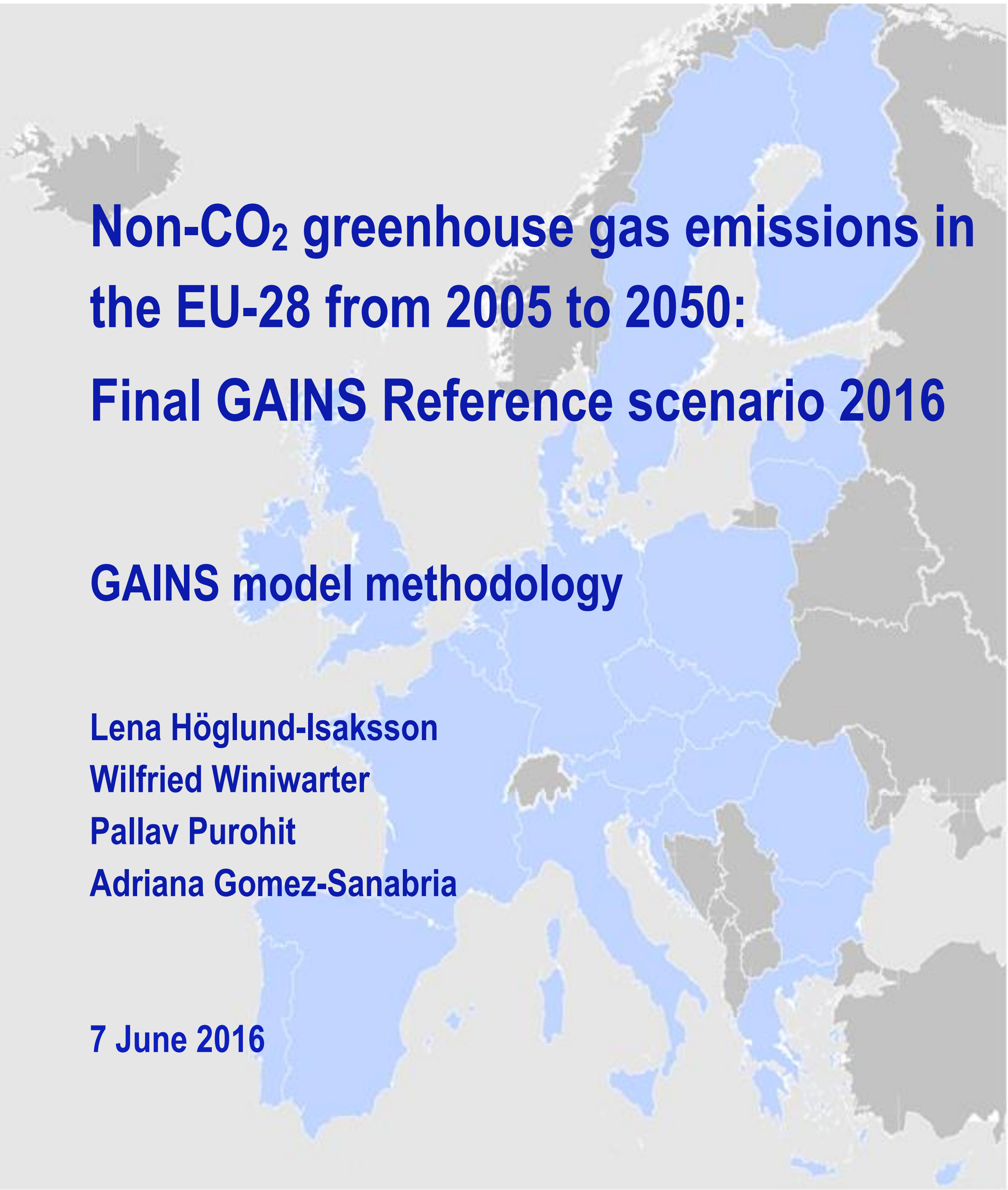
International Institute for Applied Systems Analysis
Schlossplatz 1, A-2361 Laxenburg, Austria
Tel: +43 2236 807 Fax: +43 2236 71313
www.iiasa.ac.at



Non-CO$_2$ greenhouse gas emissions in the EU-28 from 2005 to 2050: Final GAINS Reference scenario 2016

GAINS model methodology

Lena Höglund-Isaksson
Wilfried Winiwarter
Pallav Purohit
Adriana Gomez-Sanabria

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About the authors

Lena Höglund-Isaksson, Wilfried Winiwarter, Pallav Purohit and Adriana Gomez-Sanabria are researchers in the Mitigation of Air pollutants and Greenhouse gases program of the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

List of Abbreviations

API	American Petroleum Institute
CAPRI	Common Agricultural Policy Regionalized Impact (agro-economic model by University of Bonn)
CDD	Cooling degree days
CRF	Common Reporting Format (of official reportings of national greenhouse gas inventories to UNFCCC)
CWPB	Center-worked prebake (specific technology in aluminium production)
DG-ECFIN	Directorate General for Economic and Financial Affairs
DPI	Dry powder inhaler
EEA	European Environment Agency
EFMA	European Fertilizer Manufacturers Association
EHPA	European Heat Pump Association
EIA	Energy Information Administration
ESIA	European Semiconductor Industry Association
ETP	Energy Technology Perspective
ETS	Emissions Trading System
EU	European Union
EU-15 (EU-27, EU-28)	15 member countries of the European Union before 2004 (in analogy: 27 or 28 member countries before and after 2013)
FAO	United Nation’s Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization’s statistical database
FBC	Fluidized bed combustion
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies (integrated assessment model by IIASA)
GHG	Greenhouse Gas
GIS	Gas Insulated Switchgear
GSHP	ground source heat pumps
GWP	Global Warming Potential
IIASA	International Institute for Applied Systems Analysis
IEA	International Energy Agency
IFA	International Fertilizer Association
IPCC	Intergovernmental Panel on Climate Change
LABORSTA	Labour Statistics database from International Labor Organization
MAC	Mobile air-conditioners
MDI	Metered dose inhaler
NTUA	National Technical University of Athens
OECD	Organization for Economic Co-operation and Development
PCAs	Pollution Control Agreements
PFPB	Point-feeder prebake (specific technology in aluminium production)

PRIMES	Modelling system for energy supply and demand in EU-28 (by NTUA)
SWPB	Side-worked prebake (specific technology in aluminium production)
TEAP	Technology and Economic Assessment Panel of UNEP
TIMER	Targets IMage Energy Regional (simulation model by Netherlands Environmental Assessment Agency)
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VAM	Ventilation air methane
VSS	Vertical stud Söderberg (specific technology in aluminium production)
XPS	Extruded polystyrene

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1 Introduction

This report presents the GAINS model methodology for the 2016 Reference scenario for emissions of non-CO_2 greenhouse gases (GHGs), mitigation potentials and costs in the EU-28 with projections to 2050. The non-CO_2 emission scenarios form part of the work under the EUCLIMIT2 project[1]. The project aims at producing projections for all emissions of GHGs in the EU-28 consistent with the macroeconomic and population projections presented in EC/DG ECFIN (2015). Four modelling groups were involved in the work: PRIMES (National Technical University of Athens), CAPRI (Bonn University), GLOBIOM (IIASA-ESM program) and GAINS (IIASA-MAG program). This report focuses on describing the methodology of the GAINS model for the estimation of the non-CO_2 GHGs, i.e., methane (CH_4), nitrous oxide (N_2O) and three groups of fluorinated gases (F-gases) viz. hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6).

The report is structured as follows. Section 2 presents the general GAINS methodology for estimating draft non-CO_2 greenhouse gas emissions for EU-28. Sections 3, 4 and 5 describe in detail the methodology applied for estimation of emissions by source for CH_4, N_2O and F-gases, respectively. Finally, Section 6 provides a comparison between emissions reported by member states to the UNFCCC for years 2005 and 2010 and the emissions estimated by the GAINS model for the same years.

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[1] The EUCLIMIT2 project is financed by the European Commission under Service contract EC No.071201/2013/665134/SER/CLIMA.A4 between the National Technical University of Athens and DG-CLIMA.

2 GAINS emission estimation methodology

2.1 Estimation of emissions

In the general GAINS methodology (Amann et al. 2011), emissions from source s in region i and year t are calculated as the activity data A_{its} times an emission factor ef_{ism}. If emissions are controlled through implementation of technology m, the fraction of the activity controlled is specified by $Appl_{itsm}$, i.e.,

$$E_{its} = \sum_{m} \left[A_{its} * ef_{ism} * Appl_{itsm} \right], \tag{1}$$

where $ef_{ism} = ef_{is}^{NOC} * (1 - remeff_{sm})$ and $\sum_{m} Appl_{its} = 1$, (2)

and where		
	A_{its}	is the activity (e.g., number of animals, amounts of fuel or waste),
	ef_{ism}	is the emission factor for the fraction of the activity subject to control by technology m,
	$Appl_{itsm}$	is the application rate of technology m to activity s,
	ef_{is}^{NOC}	is the no control emission factor for activity s, and
	$remeff_{sm}$	is the removal efficiency of technology m when applied to activity s.

Hence, for each emission source sector, country and year specific sets of application rates for all the possible technologies (including no control among the possible technologies) are defined such that application rates always sum to unity.

2.2 Activity data

In GAINS, activity drivers for emission projections enter calculations externally using projections from different internationally recognized sources. For EU projects, the GAINS model uses energy scenarios produced by the PRIMES model (E3Mlab/ICCS, National Technical University of Athens) and agricultural scenarios from the CAPRI model (Bonn University/EuroCare). These activity scenarios are produced in consistency with the macroeconomic scenarios developed for the EU by DG-ECFIN. These are also the basis for deriving activity data in GAINS which are not part of the input data provided by the PRIMES or CAPRI models.

2.3 Emission factors

The choice of emission factors for estimation of non-CO_2 greenhouse gas emissions in GAINS follows the methodology recommended in IPCC 2006 guidelines (IPCC, 2006) as closely as available data allows. This includes conversion to CO_2 equivalents using Global Warming Potentials (GWP) of 25 times that of CO_2 for methane, 298 times that of CO_2 for nitrous oxide, and various species specific GWPs for the various F-gases. With the ambition to produce as consistent estimates across countries as possible, an extensive survey and compilation of available country-specific information on parameters with significant effects on emissions was undertaken. For several emission sources, there is enough country-specific information available to derive emission factors that are closer to IPCC Tier 2 factors than Tier 1 default factors. Emission factors that are derived from underlying country-specific information improve consistency in estimates across countries and provide an opportunity to better understand inconsistencies and uncertainty in emission estimates reported by countries to UNFCCC and other inventories.

2.4 GAINS model results and nationally reported emission data

The principal difference between GAINS model estimates and those reported by member states to UNFCCC is that the GAINS model applies a consistent methodology across all countries, whereas estimation methodologies applied by countries tend to differ in various respects across countries. Discrepancies are carefully investigated and adjustments made when appropriate, i.e. to the extent that the consistency in methodology across countries is preserved. For CH_4 and N_2O, any remaining deviations in total country emissions according to the Common Reporting Format (CRF) tables as of November 2015 and GAINS model results have been included as “calibration residual” for the year 2005, such that totals fully agree for this year. This calibration is maintained constant over future years, and can also not be affected by any mitigation measure. Thus, any emissions not covered elsewhere is included here but would not be affected by future projections or mitigation. For F-Gases, such a final calibration to reported total emissions for 2005 via calibration residual has not been conducted due to large unexplained variation in reported leakage rates across countries and due to incompleteness in national reporting for some sources.

2.5 Non-CO_2 GHG mitigation and cost estimation in GAINS

2.5.1 Technically feasible mitigation

The mitigation potential assessed in the GAINS model refers to feasible reductions in emissions through adoption of mitigation technologies defined as installations or applications of physical equipment or material or modifications in physical parameters affecting emissions. Non-technical mitigation options that involve changes in human behavior and preferences, e.g., changes in human diets towards consumption of less meat and milk products, are excluded from the analysis. It should be noted that the technical mitigation potential may differ from the politically feasible mitigation potential as the latter also takes into account costs and political barriers for implementation. In the 2016 Reference scenario for non-CO_2 greenhouse gases and associated mitigation cost curves, no effects on costs and removal efficiencies from technological development are accounted for. The reason for this is that incentives to adopt (and therefore further develop) technology that will reduce non-CO_2 greenhouse gases to a large extent are driven by the introduction of policies directed specifically at non-CO_2 mitigation. An exception would be technologies that simultaneously reduce methane emissions and recover or save gas that can be utilized for energy purposes. Demand for the latter technologies may arise spontaneously if the future price of gas is expected to remain at a level high enough to make gas recovery profitable in the long run. Hence, in contrast to most CO_2 mitigation opportunities, where demand for adoption and development of more energy-efficient technologies is primarily driven by a wish to save on energy costs, there is generally less reason to invest in development of improved mitigation technologies for non-CO_2 greenhouse gases (since most of them have only additional costs and do not generate revenues – with exceptions such as anaerobic digestion) unless directed policies are put in place and maintained for a foreseeable future. The development of non-CO_2 abatement technology therefore rely heavily on the stringency of the policies implemented and their effectiveness in stimulating continues technological development. E.g., policies that merely require adoption of pre-defined best-available-technology are less likely to stimulate continuous technological development than policies that financially penalize every additional unit of emissions released (see e.g., Popp 2003; Pizer and Popp 2008; OECD 2011). The existence of incentives for continuous technological development of non-CO_2 abatement technology is therefore considerably more uncertain than for CO_2 mitigation technology..

