Switzerland	-20.3%	Differences in estimates on agricultural N-input
Turkey	-958.1%	Sector “agriculture” is missing from national data

Ukraine	-28.5%	Differences in agricultural N-input; GAINS estimates a higher share of fluidized bed combustion for solid fuels
United Kingdom	-14.9%	GAINS estimates a higher share of fluidized bed combustion for solid fuels; national data on nitric and adipic acid production are about half of those from GAINS
United States	28.6%	National sector not considered by GAINS: organic matter and asymbiotic N fixation (source according to national US data)

9.2 Uncertainties

It is not easy to correctly assess emissions of non-CO_2 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 be traced, and CH_4 as well as N_2O are primarily produced by biological processes which tend to be irregular in behaviour and difficult for an exact quantitative assessment. 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-CO_2 greenhouse gases are generally associated with high uncertainty. Despite its only minor contribution, N_2O from soil (direct emissions) has been shown to provide the highest contribution to the overall uncertainties of national greenhouse gas inventories.

Seen in this perspective, it is almost surprising that the agreement between the GAINS model and the nationally submitted emission data presented in Table 54 and Table 55 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-CO_2 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.

9.3 Outlook

The aim of this report is to document the current status of the work on representing non- CO_2 greenhouse gases in the GAINS model. The results obtained need to be seen in comparison with emissions of other gases, first of all with respect to CO_2. Preliminary results of such a comparison indicate that, while CO_2 emissions currently and in the future constitute the major share in overall greenhouse gas emissions, non-CO_2 gases provide an opportunity for emission abatement at remarkably low costs. Even when seen against the known issues on data reliability (see above), reduction of these gases is an option which will need to be taken. An ex-post analysis using independent sets of data (atmospheric measurements, e.g., satellite observation combined with top-down modelling) may serve the purpose to link emission abatement efforts with real emission reductions as the atmosphere sees it.

In this analysis, we have not covered the effects the strategies discussed may have on air pollution. The GAINS model is on integrating efforts across pollutants. The interactions between measures and their effects on pollutants and greenhouse gases, also with respects to costs, have been the focus of study already. The future development of GAINS will even enhance this focus, when aiming for a mass consistent approach to simulate fluxes of reactive nitrogen across the agricultural system. As agriculture is the main source of non-CO_2 greenhouse gases, this improvement definitely will affect the topics presented here.

While further efforts will be useful and urgently needed, at this stage we provide a homogenous set of data which supports a first evaluation of greenhouse gases, their abatement potential and costs across all Annex I countries. Further developments require the results of this evaluation to be completed and the most critical points – primary elements of further study – to be identified.

References

ADB (1998). ALGAS -Asia Least cost Greenhouse gas Abatement Strategy -People's Republic of China. Manila, the Philippines, Asia Development Bank, Global Environment Facility, United Nations Development Programme.

AEAT (1998). Options to Reduce Methane Emissions -A Report produced for DGXI, European Commission. UK, AEA Technology.

AEAT (2001). Economic Evaluation of Emission Reductions of Methane in the Waste Sector in the EU. UK, AEA Technology Environment.

AEAT (2003) Emissions and projections of HFCs, PFCs and SF6 for the UK and Constituent Countries, Draft Final Report prepared for the Department for Environment, Food and rural Affairs, ED50090 Draft F, AEA Technology, Culham (UK).

Amann, M., W. Asman, et al. (2007). NEC Scenario Analysis Report Nr. 4: Updated Baseline Projections for the Revision of the Emission Ceilings Directive of the European Union. Laxenburg, Austria, International Institute for Applied Systems Analysis (IIASA).

Amann, M., et al. (2008a). GAINS - potential and costs for greenhouse gas mitigation in Annex I countries. Methodology. Laxenburg, International Institute for Applied Systems Analysis.

Amann, M., L. Höglund Isaksson, W. Winiwarter, A. Tohka, F. Wagner, W. Schöpp, I. Bertok and C. Heyes (2008b). Emission scenarios for non-CO_2 greenhouse gases in the EU-27 - Mitigation potentials and costs in 2020. Laxenburg, International Institute for Applied Systems Analysis.

An, B. X., T. R. Preston, et al. (1997). "The introduction of low-cost polyethylene tube biodigesters on small scale farms in Vietnam." Livestock Research for Rural Development **9**(2).