A common way to include the effect of technological change in mitigation technology in assessment models is to make assumptions about the learning effect on costs from cumulative technology adoption (see e.g., Jamasb and Köhler 2007). In such experience curves, the learning effect is usually measured in terms of a percentage reduction in unit costs *C* for each doubling of the cumulative capacity installed *Cap*, i.e.,

$$C = \alpha \times Cap^{-\varepsilon} \tag{3}$$

$$LR = 1 - 2^{-\varepsilon} \tag{4}$$

where α is a constant, ε is the learning elasticity and *LR* is the learning rate.

Jamasb and Köhler (2007) survey the literature on experience curves to sample empirical estimates of learning rates. They conclude that the variability is very large both between technologies and sectors and for different time periods. A majority of published learning rate estimates refer to development in electricity generation technologies. McDonald and Schrattenholzer (2001) survey these technologies and find empirical measurements of learning rates ranging from 1.4 to 35 percent reduction in unit costs for every doubling in the cumulative technology capacity. They conclude that a 17% learning rate would be appropriate for long-term energy models. However, Jamasb and Köhler (2007) point out that the evidence on declining learning rates over time suggests that a 20 percent learning rate might be on the high side when taken as a general assumption. This is particularly true when modeling further development of already existing technologies. For non-CO_2 mitigation technology we adopt effects on costs from a 15 percent learning rate, which in Equation 4 implies a learning elasticity of 23.4% and a doubling of the adopted capacity every 15 years. Depending on whether the estimates available from literature on costs of specific technologies are representative of the situation today or reflect costs expected in the future, the starting year for the learning effect on costs differs between technologies. The resulting adjustment factors applied to investment and operation and maintenance costs to account for learning are presented in Table 2.

Apart from lowering costs, technological development in abatement technology can also come in the form of improved removal efficiency. The effect on removal efficiency is closely linked to whether or not policies target emissions directly, e.g., through emission charges. Command-and-control regulations which require installations of best available technology are poor stimulators of improvements in removal efficiency, while market-based instruments that are directly linked to emission reductions are more likely to stimulate improvements in the removal efficiency (Popp, 2003). Empirical analyses of how environmental regulations affect technological development through effects on application rates for abatement technology patents usually show “peak” patterns, i.e., a sharp increase in technological development activities just after the introduction of a regulation, then a high level of development for a few years, and finally a leveling off reflecting that much of the readily available opportunities for technological development have been exhausted (OECD, 2011). Similar “peak” patterns have also been found for improvements in removal efficiencies following introductions of incentive-based environmental regulations (Popp, 2003; Höglund-Isaksson and Sterner, 2010). As no information is available in the literature for control of non-CO_2 emissions per se, we survey the literature for known effects on patent application rates and removal efficiencies of technologies in response to waste management regulations and air pollution control. Similar to non-CO2 control, development of waste management and air pollution technologies relies to a high degree on implementation of directed policies to drive incentives for further technological development.

OECD (2011, p.30) shows how the number of patent applications for solid waste management technologies (recycling, composting and incineration) closely responds to the timing of regulation introductions in different countries. Denmark was the first country to adopt an environmental protection law in 1973 and an important objective was to control the amount of waste deposited to landfills when land area was becoming scarce (Copenhagen Cleantech Cluster 2012; Civilstyrelsen 2012). Danish patent applications in this sector started to rise sharply in the beginning of the 1980s, peaked in the early 1990s and have since declined (OECD 2011). Similar increases in patent applications for waste management technology occurred in the US in the late 1980s and in Japan in the early 1990s following the amendment of the US Resource, Conservation and Recovery Act in 1984 and the Japanese Recycling Law in 1991, respectively (OECD 2011, p.131).

From the early 1990s the US and Sweden introduced market-based instruments complementing or replacing command -and control regimes in air pollution control. As shown by Popp (2003), the command –and control regulations of SO_2 emissions from coal-fired utility plants in the US introduced under the Clean Air Acts of 1970 and 1977, are reflected in a considerable increase in US patent applications for scrubbers during this period. Notable is that this technological development was primarily focused on developing technology at lower costs and without significant improvements in removal efficiencies. Only after the 1990 Clean Air Act, when a cap- and trade scheme for SO_2 emissions was introduced, does the removal efficiency of the available technologies improve significantly. Popp (2003) interprets this as a result of a switch in policy target from targeting adoption of certain technology to targeting emission reductions directly. Table 1 summarizes the empirical findings of the short and long-term effects of air pollution regulations in the US (Popp, 2003), Sweden (Höglund-Isaksson and Sterner, 2010) and Japan (Matsuno et al., 2010). While Popp (2003) measures technological development directly when he measures the annual improvement in removal efficiency of a certain technology (scrubbers), the other studies use indirect measures, where the effect of technological development on emissions is summed up with the effect on emissions of adopting existing technology. The latter produces higher annual changes in emission rates, in particular in the short run as it then also reflects the plants’ initial adoption of technology in responses to the regulations. In the long run, it can be expected that a larger fraction of the annual change is due exclusively to the effects of technological development.

Table 1: Some empirical evidence of the effects of air pollution regulations on targeted emissions in short and long runs.

Source	Regulation	Year of first imple-menta-tion	Number and type of plants in analyzed sample	Emission parameter description	Total effect		Short-term effect		Long-term effect	
					Entire period	Average annual change in parameter	Period with rapid decline in parameter	Average annual change in parameter	Period with slower decline in parameter	Average annual change in parameter
Popp (2003)	US 1970, 1977, 1987 CAA (command -and control)	1970	193 coal-fired plants with scrubber	SO_2 emission rate of new scrubbers	1974-1990	about -0.4%	1974-1978	about -1.5%	1978-1990	about 0
	US 1990 CAA (cap -and trade)	1990			1990-1997	about -1.6%	not available		not available	
Höglund-Isaksson and Sterner (2010)	Swedish NOx charge -plants not (yet) adopting abatement technology	1992	180 to 280 power plants (> 50 MWh) targeted in 1992 to 2007	NO_X emissions per energy output of targeted plants	1992-2007	-3.5%	1992-1997	-5.8%	1997-2007	-2.4%
	Swedish NOx charge -plants having adopted abatement technology	1992			1992-2007	-5.7%	1992-97	-11.2%	1997-2007	-2.9%
Matsuno et al. (2010)	Japanese SO_2 compensation law	1974	>3000 sites targeted by pollution load regulation	SO_2 emissions of targeted plants	1973-2003	-7.1%	1973-1987	-11.5%	1987-2003	-3.0%

On the basis of the long-term effects found in the literature survey presented in Table 1, we assume a long-term improvement in the effectiveness of non-CO_2 mitigation technology to remove emissions of 1 percent per year.

For existing technologies, improvements over time of costs and removal efficiencies are assumed to start from 2020 in response to further adoption and implementation of policies. For some technologies, assumptions taken from literature on costs and removal efficiencies are estimates of the expected future costs and removal efficiencies. These include options to reduce nitrous oxide emissions from agricultural soils as well as options to reduce methane emissions from enteric fermentation in livestock. For these technologies, effects of technological development on costs and removal efficiencies are assumed to start in 2030. Table 2 summarizes the assumptions made on technological development of non-CO_2 mitigation technology in GAINS.

Table 2: Adjustment factors for investment costs, operation and maintenance (O&M) costs, and emission factors used in GAINS to account for effects of technological development of non-CO_2 mitigation technology from 2020 to 2050.

	Technologies with current costs and removal efficiencies provided in literature		Technologies with future expected costs and removal efficiencies provided in literature	
Year	Investment and O&M costs	Emission factors	Investment and O&M costs	Emission factors
2020	1	1	1	1
2025	0.88	0.95	1	1
2030	0.82	0.9044	1	1
2035	0.765	0.8601	0.88	0.95
2040	0.72	0.8179	0.82	0.9044
2045	0.68	0.7778	0.765	0.8601
2050	0.651	0.7397	0.72	0.8179

2.5.2 *Mitigation costs*

Costs for mitigation of non-CO_2 GHGs per unit of activity are in GAINS calculated as the sum of investment costs, labour costs, non-labour operation and maintenance costs, cost-savings due to recovery or saving of electricity, heat or gas, and non-energy cost savings. The unit cost of technology *m* in country *i* and year *t* is defined as:

$$C_{itm} = I_{im}\left[\frac{(1+r)^{T_m}\times r}{(1+r)^{T_m}-1}\right] + M_{im} + \left(L_{im}\times W_{it}\times w_{is}\right) - S_{im} - \rho\left(E_{im}\times p_{it}^{electr}\right) - \left(G_{im}\times p_{it}^{gas}\right) \quad (5)$$

where I_{im} $\mathrm{I_{im}}\left[\frac{(1+r)^{\mathrm{T}}\times \mathrm{r}}{(1+r)^{\mathrm{T}}-1}\right]$ is the upfront investment cost for technology *m* in country *i*,

$\left[\frac{(1+r)^{T_m}\times r}{(1+r)^{T_m}-1}\right]$ $\mathrm{I_{im}}\left[\frac{(1+r)^{\mathrm{T}}\times \mathrm{r}}{(1+r)^{\mathrm{T}}-1}\right]$ is the annualization factor for the investment cost with interest rate *r* and technology lifetime of T_m years,

M_{im} $\mathrm{M_{im}}$ is the annual operation and maintenance cost for technology *m*,

L_{im} $\mathrm{L_{im}}$ is the fraction of annual work hours for operating technology *m*,

W_{it} is the annual average wage in country *i* in year *t*,

w_{is} is a country-specific wage adjustment factor for type of sector *s* (agriculture or manufacturing industry),

S_{im} is the sum of non-energy annual cost-savings,

E_{im} is the amount of energy recovered and utilized as electricity or heat,

p_{it}^{electr} $\mathrm{p_{it}^{electr}}$ is the industry electricity price in country *i* in year *t*,

ρ is a fixed factor between 0 and 1 reflecting the utilization rate of the energy generated as electricity and heat, respectively,

G_{im} $\mathrm{G_{im}}$ is the amount of gas recovered, and

p_{it}^{gas} $\mathrm{p_{it}^{gas}}$ is the industry gas price in country *i* in year *t*.

In the 2015 Reference scenario, the unit costs are expressed in constant 2013 Euros per unit of activity and a market interest rate of 10 percent is adopted in order to be consistent with the relevant (market) interest rate used in PRIMES (2015) mitigation costs for CO_2.

Country and sector specific annual average wages are taken from LABORSTA (ILO, 2010) for historical years and growth in future wages is proportional to the expected future development in sector value added as provided from EC/DG ECFIN (2015).

In the GAINS estimation of CH_4 mitigation costs, energy recovery from biogas production or reduced leakage of natural gas during production, transmission and distribution is valued at the electricity or gas consumer price in industry as estimated and projected by PRIMES (2015). To the extent that heat is recovered, it is valued at half of the electricity price in industry.

Gas recovery refers to recovering gas of an upgraded quality of 97 percent CH_4. For some mitigation options, e.g., when biogas is recovered from large-scale anaerobic digestion (note not applicable to small farm anaerobic digesters), upgrading from 60 to 97 percent CH_4 is necessary for supplying the gas to the grid (Persson, 2003). Costs for upgrading gas have in these cases been included in investment costs.

Similar to how the country and year specific emission level E_{its} is estimated for each sector in equation (1), the total mitigation cost in sector s in country i and year t is defined for sets of application combinations of the possible technologies applicable in the sector. For a given country, year and sector, a technology setting is defined such that the sum of all application rates $Appl_{itsm}$ of possible technologies m (including the no control option) is always unity. The total cost of each technology setting is defined as:

$$TC_{its} = \sum_m \left[A_{its} * C_{itm} * Appl_{itsm} \right] , \tag{6}$$

where A_{its} is the activity level, C_{itm} is the cost per unit of activity and $\sum_m Appl_{itsm} = 1$.

The marginal cost per unit of reduced emissions is first defined for each technology available to a sector as the unit cost divided by the difference between the technology emission factor and the no control emission factor, such that:

$$MC_{itm}^{Tech} = \frac{C_{itm}}{ef_{it}^{No\_control} - ef_{itm}} . \tag{7}$$

We refer to this as the “technology marginal cost”. Within a sector, the technologies available are first sorted by their respective technology marginal cost. The technology with the lowest technology marginal cost is ranked the first-best technology and assumed adopted to its full extent in a given sector. The second-best technology is the technology with the second lowest technology marginal cost and is assumed available for adoption provided it can achieve an emission factor that is lower than the first-best technology. The marginal cost of the second-best technology when implemented in the cost curve is defined as:

$$MC_{it2} = \frac{C_{it2} - C_{it1}}{ef_{it1} - ef_{it2}} . \tag{8}$$

In a similar manner, each additional technology available to a sector is added on top of the next best available technology. Note that a technology with both a higher marginal cost and a higher emission factor than another technology available to a sector will not adopted at all as it is less effective in reducing emissions and come at a higher cost than other available technologies. In this way, a marginal mitigation cost curve with strictly convex properties is built up sector-wise by country and year.

3 CH_4 emission sources

3.1 Overview of CH_4 emission sources and control implemented in the reference scenario

CH_4 emission sources in the GAINS model include anthropogenic CH_4 emissions from livestock, rice cultivation, biodegradable solid waste, wastewater, coal mining, oil and gas production, gas transmission pipelines, gas consumer distribution networks, and combustion emissions from fuel used for energy consumption and from open burning of agricultural waste residuals. Other types of open burning of biomass for non-energy purposes, e.g., human-induced forest fires, have been excluded from the analysis due to lack of systematic information. Table 3 provides an overview of the structure of CH_4 sources in GAINS and their respective control options.

In addition to the structure presented in Table 3, it should be mentioned that the livestock categories dairy cows, non-dairy cattle, pigs, poultry and sheep have been further split into the following farm-size classes; less than 15 livestock units (LSU), 15 to 50 LSU, 50 to 100 LSU, 100 to 500 LSU, and above 500 LSU. This allows for considering the impact of scale on mitigation potentials and costs.

Table 4 presents a list of current legislation affecting CH_4 emissions in the EU member states. Regulations adopted EU-wide include the different Waste sector Directives. The Landfill Directive specifies the targets for the amounts of biodegradable waste that must be diverted away from landfills to different types of waste treatment. The Waste management framework Directive defines a waste treatment hierarchy in which recycling of waste is preferred to energy recovery, which in turn is preferred to landfill of untreated waste. In addition to the EU-wide Directives in the waste sector, six member states have introduced complete bans on landfill of biodegradable waste (Austria, Belgium, Denmark, Germany, Netherlands, Sweden).

CH_4 emissions will also be affected by the EU Effort Sharing Decision, which defines legally binding national GHG emission targets for non-ETS sectors. In addition, the adoption of anaerobic digestion of animal manure is consistent with PRIMES (2015) biomass supply as driven by the 2020 renewable targets and consistent with historical data (EurObserv’ER, 2014).

Table 3: Overview of GAINS structure of CH_4 emission sources and mitigation options.

Emission source	GAINS sector	Sector description	GAINS technology	Technology description
Coal mining	MINE_BC_PRE	Brown coal mining: pre-mining emissions	BC_DEGAS	Pre-mining degasification
	MINE_BC_VAM	Brown coal mining: emissions during mining	none	none identified
	MINE_BC_POST	Brown coal mining: post-mining emissions	none	none identified
	MINE_HC_PRE	Hard coal mining: pre-mining emissions	HC_DEGAS	Pre-mining degasification
	MINE_HC_VAM	Hard coal mining: emissions during mining	VAMOX	Oxidation of ventilation air methane
			VAMOX_VENT	VAMOX combined with improved ventilation system
	MINE_HC_POST	Hard coal mining: post-mining emissions	none	no option identified
Oil production	PROD_AGAS -CRU	Oil production: venting associated gas	REC_USE	Extended recovery and utilization of associated gas
	PROD_LEAK -CRU	Oil production: unintended leakage	GP	Good practice: leakage control
Oil refinery	PR_REF	Oil transportation, storage and refining	FLA_REF	Extended flaring of waste gas
Gas production	PROD_AGAS -GAS	Gas production: venting associated gas	REC_USE	Extended recovery and utilization of associated gas
	PROD_LEAK -GAS	Gas production: unintended leakage	GP	Good practice: leakage control
Long-distance gas transportation	TRANS -GAS	Gas transmission pipelines	COMPRESS	A leakage rate of maximum 10 kg CH4/(bcm*km) is considered possible in all EU.
Consumer gas distribution networks	DOM -GAS	Domstic sector: gas fuel	CONT_NET	Doubled control frequency
			REPL_NET	Replacement of grey cast iron networks
	IN_BO -GAS	Industrial boilers: gas fuel	CONT_NET	Doubled control frequency
			REPL_NET	Replacement of grey cast iron networks
	IN_OC -GAS	Other industry combustion: gas fuel	CONT_NET	Doubled control frequency
			REPL_NET	Replacement of grey cast iron networks
	PP_EX_OTH -GAS	Power plants existing: gas fuel	CONT_NET	Doubled control frequency
			REPL_NET	Replacement of grey cast iron networks
	PP_NEW -GAS	Power plants new: gas fuel	CONT_NET	Doubled control frequency
			REPL_NET	Replacement of grey cast iron networks
	TRA_RD_HDB/HDT/ LD4C/LD4T -GAS	Road transport/bus/trucks/cars/ vans: gas fuel	CONT_NET	Doubled control frequency
			REPL_NET	Replacement of grey cast iron networks
	CON_COMB -GAS	Other combustion sources: gas fuel	CONT_NET	Doubled control frequency
			REPL_NET	Replacement of grey cast iron networks
	NONEN -GAS	Non-energy use: gas	CONT_NET	Doubled control frequency
			REPL_NET	Replacement of grey cast iron networks

Continued Table 3: Overview of GAINS structure of CH_4 emission sources and mitigation options.

Emission source	GAINS sector	Sector description	GAINS technology	Technology description
Livestock	AGR_BEEF -OL_F	Non-dairy cattle with liquid manure management: enteric fermentation emissions	FEED	Feed additives & feed management
			BREED	Breeding to enhance feed efficiency and reduce methane emissions
			VACCIN	Vaccination against methanogenic bacteria
	AGR_BEEF -OL	Non-dairy cattle with liquid manure management: manure management emissions	FARM_AD	Farm-scale anaerobic digestion on farms with minimum size 100 LSU
	AGR_BEEF -OS	Non-dairy cattle with solid manure management: enteric fermentation and manure management emissions	FEED	Feed additives & feed management
			BREED	Breeding to enhance feed efficiency and reduce methane emissions
			VACCIN	Vaccination against methanogenic bacteria
	AGR_COWS -DL_F	Dairy cows with liquid manure management: enteric fermentation emissions	FEED	Feed additives & feed management
			BREED	Breeding with dual objective to increased productivity and maintain health and fertility
			VACCIN	Vaccination against methanogenic bacteria
	AGR_COWS -DL	Dairy cows with liquid manure management: manure management emissions	FARM_AD	Farm-scale anaerobic digestion on farms with minimum size 100 LSU
	AGR_COWS -DS	Dairy cows with solid manure management: enteric fermentation and manure management emissions	FEED	Feed additives & feed management
			BREED	Breeding with dual objective to increased productivity and maintain health and fertility
			VACCIN	Vaccination against methanogenic bacteria
	AGR_PIG -PL	Pigs with liquid manure management	FARM_AD	Farm-scale anaerobic digestion on farms with minimum size 100 LSU
	AGR_PIG -PS	Pigs with solid manure management	none	no option identified
	AGR_POULT -LH	Laying hens	none	no option identified
	AGR_POULT -OP	Other poultry	none	no option identified
	AGR_OTANI -BS	Buffaloes	none	no option identified
	AGR_OTANI -HO	Horses	none	no option identified
	AGR_OTANI -SH	Sheep and goats	BREED	Breeding to enhance feed efficiency and reduce methane emissions
			VACCIN	Vaccination against methanogenic bacteria
Agricultural waste burning	WASTE_AGR	Open burning of agricultural waste	BAN	Ban on open burning of agricultural waste

Continued Table 3: Overview of GAINS structure of CH_4 emission sources and mitigation options

Emission source	GAINS sector	Sector description	GAINS technology	Technology description
Solid waste	MSW_FOOD	Municipal solid waste: food and garden	MSW_FOOD_AD	Separate collection and anaerobic digestion for biogas production
			MSW_FOOD_HSC	Household composting
			MSW_FOOD_LSC	Separate collection and large-scale composting
			MSW_FOOD_INC	Incineration of mixed waste
			MSW_FOOD_SWD_FLA	Landfill with recovery and flaring of landfill gas
			MSW_FOOD_SWD_USE	Landfill with recovery and utilization of landfill gas
	MSW_PAP	Municipal solid waste: paper	MSW_PAP_REC	Separate collection and recycling
			MSW_PAP_INC	Incineration of mixed waste
			MSW_PAP_SWD_FLA	Landfill with recovery and flaring of landfill gas
			MSW_PAP_SWD_USE	Landfill with recovery and utilization of landfill gas
	MSW_WOOD	Municipal solid waste: wood	MSW_WOOD_INC	Incineration of mixed waste
			MSW_WOOD_SWD_FLA	Landfill with recovery and flaring of landfill gas
			MSW_WOOD_SWD_USE	Landfill with recovery and utilization of landfill gas
	INW_FOOD	Industrial solid waste: food, beverages	INW_FOOD_AD	Anaerobic digestion for biogas production
			INW_FOOD_COM	Composting
			INW_FOOD_INC	Incineration
			INW_FOOD_SWD_FLA	Landfill with recovery and flaring of landfill gas
			INW_FOOD_SWD_USE	Landfill with recovery and utilization of landfill gas
	INW_PAP	Industrial solid waste: pulp and paper	INW_PAP_INC	Recovery of black liqour for energy utilization
			INW_PAP_SWD_FLA	Landfill with recovery and flaring of landfill gas
			INW_PAP_SWD_USE	Landfill with recovery and utilization of landfill gas
	INW_TEX	Industrial solid waste: Textile, footwear, leather	INW_TEX_INC	Incineration with energy recovery
			INW_TEX_SWD_FLA	Landfill with recovery and flaring of landfill gas
			INW_TEX_SWD_USE	Landfill with recovery and utilization of landfill gas
	INW_WOOD	Industrial solid waste: wood and wood products	INW_WOOD_REC	Recycling for wood board production
			INW_WOOD_INC	Incineration with energy recovery
			INW_WOOD_SWD_FLA	Landfill with recovery and flaring of landfill gas
			INW_WOOD_SWD_USE	Landfill with recovery and utilization of landfill gas

Continued Table 3: Overview of GAINS structure of CH_4 emission sources and mitigation options

Emission source	GAINS sector	Sector description	GAINS technology	Technology description
Wastewater	WW_DOM_CC_TRM	Domestic wastewater: centralized collection	DOM_CC_AER	Aerobic treatment
			DOM_CC_23	Anaerobic treatment
			DOM_CC_23U	Anaerobic treatment with biogas recovery
	WW_DOM_DC_NOC	Domestic wastewater: decentralized collection, no treatment	none	no option identified
	WW_DOM_DC_TRM	Domestic wastewater: decentralized collection, with treatment	none	no option identified
	IND_FOOD_TRM	Industrial wastewater: food, beverages	IND_FOOD_AERO	Aerobic treatment
			IND_FOOD_ANAE_NON	Anaerobic treatment without biogas recovery
			IND_FOOD_ANAE_USE	Anaerobic treatment with biogas recovery
	IND_PAP_TRM	Industrial wastewater: pulp and paper	IND_PAP_AERO	Aerobic treatment
			IND_PAP_ANAE_NON	Anaerobic treatment without biogas recovery
			IND_PAP_ANAE_USE	Anaerobic treatment with biogas recovery
	IND_OTH_TRM	Industrial wastewater: organic chemical	IND_OTH_AERO	Aerobic treatment
			IND_OTH_ANAE_NON	Anaerobic treatment without biogas recovery
			IND_OTH_ANAE_USE	Anaerobic treatment with biogas recovery
Combustion in stationary sources	DOM -various fuels	Domestic sector: various fuels	none	no option identified
	IN_BO -various fuels	Industrial boilers: various fuels	none	no option identified
	IN_OC -various fuels	Other industry combustion: various fuels	none	no option identified
	PP_EX_OTH -various fuels	Power plants existing: various fuels	none	no option identified
	PP_NEW -various fuels	Power plants new: various fuels	none	no option identified
	CON_COMB -various fuels	Other combustion sources: various fuels	none	no option identified
	WASTE_FLR	Combustion emissions from flaring of associated gas from oil and gas	none	no option identified
Combustion in mobile sources	TRA_RD_HDB/HDT/LD4C/LD4T -various fuels	Road transport/bus/trucks/cars/vans: various fuels	none	no option identified
	TRA_OT_AGR/CNS/INW/LB/RAI -various fuels	Non-road transport: various modes and fuels	none	no option identified

Table 4: Current legislation affecting CH_4 emissions in EU member states.

Emission source	Regulation/ agreement	Region scope	Content that concerns CH_4 emissions	Date entering into force
Agriculture	Current and future adoption of farm AD in the Reference scenario	All EU-28	Current and future adoption of farm AD accounted for in the Reference scenario is consistent with the total energy output from manure-based anaerobic digesters estimated by the PRIMES model (and assuming renewable targets are met).	Adoption rate in 2015 derived from adoption in 2013 reported in Eur'Observer (2014)
Energy	Leakage control of natural gas systems	Germany	Introduction of an electronic registration system for structure and damage submissions by operators of natural gas networks and installations.	Introduced in 2012
Waste	EU Landfill Directive (EC/31/1999)	EU-wide	Biodegradable waste should be diverted away from landfills corresponding to reductions from amounts landfilled in 1990 by -25% in 2006, -50% in 2009 and -65% in 2016. All landfill sites equipped with gas recovery by 2009.	1999
	EU Waste Management Framework Directive (EC/98/2008)	EU-wide	In waste treatment the following hierarchy needs to be respected: recycling and composting preferred to incineration/energy recovery, which in turn is preferred to landfill disposal.	2008
	Decree on waste landfill	Slovenia	Decree on landfill of waste beyond EU Landfill Directive. Includes partial ban on landfill of biodegradable waste.	Feb-14
	Policy addressing landfill of biodegradable waste	Portugal	Target is to reduce landfill of biodegradable waste to 26% of waste landfilled in 1995 (35% in the Landfill Directive)	Date of enforcement unclear, but in place in 2014
	Ban on landfill of biodegradable waste.	Austria, Belgium, Denmark, Germany, Netherlands, Sweden	Complete ban on landfill of untreated biodegradable waste	2005 or earlier
Wastewater	EU urban wastewater treatment directive (EEC/271/1991)	EU-wide	"Appropriate treatment" of wastewater from urban households (all agglomerations > 2000 people) and food industry must be in place latest by end of 2005. This means discharge must ensure receiving waters meet relevant quality objectives.	1993
All non-ETS sectors	EU Effort Sharing Decision (EC/406/2009)	EU-wide	Decision defines legally binding national GHG emission targets for non-ETS sectors. Target year is 2020, but countries need to comply with a linear emission path between 2013 and 2020.	2013

3.2 Energy sector

3.2.1 Coal mining

Formation of coal produces CH_4, which is released to the atmosphere during mining. IPCC (2006, Vol.2, p.4.9) 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. Due to difficulties with obtaining systematic information about the number and size of abandoned coal mines, the emission source is excluded in this study. Hence, only emissions from coal mines in operation are regarded.