Andersen, M. S. (2005). Effectiveness of urban wastewater treatment policies in selected countries: an EEA pilot study. EEA Report, European Environment Agency.

Barrett, C. B., C. M. Moser, et al. (2004). "Better Technology, better plots, or better farmers? Identifying changes in productivity and risk among Malagasy rice farmers." Anerican Journal of Agricultural Economics **86**(4): 869-888.

Bates, J. (2001). Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU. Bottom-up Analysis. Culham, AEAT.

Boadi, D., C. Benchaar, et al. (2004). "Mitigation strategies to reduce enteric methane emissions from dairy cows: Update review." Canadian Journal of Animal Science **84**(3): 319-335.

Bontoux, L. (1999). The incineration of waste in Europe: issues and perspectives - a report prepared by IPTS for the Committee for Environment, Public health and Consumer Protection of the European Parliament. Seville, Spain, Joint Research Centre.

Brink, C. (2003). Modelling cost-effectiveness of interrelated emission reduction strategies - the case of agriculture in Europe. Wageningen, the Netherlands, Wageningen university.

Brink C., C. Kroeze, and Z. Klimont (2001), Ammonia abatement and its impact on emissions of nitrous oxide and methane in Europe – Part 1: method. Atmos. Environ., 35 (36), 6299-6312.

Cedigaz (2001). Natural gas in the world in 2001. Rueil-Malmaison Cedex, France.

de Beer, J., D. Phylipsen, J. Bates (2001). Economic Evaluation of Carbon Dioxide and Nitrous Oxide Emission Reductions in Industry in the EU. Bottom-up Analysis. Final Report, ECOFYS, Utrecht, The Netherlands.

de Jager, D., K. Blok, M. Van Brummelen (1996), Cost-effectiveness of emission-reducing measures for nitrous oxide in the Netherlands. Report M704, ECOFYS, Utrecht, The Netherlands

de Soete, G.G. (1993), Nitrous Oxide from Combustion and Industry: Chemistry, Emissions and Control. Paper for presentation at the International Workshop “Methane and Nitrous Oxide”, 3-5 February 1993, Amersfoort – The Netherlands.

Delmas, R. (1994). "An overview of present knowledge on methane emission from biomass burning." Fertilizer Research **37**: 181-190.

Denier van der Gon, H. A., P. M. van Bodegom, et al. (2001). "Sulfate-containing amendments to reduce methane emissions from rice fields: mechanisms, effectiveness and costs." Mitigation and Adaptation Strategies for Global Change **6**: 71-89.

Devotta S., Asthana S., Joshi R. (2004) Challenges in recovery and recycling of refrigerants from Indian refrigeration and air-conditioning service sector, Atmospheric Environment, 38: 845-854.

EC (1999) Auto-Oil II Study. CEC, Brussels.

EC (2000) Regulation (EC)No 2037/2000 of the European Parliament and of the Council on substances that deplete the ozone layer 29.6.2000

EC (2003) Consultation paper: how to considerably reduce greenhouse gas emissions fue to mobile air conditioners. European Commission, DG Environment, February 2003, Brussels.

EC (2003b) European energy and transport: Trends to 2030. European Commission, KO-AC-02-001-EN-C, ISBN 92-894-4444-4, Luxembourg.

EC (2003c) Proposal for a regulation of the European Parliament and of the Council of certain fluorinated greenhouse gases. Commission of the European Communities, COM(2003)492, final.

ECCP (2003). Mitigation potential of Greenhouse Gases in the Agricultural Sector -Final Report by Working Group 7. A. Directorate-General. Brussels, European Commission.

Ministry of Energy (2003). Energy Strategy for Russia for the Period up to the year 2020, Russian Federation Ministry of Energy. **28 August 2003**.

EPA (2006). **Global Mitigation of Non-CO_2 Greenhouse Gases. Report** EPA 430-R-06-005, USEPA Office of Atmospheric Programs, Washington.

EU (2002) Directive 2000/53/EC on end-of life vehicles, Official Journal L 269, 21/10/2000, p 0034-0043.

EU (2003) Directive 2002/96/EC on waste on electric and electronic equipment of 17 January 2003, Official Journal L37, 13/02/2003, p. 24-37.

European Communities (2001). Waste Management Options in Climate Change. Brussels, European Commission.

EUROSTAT (2001), EU Energy and Transport in Figures, Statistical pocketbook, European Commission, 195p, Belgium.

EUROSTAT (2003) Energy and transport in figures. Statistical pocketbook 2003, European Communities, Brussels.

EUROSTAT (2005). European Commission.

EUROSTAT (2008). European Commission.

FAO (2003). World Agriculture: towards 2015/2030. J. Bruinsma. Rome, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS.

FAOSTAT (2008). FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS.

Farooq Iqbal, M., Y.-F. Cheng, et al. (2008). "Mitigation of ruminant methane production: current strategies, constraints and future options." World Journal of Microbiology and Biotechnology **24**: 2747-2755.

Ferrero, A. and N. V. Nguyen (2004). Constraints and opportunities for the sustainable development of rice-based production systems in Europe. FAO RICE CONFERENCE. Rome.

Freibauer, A. (2001), Biogenic Greenhouse Gas Emissions from Agriculture in Europe – Quantification and Mitigation. Ph.D. Thesis, Universität Hohenheim, Stuttgart, Germany.

Gale, J.J., P. Freund (2002), An assessment of the costs and global impact of nitrous oxide abatement measures. In: J. van Ham et al., Eds., Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects, pp. 463-468. Millipress, Rotterdam, The Netherlands.

Gerbens, S. (1998). Cost-effectiveness of methane emission reduction from enteric fermentation of cattle and buffalo. the Netherlands, Department of Agricultural, Environmental and Systems Technology, Agricultural University Wageningen.

Gibson, A.I. (2001), Mitigation Options for Greenhouse Gas Emissions from Agriculture. Ph.D. Thesis, Imperial College of Science, Technology and Medicine, University of London.

Groningen (2008). 60-industry database, Faculty of Economics, University of Groningen.

Harnisch, J, I. Sue Wing, H.D. Jacoby, R.G. Prinn (1998); Primary Aluminum Production: Climate Policy, Emissions and Costs; MIT-Joint Program on the Science andPolicy of Global Change Report Series, Report No. 44. 18p. (Revised version).

Harnisch, J., and Hendriks, C., (2000) Economic Evaluation of Emission Reductions of HFCs, PFCs and SF6 in Europe, Special Report. Ecofys, Utrecht.

Harnisch, J. and Schwarz, W. (2003) Costs and the impact on emissions of potential regulatory framework for reducing emissions of hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride (B4-3040/2002/336380/MAR/E1), Final Report, Ecofys and Oko-Recherche, Utrecht.

Heijnes, H., van Brummelen M., Blok K. (1999), Reduction of the emissions of HFC's, PFC's and SF6 in the European Union, Final Report, Ecofys, Utrecht.

Hendriks, C., D. de Jager, et al. (1998). Emission Reduction Potential and Costs for Methane and Nitrous Oxide in the EU-15. Utrecht, Ecofys.

Hendriks, C., D. de Jager, J. de Beer, M. v. Brummelen, K. Blok, M. Kerssemeeckers (2001). Economic Evaluation of Emission Reduction of Greenhouse Gases in the Energy Supply Sector in the EU. Bottom-up Analysis. Final Report, ECOFYS, Utrecht, The Netherlands

Hernandez-Sancho, F. and R. Sala-Garrido (2008). Cost modelling in waste water treatment processes: an empirical analysis for Spain. Dangerous Pollutants (Xenobiotics) in Urban Water Cycle. P. Hlavinek, O. Bonacci, J. Marsalek and I. Mahrikova, Springer.

Höglund-Isaksson L, R. Mechler (2005). The GAINS Model for Greenhouse Gases - Version 1.0: Methane (CH_4). IIASA Interim Report IR-05-054, IIASA, Laxenburg.

Höglund-Isaksson, L. (2007). Waste and wastewater generation in Europe: implications for future CH_4 emissions. IIASA Draft Interim Report. Laxenburg, Austria, IIASA.

Houghton, T., L.G. Meira Filho, B. Lim, K. Tréanton, I. Mamaty, Y. Bonduki, D.J. Griggs and B.A. Callander (eds.)(1997a). Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Paris, IPCC/OECD/IEA.

IEA (2008). World Energy Outlook 2008.

IEA-Bioenergy (2007). "IEA-Bioenergy Task 37." Retrieved March 8, 2007, from http://www.iea-biogas.net/.