Following the split of the activity data into brown and hard coal, emissions are calculated separately for the two coal types. All brown coal is assumed to be surface mined, while hard coal is assumed being partly surface mined and partly mined underground. Emissions from peat production are understood to be negligible and have been set to zero.

Emissions from brown and hard coal production are calculated as follows:

$$E_{BC;it} = A_{BC;it} \times \left[ef_{m;i}^{surface} + ef_{postm;i}^{surface} \right] \tag{9}$$

$$\begin{aligned} E_{HC;it} &= A_{HC;it} \times \left[\gamma_{HC;i}^{undergr} \times \left(ef_{m;i}^{undergr} + ef_{postm;i}^{undergr} \right) \right] + \\ &+ A_{HC;it} \times \left[\left(1 - \gamma_{HC;i}^{undergr}\right) \times \left(ef_{m;i}^{surface} + ef_{postm;i}^{surface} \right) \right] \end{aligned} \tag{10}$$

where

$$ef_{m;i}^{surface} = ef_{m;i;NOC}^{surface} \times \left(1 - r_{dgas}\right) \times CLEappl_{dgas;i} \text{ ,} \tag{11}$$

$$\begin{aligned} ef_{m;i}^{undergr} &= ef_{m;i;NOC}^{undergr} \times \left[\alpha_{VAM;i} \times \left(1 - r_{VAM}\right) \times CLEappl_{VAM;i} \right] \\ &+ ef_{m;i;NOC}^{undergr} \times \left[\left(1 - \alpha_{VAM;i}\right) \times \left(1 - r_{dgas}\right) \times CLEappl_{dgas;i} \right] \end{aligned} \tag{12}$$

and where

$A_{BC;it}$ and $A_{HC;it}$	are amounts of brown and hard coal produced in country *i* in year *t*,
$ef_{m;i;NOC}^{surface}$	is a country-specific no control emission factor for surface mining emissions,
$ef_{postm;i}^{surface}$	is the average world IPCC default emission factor for post-mining emissions from surface mines,
$ef_{m;i;NOC}^{undergr}$	is a country-specific no control emission factor for underground mining emissions,
$ef_{postm;i}^{undergr}$	is the average world IPCC default emission factor for post-mining emissions from underground mines,
$\gamma_{HC;i}^{undergr}$	is a country-specific fraction of hard coal being mined underground as opposed to surface mining,
$\alpha_{VAM;i}$	is a country-specific fraction of underground mining emissions being released through the ventilation air as opposed to pre-mine degasification emissions,
r_{dgas} and r_{VAM}	are the removal efficiencies of technologies removing degasification and ventilation air methane, respectively,

$CLEappl_{VAM;i}$ is the application of technology removing ventilation air methane, and

$CLEappl_{dgas;i}$ is the application of technology removing degasification methane.

Country-specific information about emissions released from surface and underground mines in year 2005 were taken from UNFCCC-CRF (2010) together with information about the fraction of hard coal mined in surface mines. Information on the current application of pre-mining degasification was extracted from the same source. The fraction of underground mine gas exiting as ventilation air methane as opposed to being released during pre-mining degasification is taken from USEPA (2003). No country-specific information about post-mining emissions was found and, hence, IPCC (2006) default emission factors for surface and underground mining, respectively, were applied to all countries for post-mining emissions. The resulting derived emission factors for coal-mining in EU-28 countries are presented in Table 5. For comparison the derived emission factors presented in Table 5 are reproduced in Table 6 in terms of ton CO_2eq per TJ coal produced using country-specific calorific values of coal from IEA-WEO (2009).

Emissions from both surface and underground mines can be reduced if CH_4 is recovered through pre-mine drainage up to ten years before the mining starts (USEPA, 2008a).Currently in the US, at least 90 percent of degasification emissions from underground coal mines are recovered and utilized (USEPA, 2010). In GAINS, this is assumed technically possible in other countries as well. There is, however, only one project known to be recovering and utilizing CH_4 from pre-mine drainage at a surface mine and details about the removal efficiency of this option are uncertain (Sino-US New Energy Sci-Tech Forum, 2009). In GAINS, it is considered technically possible to recover 90 percent of the drainage gas also from surface mines. Costs for degasification are taken from Thakur (2006) and include costs for in-mine drilling, underground pipeline costs, and hydraulic fractioning of vertical wells and other gob wells.

Ventilation air methane (VAM) from underground coal mines can be recovered and oxidized through installation of VAM oxidizers (Mattus and Källstrand, 2010). Although the application on coal mines is still in a starting phase, the technology used is well known from control of odor and VOC emissions worldwide. The technology oxidizes at least 95 percent of VAM when applied to a ventilation shaft. It uses the energy released during the oxidation to keep the process running, which keeps fuel costs limited to the initial start-up phase. A prerequisite for the oxidation process to run without interruptions is that the CH_4 concentration in the ventilation air is at least 0.3 percent. Securing this concentration level without increasing explosion risks (i.e. CH_4 concentrations in the air should never be in the explosive range between 5 and 15 percent), may in some mines require investments in more efficient ventilation systems.

A general assumption is made that it is technically possible to keep CH_4 concentration levels at a steady rate of at least 0.3 percent, and therefore to install self-sustained VAM oxidizers (Mattus and Källstrand, 2010), on 50 percent of the ventilation air emitted from underground coal mines in all countries. With more detailed information about the distribution of VAM concentration rates in different countries and mine sites, this assumption may need to be revised in the future. Costs for VAM oxidation technology and installation are taken from USEPA (2003, p.30) and GMI (2008) and refer to installations in the US and China.

If VAM oxidizer technology is combined with improved ventilation systems, it may be possible to extend the installation of oxidizers as it then becomes possible to better control a steady rate of at least 0.3 percent CH_4 in the ventilation air without jeopardizing security. It is assumed that with improved ventilation it is possible to extend the application of VAM oxidizers to 70 percent of VAM emitted from underground mines in all countries. An improved ventilation system is assumed to double the ventilation capacity of the mine compared with a conventional system. This would then double the amount of electricity used for ventilation. Costs for increased electricity use for ventilation in mines were based on information from Unruh (2002) and Papar et al. (1999).

For further details on mitigation costs for control of coal mine emissions, see the Supplement of Höglund-Isaksson (2012).

No mitigation potential is assumed for post-mining emissions.

Table 5: Coal mining emission factors for EU-28 countries in the GAINS model.

	Derived no control CH_4 emission factors								Implied emission factor 2005	
	Brown coal mining				Hard coal mining				All coal types and sources	
	total	pre-mining	mining	post-mining	total	pre-mining	mining	post-mining	No control	Including current control
Country	kt CH_4 /Mt coal produced									
Belgium	0.871	0.322	0.482	0.067	13.735	4.824	7.236	1.675	13.7	13.7
Bulgaria	0.832	0.306	0.459	0.067	8.555	2.986	4.479	1.090	0.9	0.8
Czech Rep.	0.707	0.173	0.467	0.067	9.792	2.267	6.130	1.395	3.2	2.7
Estonia	0.871	0.322	0.482	0.067	8.375	2.680	4.020	1.675	0.9	0.9
France	0.871	0.322	0.482	0.067	13.735	4.824	7.236	1.675	13.7	13.7
Germany	0.077	0.004	0.006	0.067	9.650	3.209	5.019	1.422	1.5	1.2
Greece	1.134	0.427	0.640	0.067	8.375	2.680	4.020	1.675	1.1	1.1
Hungary	0.871	0.322	0.482	0.067	8.375	2.680	4.020	1.675	0.9	0.9
Italy	0.871	0.322	0.482	0.067	12.842	4.467	6.700	1.675	13.0	12.8
Latvia	0.871	0.322	0.482	0.067	8.375	2.680	4.020	1.675	0.9	0.9
Lithuania	0.871	0.322	0.482	0.067	8.375	2.680	4.020	1.675	0.9	0.9
Poland	0.077	0.003	0.007	0.067	5.560	1.108	2.850	1.602	3.5	3.1
Romania	0.717	0.260	0.390	0.067	5.625	1.955	2.933	0.737	0.8	0.7
Slovakia	0.871	0.322	0.482	0.067	8.375	2.680	4.020	1.675	0.9	0.9
Slovenia	0.871	0.322	0.482	0.067	8.375	2.680	4.020	1.675	0.9	0.9
Spain	0.320	0.101	0.152	0.067	4.436	1.262	1.893	1.281	2.7	2.7
United Kingdom	0.871	0.241	0.563	0.067	9.323	2.793	5.912	0.618	9.3	7.7

Sources: UNFCCC-CRF 2010 for reported emissions from surface and underground coal mines, for the fraction of hard coal surface mined, and for current control through degasification.; USEPA 2003 for the fraction of underground mine gas exiting as ventilation air methane as opposed to released during pre-mining degasification; IPCC (2006) for default post-mining emission factors specified for surface and underground mining, respectively.

Table 6: Coal mining emission factors for EU-28 countries expressed in tCO_2eq/TJ coal produced. Energy conversion factor: 41.868 GJ/toe.

	Calorific values used in GAINS (source is IEA-WEO)		Derived no control CH_4 emission factors							
			Brown coal mining				Hard coal mining			
	toe/t coal	toe/t coal	total	pre-mining	mining	post-mining	total	pre-mining	mining	post-mining
Country	Brown coal (lignite)	Hard coal (bitumen coal)	t CO_2eq/TJ coal mined (with CH_4 GWP of 25 times that of CO_2 over 100 years)							
Belgium	0.515	0.666	0.725	0.268	0.401	0.056	8.840	3.105	4.657	1.078
Bulgaria	0.165	0.600	2.161	0.795	1.192	0.174	6.112	2.133	3.200	0.779
Czech Rep.	0.301	0.435	1.007	0.246	0.665	0.095	9.649	2.234	6.040	1.375
Estonia	0.200	n.a.	1.867	0.690	1.033	0.144	n.a.	n.a.	n.a.	n.a.
France	0.409	0.631	0.913	0.337	0.505	0.070	9.330	3.277	4.915	1.138
Germany	0.212	0.583	0.156	0.008	0.012	0.135	7.095	2.359	3.690	1.045
Greece	0.130	n.a.	3.739	1.408	2.110	0.221	n.a.	n.a.	n.a.	n.a.
Hungary	0.335	0.348	1.114	0.412	0.617	0.086	10.316	3.301	4.951	2.063
Italy	0.250	0.641	1.493	0.552	0.826	0.115	8.587	2.987	4.480	1.120
Latvia	0.350	n.a.	1.067	0.394	0.590	0.082	n.a.	n.a.	n.a.	n.a.
Lithuania	0.350	n.a.	1.067	0.394	0.590	0.082	n.a.	n.a.	n.a.	n.a.
Poland	0.203	0.525	0.163	0.006	0.015	0.141	4.539	0.905	2.327	1.308
Romania	0.181	0.607	1.698	0.616	0.924	0.159	3.972	1.381	2.071	0.520
Slovakia	0.301	n.a.	1.240	0.459	0.686	0.095	n.a.	n.a.	n.a.	n.a.
Slovenia	0.312	0.620	1.197	0.442	0.662	0.092	5.790	1.853	2.779	1.158
Spain	0.174	0.539	0.788	0.249	0.374	0.165	3.528	1.004	1.505	1.019
United Kingdom	0.200	0.604	1.867	0.517	1.207	0.144	6.616	1.982	4.195	0.439

3.2.2 Oil and gas production and processing

Extraction of crude oil and natural gas gives rise to CH_4 emissions, partly as a result of intended flaring or venting of associated gas for security reasons and partly due to unintended leakage of fugitive emissions, which occur along the whole production process from well head to upgrading and storage (IPCC, 2006, Vol.2, Section 4.2). Associated gas is a gas compound mainly consisting of CH_4, which is released as oil or natural gas is pumped to the surface. For security reasons, the associated gas needs to be released and is therefore flared off or simply vented. Alternatively, the associated gas can be recovered and utilized for energy purposes provided there is an infrastructure present to transport the recovered gas to consumers.

Emissions from venting and flaring of associated gas are calculated separately for fugitive emissions and unintended leakage. Total emissions from oil and gas production are the sum of venting, flaring and leakage emissions:

$$E_{its} = E_{its}^{venting} + E_{its}^{flaring} + E_{its}^{leakage} \tag{13}$$

Venting emissions from production of oil and gas, respectively, are calculated as:

$$E_{it;oil}^{venting} = A_{it}^{oil} * 20 * (1 - r_i) * \left(c_i a_i^{conv} v_i^{conv} + (1 - c_i) a_i^{heavy} v_i^{heavy}\right) \tag{14}$$

$$E_{it;gas}^{venting} = A_{it}^{gas} * 20 * a_i^{gas} (1 - r_i) v_i^{gas} \tag{15}$$

where $A_{it}^{oil;gas}$ is energy content of crude oil or dry gas produced in country *i* in year *t*,

20	20 kt CH_4/PJ conversion of energy content to amount of CH_4,
c_i	fraction of conventional oil (as opposed to heavy oil) produced,
$a_i^{conv}, a_i^{heavy}, a_i^{gas}$	are associated gas as fractions of the total energy content of conventional, heavy oil, or gas produced in year *t*,
r_i	is the fraction of associated gas recovered for utilization or reinjection in year *t*, and
$v_i^{conv}, v_i^{heavy}, v_i^{gas}$	are fractions of unrecovered associated gas that is vented (as opposed to flared).