IMF (2006). "International Financial Statistics." Retrieved September, 2006.

IPCC (2000), Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. J. Penman et al., eds. IPCC National Greenhouse Gas Inventories Programme, Institute for Global Environmental Strategies, Kanagawa, Japan.

IPCC (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. L. B. S. Eggleston, K. Miwa, T. Ngara, K. Tanabe. IGES, Japan, Intergovernmental Panel on Climate Change.

IPPC (2001). Reference Document on Best Available Techniques in the Pulp and Paper Industry. Brussels, Integrated Pollution Prevention and Control (IPPC), European Commission.

IRRI (2007) Rice around the World.

Jimenez, J.L., J.B. McManus, J.H. Shorter, D.D. Nelson, M.S. Zahniser, M. Koplow, G.J. McRae, C.E. Kolb (2000), Cross road and mobile tunable infrared laser measurements of nitrous oxide emissions from motor vehicles. Chemosphere – Global Change Science 2, 397-412.

Johansson, L. S., B. Leckner, et al. (2004). "Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets." Atmospheric Pollution **38**: 4183-4195.

Jyrkkonen M. (2004), Suora kaytto kuljetusjaahdytyksessa (Direct use in refrigerated transport), presentation in seminar: Hiilidioksidi jaahdytyslaitoksissa (CO_2 in refrigeration units), 10.2.2004. Helsinki, Finland.

Kaapola, E. (1989) Pienkylmalaitoksen kayttajaopas (Guide for using refrigerator devices). Kylmatuki, Helsinki. (in Finnish).

Kjällstrand, J. and M. Olsson (2004). "Chimney emissions from small-scale burning of pellets and fuelwood -examples referring to different combustion appliances." Biomass&Bioenergy **27**: 557-561.

Klimont, Z. and C. Brink (2003). The RAINS model update of the ammonia module and introduction of agricultural greenhouse gases -Final report to the Royal Ministry of the Environment, Norway. Laxenburg, Austria, International Institute for Applied Systems Analysis.

Kuiper, J. (2001), High Temperature Catalytic Reduction Of Nitrous Oxide Emission From Nitric Acid Production Plants. NOVEM PROJECT NUMBER 375001/0080. CE Ref. J-4586-02 Continental Engineering BV, Amsterdam.

Lettinga, G. (1995). "Anaerobic digestion and wastewater treatment systems." Antonie van Leeuwenhoek, International Journal of General and Molecular Microbiology **67**(1): 3-28.

Maljanen, M., J. Hytönen, P. Mäkiranta, J. Laine, P. Martikainen (2004), Does Afforestation Lower N_2O Emissions from Organic (Histosols) Agricultural Soils? In: Achim Weiske (ed.) Proceedings of the International Conference Greenhouse Gas Emissions from Agriculture Mitigation Options and Strategies, February 10 –12, 2004, Leipzig, Germany, pp. 331-2. Institute for Energy and Environment, Leipzig.

Nakata, Y., T.Goto, Y. Niimi, S. Morita (1999), Cost analysis of xenon anesthesia: a comparison with nitrous oxide-isoflurane and nitrous oxide-sevoflurane anesthesia. Journal of Clinical Anesthesia 11(6), 477-481.

Oinonen T. and Soimakallio S. (2001) HFC- ja PFC- yhdisteiden sekä SF6:n päästöjen tekniset vähentämiskeinot ja niiden kustannukset Suomessa (HFC and PFC compounds and SF6 emission reduction options and costs in Finland), VTT tiedotteita 2099 (in Finnish).

Olsson, M. and J. Kjällstrand (2006). "Low emissions from wood burning in an ecolabelled residential boiler." Atmospheric Environment **40**: 1148-1158.

Pedersen P. (1998). Substitutes for Potent Greenhouse Gases (HFCs, PFCs and SF6), Danish Technological Institute, Denmark.

Peek, K. (2004) Personal communication. June 24th, RIVM, Bilthoven.

Persson, M. (2003). Utvärdering av uppgraderingstekniker för biogas (in English: Evaluation of upgrading technologies for biogas). Rapport SGC. Malmö, Sweden, Svenskt gastekniskt center (Swedish Centre for Gas Technologies). **142**.