Amounts of associated gas flared are calculated as the residual when the sum of the amounts of associated gas recovered/reinjected (*rec*) and vented (*vented*) are subtracted from the total amount of associated gas generated (*total*), i.e.,

$$E_{it}^{flaring} = 0.02 * \left[\text{Totalassgas-assgasreinj. orrecovered-assgasvented} \right] \tag{16}$$

Combustion emissions from flaring are derived assuming two percent incomplete combustion of CH_4 from flares (Johnson and Kostiuk, 2002).

Country-specific information for the year 2005 on amounts of associated gas and the fraction of associated gas reinjected or recovered are taken from EIA (2014) International Energy Statistics and used as starting point for emission estimates. From EIA (2015) Country Analysis Briefs, types of hydrocarbon produced are identified, i.e. conventional crude oil, heavy crude oil (API gravity <22.3°), oil sands and natural gas, as well as the fraction of offshore production. For gas production only two measurement results have been found for the fraction of associated gas to the energy content of gas produced. These are 0.03 percent for Canada (Johnson and Coderre, 2011), which is adopted as representative also for EU countries.

Measurement data on unrecovered associated gas vented as opposed to flared from oil and gas wells are extremely rare and no such measurements from European oil and/or gas wells have been found in published sources. We therefore resort to the use of direct measurements published by Johnson and Coderre (2011) measured for all of the over 18000 oil and gas wells active in the province of Alberta 2002 to 2008 and specified for different types of hydrocarbons produced (i.e., conventional or heavy oil and conventional natural gas). The results of the Canadian measurements are presented in Table 7 and the last row shows the fraction of unrecovered associated gas that is vented instead of flared. The factors presented in this last row have been adopted in the estimations for EU-28 on the fraction of unrecovered associated gas that is vented instead of flared. Note that the assumptions on the total associated gas generated, recovered and reinjected are country-specific and taken from EIA (2015).Finally, by adjusting the country-specific recovery rate, the estimated volumes of associated gas vented and flared were calibrated to match the total volumes of associated gas flared with the volumes of gas flared estimated from satellite images of gas flares (NOAA, 2011). The resulting derived emission factors for venting of associated gas are presented in Table 8.

Table 7: Recovery, venting and flaring from oil and gas wells in the province of Alberta 2002-2008. Adapted from Johnson and Coderre (2011).

		Conventional oil	Heavy oil	Natural gas
Associated gas	% of production	35.5%	5.1%	0.03%
Recovered/ reinjected	% of associated gas	97.1%	85.8%	0%
Flared		2.1%	1.7%	60%
Vented		0.8%	12.4%	40%
Sum		100%	100%	100%
Vented	% of flared/vented	29.1%	87.7%	40%

Maximum technically feasible reduction of CH_4 emissions from oil and gas production is defined such that all countries are assumed able to recover and utilize at least 95 percent of the associated gas generated. As shown in Table 8, most EU countries are already recovering almost 95% or more. Hence, the additional potential for mitigation of methane emissions through extending recovery rates for associated gas are limited. Costs are taken from OME (2001). Further details on emission estimations and costs can be found in the Supplement of Höglund-Isaksson (2012).

Table 8: Assumptions for deriving emission factors for CH_4 venting, flaring and unintended leakage from oil and gas production in EU production countries.

	Types of crude oil produced as fraction of total production (EIA, 2010)		Fraction offshore production (EIA, 2010)	Oil production: venting and unintended leakage			Gas production: venting and unintended leakage		Oil and gas production: methane from inefficient combustion of gas flares						
				Recovery/ reinjection of associated petroleum gas (calibrated to satellite images of gas flares)	Implied emission factor: venting of associated gas	Implied emission factor: unintended leakage (IPCC, 2006, Vol.2, Table 4.2.4)	Implied emission factor: venting of associated gas	Implied emission factor: unintended leakage (IPCC, 2006, Vol.2, Table 4.2.4)	Derived bcm associated gas flared from both oil and gas production				Estimates from satellite image of gas flares (NOAA, 2010)		Implied emission factor: flaring of associated gas (98% combustion efficiency, 86 vol% CH_4)
	Conventional oil	Heavy oil		%	kt CH_4/PJ oil produced		kt CH_4/PJ gas produced		2005		2010		2005	2010	kt CH_4/PJ gas flared
Country									bcm	PJ	bcm	PJ	bcm	bcm	
Austria	100%	0%	0%	94.1%	0.078	0.060	0.00194	0.06	0.012	0.565	0.012	0.564	n.a.	n.a.	0.2892
Bulgaria	100%	0%	0%	94.1%	0.078	0.060	0.00194	0.06	0.001	0.032	0.001	0.032	n.a.	n.a.	0.2892
Croatia	100%	0%	0%	94.1%	0.078	0.060	0.00194	0.06	0.016	0.699	0.013	0.593	n.a.	n.a.	0.2892
Cyprus[a]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.00194	0.06	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.2892
Czech Republic	100%	0%	0%	94.1%	0.078	0.060	0.00194	0.06	0.005	0.211	0.003	0.123	n.a.	n.a.	0.2892
Denmark	100%	0%	100%	96.9%	0.040	0.000015	0.00194	0.000001	0.145	6.696	0.087	3.983	0.172	0.084	0.2892
France	100%	0%	80%	94.1%	0.078	0.012	0.00194	0.00396	0.015	0.692	0.013	0.586	n.a.	n.a.	0.2892
Germany	100%	0%	0%	99.0%	0.013	0.060	0.00194	0.06	0.005	0.188	0.004	0.145	n.a.	n.a.	0.2892
Greece	100%	0%	0%	99.0%	0.013	0.060	0.00194	0.06	0.0002	0.011	0.0002	0.009	n.a.	n.a.	0.2892
Hungary	100%	0%	0%	93.6%	0.084	0.060	0.00194	0.06	0.016	0.717	0.002	0.087	n.a.	n.a.	0.2892
Ireland	100%	0%	0%	n.a.	n.a.	n.a.	0.00194	0.06	0.0001	0.004	0.0001	0.003	n.a.	n.a.	0.2892
Italy	100%	0%	0%	94.1%	0.078	0.060	0.00194	0.06	0.086	3.942	0.072	3.291	n.a.	n.a.	0.2892
Lithuania	100%	0%	0%	94.1%	0.078	0.060	0.00194	0.06	0.003	0.141	0.001	0.064	n.a.	n.a.	0.2892
Netherlands	100%	0%	100%	99.0%	0.013	0.000015	0.00194	0.000001	0.015	0.491	0.017	0.602	0.0093	n.a.	0.2892
Poland	100%	0%	0%	91.6%	0.110	0.060	0.00194	0.06	0.017	0.780	0.013	0.584	n.a.	n.a.	0.2892
Romania	100%	0%	0%	91.6%	0.110	0.060	0.00194	0.06	0.101	4.647	0.018	0.793	0.103	0.019	0.2892
Slovakia	100%	0%	0%	91.6%	0.110	0.060	0.00194	0.06	0.001	0.033	0.007	0.327	n.a.	n.a.	0.2892
Slovenia	100%	0%	0%	n.a.	n.a.	n.a.	0.00194	0.06	0.000004	0.0002	0.000005	0.0002	n.a.	n.a.	0.2892
United Kingdom	100%	0%	100%	92.1%	0.052	0.000015	0.00194	0.000001	1.645	75.773	0.997	45.930	1.643	0.993	0.2892

a Cyprus may start natural gas production in the future.

Fugitive CH_4 emissions from unintended leakage during oil and gas production are estimated separately from fugitive emissions from venting and flaring of associated gas. Unintended leakage is usually irregular and therefore highly uncertain. In GAINS, fugitive leakage emissions from oil and gas production are calculated as follows:

$$E^{leakage}_{it;oil} = A^{oil}_{it} * \left(\gamma_i ef^{oil}_{offshore} + p_i ef_{oilsand} + \left(1-\gamma_i - p_i\right)\left(\left(1-c_i\right) ef^{heavy}_{onshore} + c_i ef^{conventional}_{onshore}\right)\right) \tag{17}$$

$$E^{leakage}_{it;gas} = A^{gas}_{it} * \left(\gamma_i ef^{gas}_{offshore} + \left(1-\gamma_i\right) ef^{gas}_{onshore}\right) \tag{18}$$

where $A_{i\,t}$	is the energy content of marketable oil (or gas) produced in country *i* in year *t*,
γ_i	is the fraction of oil (or gas) produced offshore,
$\mathrm{ef}^{\mathrm{oil;gas}}_{\mathrm{offshore}}$	*is the IPCC default emission factor for offshore oil production,*
p_i	is the fraction of oil produced from oilsands,
$ef_{oilsand}$	is the IPCC default emission factor for oil production from oilsands,
c_i	is the fraction of conventional oil produced,
$\mathrm{ef}^{\mathrm{heavy}}_{\mathrm{onshore}}$	is the IPCC default emission factor for heavy oil production,
$\mathrm{ef}^{\mathrm{conv}}_{\mathrm{onshore}}$	is the IPCC default emission factor for conventional oil production.
$\mathrm{ef}^{\mathrm{gas}}_{\mathrm{offshore}}$	is the IPCC default emission factor for offshore gas production,
$\mathrm{ef}^{\mathrm{gas}}_{\mathrm{onshore}}$	is the IPCC default emission factor for onshore gas production.

GAINS uses IPCC (2006, Vol.2, Tables 4.2.4 and 4.2.5) default emission factors as specified separately for developed countries and developing/transitional countries. For developed countries, the median of the emission factor range given by IPCC is used, while for developing/transitional countries the range is usually wide and therefore a general assumption is made about double factors compared with developed countries. Adopted fugitive emission factors and IPCC ranges for default emission factors are presented in Table 9.

There are several cost-effective and low cost options available to reduce unintended leakage during extraction of oil and natural gas. For an exhaustive list, see USEPA (2011a). In GAINS, this option is defined as extending leakage control in developing countries to the standard currently observed in developed countries. This means cutting emissions in developing countries to the standard currently observed for developed countries and no further mitigation potential in developed countries. As all EU countries are considered developed in this context, there is no further reduction of unintended leakage from oil and gas production considered possible in the EU.

Recently a few EU countries have shown an interest in exploring the possibilities for large-scale extraction of shale gas. According to EIA (2011) some EU countries hold considerable reserves of technically recoverable shale gas. A recent survey by AEAT (2012) of the current knowledge of CH_4 emissions from shale gas extraction shows that uncertainty in emissions is still very high. The PRIMES (2016) Reference scenario for energy does not include shale gas extraction in the future projections. Therefore all CH_4 emissions from future gas production in the EU are in this scenario estimated using emission factors for conventional gas extraction.

Table 9: Default emission factors for unintended fugitive emissions from oil and gas production used in GAINS and in comparison with IPCC (2006, Vol.2, Tables 4.2.4 and 4.2.5).

		Developed countries		**Developing/transitional countries**	
		GAINS	**IPCC (2006) range**	**GAINS**	**IPCC (2006) range**
		kt CH_4/PJ	**kt CH_4/PJ**	**kt CH_4/PJ**	**kt CH_4/PJ**
Oil production	Conventional oil on-shore	0.06	0.00004-0.094	0.12	0.00004-1.5
	Heavy oil on-shore	0.1863	0-0.3726	0.3726	0.1863-3.066
	Conventional and heavy oil off-shore	0.000015	0-0.00003	0.000015	0.000013-0.00013
	Oilsands	0.0542	0.0135-0.095	0.0542	0.018-0.135
Gas production	Natural gas on-shore	0.06	0-0.12	0.12	0.1-2.15
	Natural gas off-shore	0.00974	0-0.0195	0.00974	0.0058-0.034

3.2.3 Crude oil transportation and refining

CH_4 emissions from oil refinery and transport are fugitive emissions related to evaporation losses from storage, filling and unloading activities as well as fugitive leaks (IPCC, 2006, Vol.2, p. 4.34). The IPCC (2006, Vol.2, pp.4.52-4.61) 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 (PRIMES, 2015). Since it is not possible to find systematic 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, to calculate emissions from this source the activity data used is amount of oil refined combined with IPCC default emission factors for the sum of oil refined and transported:

$$E_{it} = \sum_{m} \left[A_{it} * \left(ef^{refined} + ef^{transported} \right) * \left(1 - remeff_{m} \right) * Appl_{itm} \right], \tag{19}$$

where	A_{it}	is amount of oil refined in country *i* in year *t*,
	$ef^{refined}$	is the IPCC default emission factor for oil refined,
	$ef^{transported}$	is the IPCC default emission factor for oil transported,
	$remeff_{im}$	is the removal efficiency of technology m, and
	$Appl_{itm}$	is the application rate of technology *m* to emissions in country *i* in year *t*.

IPCC default emission factors for this sector are presented in Table 10 together with GAINS assumptions for no control and controlled emission factors.

The maximum technically feasible reduction is defined by the sum of the lower range IPCC default emission factor for oil refined and a fifty percent reduction in leakage emissions from oil transportation. This corresponds to the relative reduction in leakage emissions considered technically feasible for oil and gas production. Costs for these measures are taken from AEAT (1998).