Poulsen T. (2001) Ozone depleting substances and the greenhouse gases HFCs, PFCs and SF6, Danish consumption and emissions 2001, Danish Environmental Protection Agency, Copenhagen Denmark.

RICARDO (2003), Emissions technology survey. Unpublished report RD03/162101.3, RICARDO plc, Leamington Spa, Warwickshire, UK.

Sakai, S.-i. (1997). "Municipal solid waste management in Japan." Waste management **16**(5/6): 395-405.

Schaefer, D.O. Bartos, S., Blackman, J. 2002, Estimating SF6 Emissions from Electrical Equipment and Magnesium Production and Processing in the U.S., In: van Ham J., A. Baede, R. Guicherit and J Williams-Jacobse (eds.) Non-CO_2 Greenhouse Gases: Scientific Understanding, control options and policy aspects.Millpress, Rotterdam. p.207-212,.

Schwarz W. (2001) Emission of Refrigerant R-134a from Mobile Air-Conditioning Systems, Annual Rate of Emission from Passenger-Car Air-Conditioning Systems up to Seven Years Old. Study conducted for the German Federal Environment Office, 51p.

Schwarz W. and A. Leisewitz (1999) Emissions and Reduction Potentials of Hydrofluorocarbons, Perfluorocarbons and Sulphur Hexafluoride in Germany. Report for the German Federal Environmental Agency (Umweltbundesamt, UBA, Berlin).

Schwarz W. and Harnisch J, (2003) Establishing the Leakage Rates of Mobile Air Conditioners, Final report prepared for the European Commission.

SEA (2007). Produktion och användning av biogas år 2005 (in English: production and use of biogas in year 2005). Stockholm, Swedish Environment Agency

Spakman, J., M.M.J. van Loon, R.J.K. van der Auweraert, D.J. Gielen, J.G.J. Olivier, E.A. Zonneveld (2003). Method for calculating greenhouse gas emissions. Environmental monitor No. 37b, March 2003: electronic update of No. 37. VROM, The Hague; available at http://www.greenhousegases.nl.

SPP (2007). "Slovak Gas Works Annual Report 2002-2006."

TAG (2007). "Nominal, Committed, Available and Used Transportation Capacities." Retrieved July 2007, from http://www.taggmbh.at/allsite_prod1/ContentView/3/FrontEnd.

Tanskanen, J.-H. (2000). "Strategic planning of municipal solid waste management." Resources, conservation and recycling **30**: 111-133.

Taylor L. E. Hillier J. A., Mills A. J. White R., Naden J., Bartlett E. L. (2003) World Mineral Statistics 1997-2001 Europe, Production, Exports, Imports, British Geological Survey, Keyworth (UK).

Tohka, A. (2005). The GAINS Model for Greenhouse Gases - Version 1.0: HFC, PFC and SF_6. IIASA Interim Report IR-05-056, IIASA, Laxenburg.

UN (2005). World Population Prospects: The 2004 Revision, United Nations Population Division.

UN (2006). United Nations Population Division, United Nations Department of Economic and Social Affairs, New York.

UNFCCC (2008). "National Inventory Submissions 2008." Retrieved July 2008, from http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/4303.php.

UNIDO (2006). "Industrial Statistics Database, 3-digit level of ISIC Code, Revision 2."

USEPA (1999). Decentralized Systems Technology Fact Sheet -Septic Tank -Soil absorption Systems. O. o. Water. Washington D.C., United States Environmental Protection Agency. **EPA 932-F-99-075**.

USEPA (2001a) US High GWP gas emissions 1990-2010: Inventories, projections and opportunities for reductions June 2001. USEPA EPA 000-F-97-000, Washington.

USEPA (2001b) Non-CO_2 Greenhouse Gas Emissions from Developed Countries: 1990-2010, USEPA EPA 430-R-01-007, Washington.

Winiwarter, W. (2005). The GAINS Model for Greenhouse Gases: Nitrous Oxide (N_2O). Interim Report IR-05-055, IIASA, Laxenburg.

Winiwarter, W., K. Rypdal (2001), Assessing the Uncertainty Associated with National Greenhouse Gas Emission Inventories: A Case Study for Austria. Atmos. Environ. 35, 5425-5440.

Woodhill (1994). Methane emissions from Oil and Gas production in the UK. D. o. t. Environment. UK. **Report 1196**.