Table 10: Default emission factors for CH_4 emissions from oil refinery and transport. Source: Derived from IPCC (2006, Vol.2, pp.4.52-4.61)

Emission source	**GAINS**		**IPCC (2006)**	**unit**
	No control	**Control**		
Fugitive emissions at oil refinery	0.0455	0.0029	0.0029 to 0.0455	kt CH_4/Mt oil refined
Fugitive emissions from transport by pipeline	0.0049	0.00245	0.0049	kt CH_4/Mt oil transported by pipeline
Fugitive emissions from transport by tanker, truck and rail cars	0.0225	0.0166	0.0225	kt CH_4/Mt oil transported by tanker/truck
All sources	0.0729	0.0166	0.0303 to 0.0729	kt CH_4/Mt oil refined

3.2.4 Long-distance natural gas transportation

Leakage of CH_4 emissions from long-distance gas pipelines arises for several reasons, e.g., untight compressor seals and valves or because pipelines are flushed with gas during start-ups (Ecofys, 1998). For Tier 1 estimations the IPCC guidelines (2006, Vol. 2, p.4.48-4.62) recommend the use of default emission factors per million m^3 of marketable gas. We find it problematic to use the IPCC default factors here as emissions from gas transmission are likely to be influenced by both the volume of gas transported, the distance the gas is transported as well as pipeline pressure and maintenance. Leakage rates are therefore likely to be specific to the circumstances prevalent in each country and pipeline system. For this reason, GAINS uses country-specific volumes of gas transported and leakage rates as reported to UNFCCC-CRF (2015) whenever such information is available. Table 11 provides an overview of the data compiled in GAINS for deriving amounts of gas transported and leakage rates for years 2005 and 2010 in EU-28 countries. Reported leakage rates range from 0.01% of gas transported in Denmark, Finland, Netherlands, Spain and Sweden to 0.2% in Lithuania. The former leakage rate is adopted as the controlled emission factor, representing the lowest technically feasible leakage rate, while the latter is defining the no control emission factor. The percent control implemented is a reflection of the leakage rate reported by countries (UNFCCC-CRF, 2015).

For future years, activity data is assumed to grow proportionally with country gas consumption while leakage rates of 2010 are maintained into the future.

Costs for reducing methane emissions from gas transmission pipelines reflect the cost of replacing, retrofitting and maintenance of high-bleed pneumatics as estimated by USEPA (2006).

Table 11: Derivation in GAINS of methane emission factors for high-pressure long-distance gas transmission pipelines in 2005 and 2010.

	Derivation in GAINS of CH4 emissions from high-pressure long-distance gas transmission pipelines in 2005 and 2010														
	Amount of gas transported through on-line pipelines			Leakage rate consistent with UNFCCC-CRF (2015) when 50 MJ/kg CH4		Reported emissions UNFCCC-CRF (2015)		implied EF UNFCCC-CRF (2015)		No control emission factor when leakage rate is 0.2%	Controlled emission factor when leakage is 0.01%	Control application corresponding to implied ef reported in UNFCCC-CRF (2015)		GAINS emission estimates (2015)	
	2005	2010	Source activity data	2005	2010	2005	2010	2005	2010	2005	2010	2005	2010	2005	2010
Country	PJ			% of PJ gas transmitted		kt CH4		ktCH4/PJ		ktCH4/PJ		% of max control		kt CH4	
Austria	1300	1336	TAG (2007)	0.013%	0.012%	3.32	3.26	0.0026	0.0024	0.04	0.002	98.5%	98.8%	3.32	3.26
Belgium	612	701	UNFCCC-CRF (2015)	0.022%	0.037%	2.70	5.17	0.0044	0.0074	0.04	0.002	93.6%	93.6%	2.70	3.10
Bulgaria	574	450	UNFCCC-CRF (2015)	0.037%	0.037%	4.23	3.32	0.0074	0.0074	0.04	0.002	85.8%	85.8%	4.23	3.32
Croatia	111	123	UNFCCC-CRF (2015)	0.140%	0.140%	3.10	3.46	0.0281	0.0281	0.04	0.002	31.4%	31.4%	3.10	3.46
Cyprus	0	0	UNFCCC-CRF (2015)	n.a	n.a	NO	NO	n.a	n.a	0.04	0.002	n.a	n.a	n.a	n.a
Czech Republic	1389	1357	UNFCCC-CRF (2015)	0.049%	0.056%	13.65	15.08	0.0098	0.0111	0.04	0.002	76.0%	76.0%	15.4	15.1
Denmark	318	313	UNFCCC-CRF (2015)	0.0022%	0.00042%	0.14	0.03	0.0004	0.00008	0.04	0.002	100%	100%	0.64	0.63
Estonia	12	11	GAINS (2013)	n.a	n.a	NO	NO	n.a	n.a	0.04	0.002	n.a	n.a	n.a	n.a
Finland	151	160	UNFCCC-CRF (2015)	0.033%	0.010%	1.0	0.31	0.0067	0.0019	0.04	0.002	100%	100%	0.30	0.32
France	2066	2015	Gas consumed PRIMES (2015)	0.058%	0.063%	23.96	25.31	0.0116	0.0126	0.04	0.002	72.2%	72.2%	26.0	25.3
Germany	3224	3079	GAINS (2013)	0.174%	0.201%	112	124	0.0347	0.0403	0.04	0.002	13.8%	13.8%	112.0	107.0
Greece	116	160	GAINS (2013)	0.037%	0.036%	0.85	1.15	0.0073	0.0072	0.04	0.002	86.1%	86.4%	0.85	1.15
Hungary	594	493	GAINS (2013)	0.038%	0.038%	4.48	3.74	0.0075	0.0076	0.04	0.002	85.3%	85.3%	4.50	3.74
Ireland	30	40	GAINS (2013)	n.a	n.a	n.a	n.a	n.a	n.a	0.04	0.002	n.a	n.a	n.a	n.a
Italy	3242	3116	UNFCCC-CRF (2015)	0.052%	0.061%	33.59	38.23	0.0104	0.0123	0.04	0.002	73.0%	73.0%	39.8	38.2
Latvia	12	13	GAINS (2013)	0.024%	0.014%	0.06	0.04	0.0049	0.0029	0.04	0.002	92.4%	97.7%	0.06	0.04
Lithuania	159	155	Gas consumed PRIMES (2015)	0.198%	0.214%	6.30	6.65	0.0397	0.0429	0.04	0.002	0.9%	0.9%	6.30	6.15
Luxembourg	49	50	UNFCCC-CRF (2015)	0.065%	0.065%	0.64	0.65	0.0130	0.0131	0.04	0.002	70.9%	70.9%	0.64	0.65
Malta	0	0	UNFCCC-CRF (2015)	n.a	n.a	n.a	n.a	n.a	n.a	0.04	0.002	n.a	n.a	n.a	n.a
Netherlands	3008	3508	UNFCCC-CRF (2015)	0.0104%	0.0092%	6.25	6.48	0.002	0.002	0.04	0.002	99.8%	100%	6.25	7.02
Poland	512	536	UNFCCC-CRF (2015)	0.070%	0.070%	7.15	7.48	0.014	0.014	0.04	0.002	68.5%	68.5%	7.15	7.48
Portugal	247	314	GAINS (2013)	0.109%	0.094%	5.39	5.88	0.022	0.019	0.04	0.002	47.8%	56.0%	5.39	5.88
Romania	576	452	GAINS (2013)	0.095%	0.092%	11.00	8.31	0.019	0.018	0.04	0.002	55.0%	56.8%	11.0	8.31
Slovakia	2803	2477	UNFCCC-CRF (2015)	0.063%	0.063%	35.47	31.34	0.013	0.013	0.04	0.002	72.0%	72.0%	35.5	31.3
Slovenia	43	40	UNFCCC-CRF (2015)	0.059%	0.056%	0.51	0.45	0.012	0.011	0.04	0.002	74.4%	75.9%	0.51	0.45
Spain	1222	1306	UNFCCC-CRF (2015)	0.0046%	0.0033%	1.11	0.86	0.0009	0.0007	0.04	0.002	100%	100%	2.44	2.61
Sweden	90	103	Gas consumed PRIMES (2015)	0.00015%	0.00033%	0.003	0.01	0.00003	0.00007	0.04	0.002	100%	100%	0.18	0.21
United Kingdom	2347	2205	UNFCCC-CRF (2015)	0.017%	0.015%	8.11	6.59	0.0035	0.0030	0.04	0.002	96.2%	97.4%	8.11	6.59

3.2.5 Consumer gas distribution networks

CH_4 emissions from gas use come from leakage in consumer distribution networks and during end-use by consumers. The activity data is amount of gas consumed by sector as provided by the PRIMES (2015) model for the EU-28 countries. IPCC (2006, Vol.2, Tables 4.2.4 and 4.2.5) provide Tier 1 default emission factors for developed and developing/transitional countries. These correspond to default leakage rates of 0.15 and 0.35 percent, respectively, with uncertainty ranges up to ± 500 percent. Because of the wide uncertainty range of the IPCC default factors, we have used country-specific leakage rates as reported for years 2005 and 2010 to UNFCCC-CRF (2015) for EU-28 countries.

Dennett and Vallender (2011) provide measurement results for the UK on how the leakage from residential mains compares to leakage from mains supplying larger users (power plants and industry). The UK measurements show that total gas losses from gas distribution grids in the UK are 0.57 percent of throughput, with 80 percent from low pressure mains systems supplying small consumers. This translates into losses from residential and non-residential sectors of 1 and 0.23 percent of gas consumption, respectively. The same proportional split (i.e., 23%) between losses in residential and non-residential sectors is assumed in GAINS for all EU countries.

A technically feasible range for leakage from gas distribution mains in the EU-28 was determined from the range of leakage reported by countries to UNFCCC-CRF (2015) and maintaining the assumption from the UK measurements that leakage from mains supplying larger users like power plants and industry is 23% of the leakage from mains supplying residential consumers. This corresponds to a leakage rate from 0.003% to 1.15% for residential distribution mains and from 0.0007% to 0.26% for non-residential distribution mains. The percent control implemented is a reflection of the leakage rate reported by countries (UNFCCC-CRF, 2015).

For future years emissions are driven by the development in gas consumption by sector as provided by the PRIMES (2015) model, leakage rates remain constant unless there are efforts made to upgrade the network (see below).

CH_4 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 typically reduces almost all fugitive emissions from this source (AEAT, 1998). In the reference scenario, the current state of gas distribution networks in the EU member states was derived from the relative leakage rates reported by countries to the UNFCCC (2015) and displayed in Table 12. The average leakage rate reported for Denmark has been used as benchmark, as the Danish gas distribution network was first introduced in the mid-1980s and is of relatively recent date compared with other European countries (Aarhus Universitet, 2015). The level of control installed in 2005 and 2010 is derived by relating the reported leakage rates to the benchmark leakage rate as shown in Table 12. The control level of 2010 remains constant in future years in the Reference scenario. Mitigation costs for replacement gas distribution networks are taken from AEAT (1998).

Table 12: Derivation of GAINS methane emission factors and implemented control for fugitive emissions from gas distribution networks.

	CH4 from gas distribution as reported by member states to UNFCCC-CRF (2015)		GAINS estimation of CH4 emissions from gas distribtuion networks											
			Residential		Non-residential		Control implemented		Residential	Non-residential	Total	Residential	Non-residential	Total
			No control emission factor (leakage: 1.15%)	Controlled emission factor (leakage: 0.003%)	No control emission factor (leakage: 0.26%)	Controlled emission factor (leakage: 0.0007%)	% of max control (same for residential and non-residential)		CH4 emissions estimated in GAINS from gas distribution					
	2005	2010					2005	2010	2005			2010		
Country	kt CH4		kt CH4/PJ						kt CH4			kt CH4		
Austria	1.63	1.58	0.23	0.0006	0.0529	0.000138	95.8%	95.8%	0.89	0.74	1.63	0.89	0.70	1.6
Belgium	16.5	15.5	0.23	0.0006	0.0529	0.000138	79.2%	82.0%	11.2	5.36	16.5	10.7	4.80	15.5
Bulgaria	3.81	3.07	0.23	0.0006	0.0529	0.000138	60.5%	56.9%	0.32	3.49	3.81	0.64	2.43	3.1
Croatia	1.55	1.70	0.23	0.0006	0.0529	0.000138	86.0%	86.4%	0.96	0.59	1.55	1.03	0.67	1.7
Cyprus	n.a.	n.a.	0.23	0.0006	0.0529	0.000138	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Czech Republic	17.9	18.0	0.23	0.0006	0.0529	0.000138	64.5%	63.7%	12.8	5.06	17.9	13.63	4.37	18.0
Denmark	0.24	0.14	0.23	0.0006	0.0529	0.000138	99.1%	99.6%	0.11	0.13	0.24	0.07	0.07	0.1
Estonia	1.24	0.87	0.23	0.0006	0.0529	0.000138	59.7%	61.2%	0.38	0.86	1.24	0.35	0.52	0.9
Finland	1.58	1.14	0.23	0.0006	0.0529	0.000138	89.9%	92.7%	0.08	1.50	1.58	0.06	1.08	1.1
France	13.4	15.8	0.23	0.0006	0.0529	0.000138	95.3%	94.4%	10.6	2.81	13.4	12.7	3.12	15.8
Germany	172	132	0.23	0.0006	0.0529	0.000138	60.9%	70.8%	123	48.8	172	95.9	36.0	132
Greece	0.95	1.49	0.23	0.0006	0.0529	0.000138	89.7%	86.1%	0.15	0.80	0.95	0.54	0.95	1.5
Hungary	19.2	18.8	0.23	0.0006	0.0529	0.000138	76.2%	70.9%	14.9	4.31	19.2	14.4	4.38	18.8
Ireland	2.41	1.49	0.23	0.0006	0.0529	0.000138	85.7%	92.9%	1.26	1.14	2.41	0.81	0.67	1.5
Italy	202	181	0.23	0.0006	0.0529	0.000138	45.1%	49.2%	140	61.9	202	135	46.3	181
Latvia	0.48	0.48	0.23	0.0006	0.0529	0.000138	92.4%	91.9%	0.16	0.32	0.48	0.21	0.27	0.5
Lithuania	4.18	4.98	0.23	0.0006	0.0529	0.000138	57.9%	50.6%	0.87	3.31	4.18	1.22	3.76	5.0
Luxembourg	1.47	1.50	0.23	0.0006	0.0529	0.000138	71.4%	73.3%	0.90	0.57	1.47	0.99	0.51	1.5
Malta	n.a.	n.a.	0.23	0.0006	0.0529	0.000138	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Netherlands	13.1	12.8	0.23	0.0006	0.0529	0.000138	94.1%	94.8%	8.36	4.70	13.1	8.68	4.12	12.8
Poland	16.4	17.1	0.23	0.0006	0.0529	0.000138	76.5%	77.8%	11.1	5.25	16.4	12.0	5.14	17.1
Portugal	12.3	6.53	0.23	0.0006	0.0529	0.000138	3.9%	55.7%	3.15	9.16	12.3	2.14	4.40	6.5
Romania	31.3	23.6	0.23	0.0006	0.0529	0.000138	50.4%	55.9%	14.9	16.3	31.3	13.7	9.93	23.6
Slovakia	8.14	6.71	0.23	0.0006	0.0529	0.000138	75.8%	77.4%	5.54	2.60	8.14	4.84	1.87	6.7
Slovenia	1.26	1.17	0.23	0.0006	0.0529	0.000138	60.5%	61.1%	0.47	0.78	1.26	0.52	0.65	1.2
Spain	18.0	21.5	0.23	0.0006	0.0529	0.000138	82.7%	83.2%	7.46	10.6	18.0	10.7	10.8	21.5
Sweden	2.89	1.86	0.23	0.0006	0.0529	0.000138	52.8%	72.3%	0.86	2.03	2.89	0.57	1.28	1.9
United Kingdom	225	190	0.23	0.0006	0.0529	0.000138	56.9%	62.8%	159	66	225	141	50	190
EU-28	788	681							529	259	788	483	198	681

3.2.6 Combustion in stationary sources

During combustion processes CH_4 emissions are released due to incomplete oxidation of fossil and biofuels. Activity data for combustion emissions from power plants is the energy content of the fuel used, which is taken from the PRIMES (2015) Reference scenario. Emission factors are differentiated for different sectors and type of fuel combusted. For industry and power plants, CH_4 emission factors were taken from IPCC (2006). For residential boilers, CH_4 emission factors are differentiated for different types of boilers and taken from Delmas (1994), Johansson et al. (2004), Kjällstrand and Olsson (2004) and Olsson and Kjällstrand (2006).

No specific mitigation options have been identified for CH_4 emissions from combustion sources.

3.2.7 Combustion in mobile sources

Incomplete combustion in mobile sources gives rise to CH_4 emissions. Activity data is amount of fuel used, which is adopted from the PRIMES (2015) model for each vehicle type as specified in Table 3. GAINS uses default emission factors from the European transport emission database COPERT (EMISIA, 2013 http://www.emisia.com/copert/General.html). Emission factors are specified by vehicle category, type of fuel used and the emission control standard of the vehicles (EURO I to EURO VI).

3.3 Agriculture sector

3.3.1 Livestock

3.3.1.1 Enteric fermentation and manure management emissions

CH_4 emissions from livestock emerge from enteric fermentation during the digestive process in the stomachs of ruminants. When the organic content in livestock manure decomposes, emissions of CH_4 and N_2O are released. CH_4 release occurs when manure is handled under anaerobic conditions, while the formation of N_2O requires aerobic conditions with access to oxygen.

Emissions from livestock are estimated as the sum of the emission types *n* (enteric fermentation and/or manure management) for a certain animal type *s* in country *i* and year *t*:

$$E_{its} = \sum_{lmns} \left[A_{itls} * ef_{ilns}^{NOC} * (1 - remeff_{mns} * h_{itsm}) * Appl_{itslm} \right], \qquad (21)$$

where A_{itls} is the number of animals of type *s* in country *i* and year t, with manure management *l* (solid or liquid),

ef_{is}^{NOC} is the no control emission factor for emission type *n*, animal type *s* in country *i* and subject to manure management *l*,

$remeff_{mns}$ is the removal efficiency of technology *m* when applied to emissions of type *n* and animal type *s*,

h_{itsm} is a factor correcting for application limitations of technology *m*, e.g., indoor housing rates for feed options or large farm rate for farm-scale anaerobic digestion,

$Appl_{itslm}$ is the application rate of technology m to animal type s with manure management l, in country i and year t.

GAINS estimates CH_4 emissions separately for the animal types dairy cows, non-dairy cattle, pigs, poultry, sheep and goats, buffaloes, and horses. For dairy cows, non-dairy cattle and pigs, animal numbers are further split by whether animals are subject to liquid or solid manure management. The split in the number of animals by liquid or solid manure management is stored in the GAINS model and was recently reviewed by member state experts during IIASA consultations for the proposal of the EU Thematic Strategy for Air Pollution (TSAP) in 2014. Activity data is number of animals by type. The source for historical animal numbers for years 2005 and 2010 is EUROSTAT (2015), except for horses and buffaloes where FAOSTAT (2013) is the source. Projections are based on future trends in animal numbers as estimated by the CAPRI model (2016).

A recent improvement in the GAINS model is the split of animal categories dairy cows, non-dairy cattle, pigs, poultry, sheep and goats by five farm size classes, i.e., less than 15 livestock units (LSU), 15 to 50 LSU, 50 to 100 LSU, 100 to 500 LSU, and above 500 LSU. The source for data on historical farm-size distributions is EUROSTAT (2015). Projections for the future development of farm-size classes have been made applying a multi-nominal logistic function weighing in the development observed in historical years from 1990 onwards. The development of farm-size classes has implications for the development of the fractions of animals on liquid and solid manure management and on the future applicability of control technology options. Typically, over time more animals tend to move into the larger farm-size classes with liquid manure management and away from smaller farm-size classes with solid manure management.

Country-specific emission factors corresponding to the implied emission factors reported to UNFCCC-CRF (2015) for year 2010 were adopted for enteric fermentation and manure management emissions, respectively.

For dairy cows, both enteric fermentation emissions and manure management 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.,

$$ef_{it;cow}^{NOC} = ef_i^{animal} + ef_i^{milk} * \left(x_{it} - 3000\right) \tag{22}$$

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.

A linear relationship between the CH4 emissions per cow and the milk yield per cow was fitted from default emission factors per cow provided by IPCC (2006, Ch.10) for different world regions representing a range of average milk yield levels. Starting from country-specific implied emission factors reported to UNFCCC for year 2005, the derived linear relationship will determine the future emission pathway from the development in milk yield and animal numbers. Hence, as milk yield per cow increases CH_4 emissions per cow increase while emissions per kg milk produced decline when fewer animals are needed to produce the same amount of milk. Whether the overall effect on methane emissions is positive or negative will depend on the importance of the effect of increased methane emissions per animal relative the effect of declining animal numbers. The derived CH_4 emissions per kg milk produced at different average milk yield levels are well in line with the ranges estimated empirically for Germany between 1990 and 2010 (Piatkowski and Jentsch, 2013).

3.3.1.2 Enteric fermentation control options

3.3.1.2.1 Breeding

Breeding through selection offers several different ways to reduce enteric methane emissions from livestock. First, an increase in productivity per animal could mean that a smaller animal stock produces the same amount of produce with potentially lower methane emissions per unit of produce. Milk cow productivity has improved significantly in the EU over the past few decades. This is primarily the result of breeding leading to an increased use of high-producing cow types, e.g., Holsteins, in the stocks. If the increase in milk yield per cow means keeping smaller animal stocks to produce the same amount of milk, then methane emissions per unit of milk produced are likely to fall. In many EU countries, methane emissions per unit of milk produced may, however, not have fallen as a consequence of increased milk yield, because the tremendous increase in milk yield in many countries has been accompanied by an increased fraction of unproductive animals in the stocks due to poorer health and fertility of the high-productive cow breeds (see e.g., Lovett et al., 2006; Berglund, 2008; Bell et al., 2011). Highly productive cows are effective in converting feed energy into milk, but may as a consequence lack enough energy reserves to maintain health and reproduction (Berglund, 2008). Many EU countries have seen falling reproductive performance of the milk cows as milk yield increased (Nyman et al., 2014; Nilforooshan et al., 2010; Nilforooshan et al., 2013; Evans et al., 2006), however, the breeding schemes in the Scandinavian EU countries have shown that it is possible through breeding for both productivity and reproduction traits, to achieve top level milk yield *and* preserved fertility and animal health (Berglund, 2008). Hence, to achieve lasting methane reductions per unit of milk produced, it is likely that breeding programs must aim at the dual objective of increasing milk yield while preserving animal health and fertility. This appears to be the case not only for animals fed on concentrates, but also for forage-fed and grazing animals (Bell et al., 2011; O'Brien et al., 2010). Preserved animal health and fertility is likely to better sustain profitability of the milk farmers in the long-run, as it is costly to keep and feed large fractions of unproductive animals in the stock (Evans et al., 2006). According to Bell et al. (2012) and the conclusions of the EU 7th Framework Programme "Animal change" project (Animal change, 2014), genetic improvement through breeding is likely to be a cost-effective measure as it achieves methane emission reductions that are cumulative and permanent. O'Brien et al. (2014a) estimate reduction potentials in 2020 from adoption of accelerated breeding schemes for Irish dairy cows at 555 kt CO2eq per year when using a lifecycle assessment method and by 596 kt CO_2eq per year when using the IPCC national inventory approach.[2] The mitigation cost is estimated at -519 and -483 €/tCO_2eq with respective methodology. There are no estimates available in the literature of what a dual objective breeding scheme could achieve in terms of methane reductions at an EU level. Several authors however mention that such a development would require large databases on the genetic variation to favorably capture the complex interactions of different positive genetic traits (De Haas et al., 2011; Berry and Crowley, 2013). In addition, time is needed for a careful selection process to run its course, often mentioned to at least 10 years (Knapp et al., 2014; De Haas et al., 2011).

Second, breeding can be used to enhance the feed efficiency in animals, which is likely to reduce methane emissions as methane production is essentially a loss of energy. Profitability in meat production systems is closely linked to the feeding costs, which makes it particularly interesting for financial and environmental reasons to use breeding to enhance feed efficiency in animals and simultaneously reduce methane emissions. Berry and Crowley (2013) show in a meta-analysis of 39 scientific publications that genetic variation in feed efficiency in cattle has a pooled heritability for residual feed intake (RFI) and feed conversion efficiency of 0.33 and 0.23, respectively (for cows, the corresponding heritability is much lower at 0.06 and 0.04, respectively). Hence, there appears to be scope for further improvements in feed efficiency through breeding in beef cattle, provided that large quantities of routinely collected feed intake information on individual animals become available (Berry and Crowley, 2013). The link between feed efficiency in cattle and methane emissions is expected. Nkrumah et al. (2006) linked the variation in RFI directly to variation in methane emissions. They found for 27 Canadian hybrid beef steers that methane production was 25% lower for low-RFI individuals than for high-RFI individuals. Hegarty et al. (2007) found among 66 Angus steers that methane emissions were lower for the most feed efficient animals (i.e., with the lowest RFI). The effect on methane emissions from selection for feed efficiency is likely to be the greatest for grazing ruminants, which includes dairy cows, non-dairy beef cattle and sheep (Animal Change, 2014). According to estimates by DEFRA (2012), 10 years of breeding on beef cattle in the UK using current approaches is expected to result in a cumulative increase in farmers' profits of 31 million pounds when measured over a twenty years period and reduce GHG emissions by 3%. Adding more selection indices to the traits currently targeted, is expected to increase profits further and extend the emission reduction potential to 10% below current emission levels.

Third, there is the possibility to use breeding to directly select for individual animals with low formation of methane in the rumen, thereby reducing enteric methane emissions per animal. De Haas et al. (2011) state that, on the basis of the existing genetic variation in Dutch dairy cows, it is theoretically possible to reduce enteric methane production per animal by selecting for more methane efficient individuals. This potential would correspond to enteric methane reductions in the order of 11 to 26% over 10 years. Although theoretically possible, realistic methane reduction rates will depend on several factors, e.g. the accuracy and intensity of selection, the number of records available, and the generation interval (De Haas et al., 2011). De Haas et al. call for an international effort to establish a reference database on genetic variation in dairy cows to be used for genomic selection.

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[2] It is not clear from the source from what baseline these emission reductions are estimated. According to the GAINS Reference 2013 estimates, Irish dairy cows are expected to emit 3383 kt CO_2eq in 2020. Hence, if we start from the GAINS baseline in 2020, the accelerated breeding option would reduce dairy cow emissions by 16 to 18%.

Fourth, breeding has the potential to reduce methane emissions if it is combined with different types of feed as different breeds appear to respond with different levels of enteric methane formation to different types of feed (Bell et al., 2012; Bell et al., 2010; Knapp et al., 2014; O'Brien et al., 2010). In addition to matching feed with the breed, Knapp et al. also mention the importance of optimizing management practices, which could otherwise limit the ability of the animals to reach their full genetic potential.

Finally, in addition to breeding through selection of traits, there are a number of reproductive technologies available that have the potential to reduce methane emissions (Hristov et al., 2013b). These include gender-selected semen, embryo transfer, and hormonal synchronization, which all have the potential to enhance the reproductive efficiency, thereby reducing the number of animals kept in the stock at a systems level. With fewer animals in the system, greenhouse gases are likely to decline per unit of output produced. Hristov et al. (2013b) estimate the methane mitigating effect of assisted reproductive technologies to between 3.5 to 5.5 percent.

We have here described a number of different ways through which breeding through selection and the use of reproductive technologies can achieve persistent reductions in system methane emissions from milk and meat production. The uncertainty of the long-term effects on systems methane emissions is high and difficult to assess with more certainty. At the same time, when taken together it is most likely that these options can offer future opportunities to reduce enteric methane emissions if policies are put in place which provide incentives for adoption of reproductive technologies and for large-scale breeding schemes that specifically target reductions in methane emissions. As a conservative estimate, we assume in GAINS that the combined mitigation effect from these types of options in 2030 is 10 percent of enteric methane emissions from dairy cows, non-dairy cattle and sheep. As a conservative estimate of the costs, and despite the estimates by DEFRA (2012) that farmers' profits are likely to increase due to enhanced productivity, we assume in the GAINS model that the measure is cost-effective (i.e., available at zero costs) in order to take into account also the costs of establishing a reference database on genetic information to enable successful breeding.

3.3.1.2.2 Feed management and feed additives

Changing animal diets or adding substances known to reduce methane formation in the rumen are possible methane mitigation options. Recent reviews from the FAO by Hristov et al. (2013a) and Gerber et al. (2013a) provide comprehensive information about the current state of knowledge with a global scope. Both reports provide limited, specific information for Europe. Gerber et al., provide information about the expected effect on mixed dairy systems in Western Europe of using lipids as feed additives and find it small (expected reduction in enteric fermentation emissions is 1.2% to 3.6%). Effects of different types of non-lipid additives or feed management options were, however, not evaluated for Western Europe by Gerber et al. (2013a).

Feed management options include mechanical ways to treat the feed to facilitate digestion, ways to combine different types of feed to minimize enteric methane formation, as well as precision feeding, which means very closely monitoring the timing and the feed mix supplied to the animals in order to optimize feeding against both economic and environmental parameters. As an effective feed management is important for the profitability of many European farmers, the scope for further reductions in methane emissions through improved efficiency in feed management is likely to be limited. There may, however, be some scope for mitigation from wider use of precision feeding (Dalgaard et al., 2011).

Knapp et al. (2014) review enteric fermentation methane mitigation measures for intensive dairy systems. They conclude that feeding and nutrition have modest reduction potential (2.5 to 15%) to mitigate enteric methane in intensive dairy operations in developed countries and that “To date, rumen modifiers other than nitrate have not shown sustained reductions in CH4/ECM”. Dalgaard et al. (2011) analyze possible measures to reduce GHG emissions in Danish agriculture to 2050. They estimate that a 50-70% reduction in Danish agricultural greenhouse gas emissions is achievable in 2050 relative the 1990 emission level. The contribution from different feed options to methane emission reductions is, however, limited to between 15 and 20% and would involve precision feeding. Results compiled by Hristov et al., (2013a) on the effectiveness of individual feed mitigation measures show a mixed bag with limited potential for intensive European livestock systems from feed management and lipid additives (due to already high efficiency with respect to these parameters in the systems), but with potential effects from some non-lipids additives e.g., nitrate, propionate precursors and phytogenic substances.

Nitrate as feed additive is reported to have significant negative effects on methane emissions, however, may also come with negative effects on animal health if the feeding is not closely monitored (Van Zijderveld et al., 2010, 2011b). Expected mitigation effects from propionate precursors as feed additives have been downplayed in recent studies, because effects shown in-vitro have not turned out to deliver in-vivo (e.g., Van Zijderveld et al., 2011b; Ungerfeld and Forster, 2011). Still, developments to bring a product based on propionate precursors to the market are on-going within the European “Clean Cow Project”, which claims a minimum 25% mitigation potential to be possible for dairy cows and with plans to launch the additive on the market in 2018 (DSM, 2014). Phytogenic substances have shown some promising results as inhibitors of enteric methane, however, more research is still needed (Flachowsky and Lebzien, 2012).

In contrast to the GAINS estimations of 2013 (Höglund-Isaksson et al., 2013) changes after the 2015 review means that we no longer include propionate precursors as a separate mitigation option due to the reasons mentioned in the previous paragraph. Instead, we make a broader category comprising reduction potentials from feed additives and/or changed feed management practices. Despite the inconclusive results and the stated needs for further research, we conclude that the list of (potentially) effective feed options is rather long and that research is vivid and continues. We therefore consider it likely that at least one or a few will be able to deliver some effect on methane emissions in the future. Hence, in addition to the effects of breeding mentioned above, we assume in GAINS that the combined mitigation effect in 2030 from different feed management changes and feed additives is 10% of enteric fermentation emissions in dairy cows and 5% of enteric fermentation emissions in non-dairy cattle and sheep during the time that animals are housed indoor. No effects on emissions from feed additives or feed management changes are accounted for during the time animals are kept outdoor. Information on the average number of days per year that animals spend indoor has been collected by animal category in the GAINS database during consultations with experts from EU member states, most recently during IIASA-member state consultations for the proposal of the EU Thematic Strategy for Air Pollution (TSAP) in 2014.

Costs will depend on the feed additive in question (e.g., nitrate-based additives are likely to be very cheap while additives based on propionate precursors are likely to be more expensive) and on the possibility and costs of effectively distributing the additive in the right dosage in order to avoid negative effects on animal health. DSM (2014) mention that for the launch in 2018 of a new feed additive, they are currently evaluating different options for dosage and distribution in order to offer a financially feasible mitigation option to farmers. With further technological development, we expect the launch of new additives on the market to be accompanied by a development in dosage technologies. With new climate policy incentives in place which effectively promotes the development of new technologies, we consider it feasible by 2030 to expect that new feed additives will become available on the market, and which are both effective in terms of reducing emissions and come at a financially feasible cost to farmers. In the absence of information on expected future costs of this option, we consider a financially and politically viable annual cost level to be about 10 Euros per head. This cost level corresponds to a marginal cost range of about 30 to 60 Euro/t CO_2eq when implemented for dairy cows and with higher marginal cost levels for non-dairy cattle and sheep.

3.3.1.3 Manure management option

Treatment of animal manure in anaerobic digesters (ADs) that generate biogas can be an efficient way to reduce methane emissions from manure handling at a low cost (Hristov et al., 2013b). The process has the advantage of not only reducing emissions, but also generating energy to be used on the farm or sold to external users, and at the same time produces an odor-free organic fertilizer, which can substitute the use of mineral fertilizers (Sommer et al., 2013).

The minimum electricity generation capacity of co-generation plants currently available on the market is 15 $kW_{electric}$ and requires at least 100 LSU (Pellerin et al., 2013). Hence, farm AD is likely to be economically infeasible for farms smaller than 100 LSU. In the GAINS model, farm-scale anaerobic digestion (AD) is assumed applicable to manure from dairy cows, non-dairy cattle and pigs kept in systems with liquid manure management on farms with at least 100 livestock units (LSU). It is further assumed that manure is only available for anaerobic digestion during the periods that animals are kept indoor. Information on the average number of days per year that animals spend indoor has been collected by animal category in the GAINS database during consultations with member state experts, most recently during IIASA-member state consultations for the proposal of the EU Thematic Strategy for Air Pollution (TSAP) in 2014. No potential for farm-scale anaerobic digestion is assumed for animals kept on farms smaller than 100 LSU, nor for animals in solid manure management systems, and nor for periods when animals are grazing outdoor.

An additional possible source of manure as input to anaerobic digesters is poultry excretion. This source of substrate has been excluded from this analysis because of its insignificance as a methane emissions source. Methane emissions from poultry manure, as reported by EU member states for year 2010 (UNFCCC, 2014), account for 4% of methane emissions from manure management and only 1% of agricultural methane emissions.

The amount of manure available for anaerobic digestion is derived from the average volatile solid excretion rate per animal per day reported by countries to the UNFCCC-CRF (2014) for year 2010. Given that volatile solids (VS) make up 80% of total solids (TS) in the manure and that the manure (or rather the slurry as it derives from liquid manure management systems) has a water content of 85% (Sommer et al., 2013), the amount of manure generated per head per year (m) in country i is calculated as:

$$m_i = 0.001\frac{(365 \times VS_i/0.8)}{(1-0.85)},$$

where VS_i is the country-specific average daily excretion rate for the analyzed animal type.

The cost of farm AD is sensitive to scale. We therefore estimate the methane reduction potential and costs separately for "large farms" defined as farms with 100 to 500 LSU and "extra large farms" with more than 500 LSU. The total amount of manure available for farm-scale anaerobic digestion in country i in a future year t is the sum of manure excreted by animals on large farms and extra large farms during times when animals are kept indoor, i.e.,

$$\mathrm{M_{it}} = \sum_{\mathrm{s}} \mathrm{A_{it}^{liquid}} \times \mathrm{VS_i} \times \mathrm{\gamma_{its}} M_{it} = \sum_s A_{it}^{liquid} \times m_i \times \gamma_{its} \times h_i,$$

where A_{it}^{liquid} is the number of animals on liquid manure management, γ_{its} is the fraction of animals found on farms of size s in country i and year t, and h_i is the fraction of a year that animals are housed indoor.

The cost of farm-scale AD is derived as the sum of the annualized investment cost and the operation costs (including costs for labour and additional organic substrate), less the revenues and cost-savings of utilizing the generated electricity and fertilizers. Hence, the unit cost per head of installing a farm AD plant for treatment of cattle and pig manure is in GAINS defined for country i in year t and for farm scale s in the following way:

$$C_{its} = I_{its} \times \frac{r(1+r)^T}{(1+r)^T - 1} + R_{its}p_R + L_{its}w_{it} - 0.6p_{it}^{ind}E_{its} - F_{its}p_f$$

where I_{its} is the fixed initial investment cost,

T is the expected lifetime of the equipment,

r is the interest rate,

R_{its} is the amount of organic substrate added to the co-digestion,

p_R is the unit price of organic substrate,

L_{its} is the fraction of annual work hours spent on operation of AD plant,

w_{it} is the average annual wage for the agricultural sector,

p_{it}^{ind} is the average electricity price for the industry sector,

E_{its} is the amount of energy generated from the AD process,

F_{its} is the amount of pure fertilizer nutrients (N-P_2O_5-K_2O) generated from the AD process, and

p_f is the unit price of fertilizer nutrients.

The efficiency in energy production of an anaerobic digester loaded with animal manure only is rather poor, because much of the organic matter in manure degrades slowly and with a relatively low content of micronutrients, which are needed by the anaerobic bacteria to produce methane. The performance can be considerably enhanced if manure is co-digested with other organic material rich in micronutrients (Sommer et al., 2013). In farm AD plants, which primarily digest manure, it is therefore typical to add at least 20% other organic substrate to enhance the energy-generating performance of the process (ETH, 2008). In GAINS is assumed that the feedstock contains 20% organic substrate and 80% manure and that both these substrates have a water content of 85%, respectively.

There is a wide range of organic waste materials available, which are suitable as additional substrate to manure in a farm AD plant (EC, 2001). These include straw and other crop residuals like maize stems, food residuals from restaurants and municipalities, food industry waste (e.g., residuals from slaughteries or waste from beverage or fat production), and sewage sludge from wastewater treatment. If there is a risk that the organic substrate contains pathogens, it will need to be pasteurized through the use of a thermophilic process or the digestate resulting from the digestion process cannot later be spread as fertilizer on fields (Sommer et al., 2013). In consistency with the European animal by-products regulation (EC 1069/2009), the digestate needs to be subject to minimum pasteurization equivalent to one hour at 70°C. In equivalence of this, some biogas plants perform pasteurization at a lower temperature, e.g., 53°C, but with the longer retention time of 10 hours (IEA Bioenergy Task 37, 2014b) in order to better preserve some of the bacterial content of the feedstock.

Because of the wide variety of sources for organic substrate and fluctuations in its availability over time and space, it is hard to make general assumptions about the unit price of organic substrate. It may vary from zero cost for organic waste, which suppliers would otherwise have had to pay to get rid of in an appropriate way, to 150 Euros per ton if feed crops (e.g., maize) are used. In the Reference scenario, we assume the price of organic substrate is 100 Euros/ton.

The amount of energy generated per ton of feedstock from a biogas digester can fluctuate widely depending on e.g., the composition of the feedstock and different operating conditions. From a survey of recently published case-studies of farm-scale AD plants, we find three European plants currently in operation for which information on both the amount of feedstock loaded and the amount of energy generated, are clearly stated. These are the McDonnell farms in Limerick, Ireland (SEAI, 2014) co-digesting 7600 ton cattle manure per year with 2800 ton food waste and 360 ton glycerine, the Stowell farms in Wiltshire, UK (EnviTec, 2012) co-digesting 4000 ton cow manure with 8000 ton maize silage, and Alviksgården, Luleå, Sweden (Svenska Gasföreningen, 2014) co-digesting 16000 ton pig slurry with 1800 ton slaughter waste. All three farms use or sell the digestate as organic fertilizer. Figure 1 plots the reported net energy generated against the amount of wet substrate loaded for the three plants as well as for a “typical” farm used in model simulations to assess the potential for farm AD in Switzerland (ETH, 2008). For the latter plants, a feedstock of 80% manure and 20% co-substrate is assumed. The energy comes in the form of electricity or heat and typically about 50% is converted to electricity and 50% is utilized as heat.

The three plants currently in operation and illustrated in Figure 1 report net energy generation of 381, 637 and 539 kWh/ton substrate, respectively, while the Swiss study assumes 245 kWh/ ton substrate. In GAINS is assumed that it is possible to generate on average 380 kWh/ton substrate loaded.

Based on the split between electricity and heat generated as reported by the surveyed farm AD plants, it is assumed in GAINS that half of the 380 kWh/ton substrate generated is converted to electricity, which is sold to local industry at the country-specific industry sector price of electricity (based on the PRIMES reference projection of 2016), 40 percent is used on farms as heat, and 10 percent is heat used up by the pasteurization process or lost without any economic value. The value of the heat utilized on the farms is set to half the industry price of electricity.

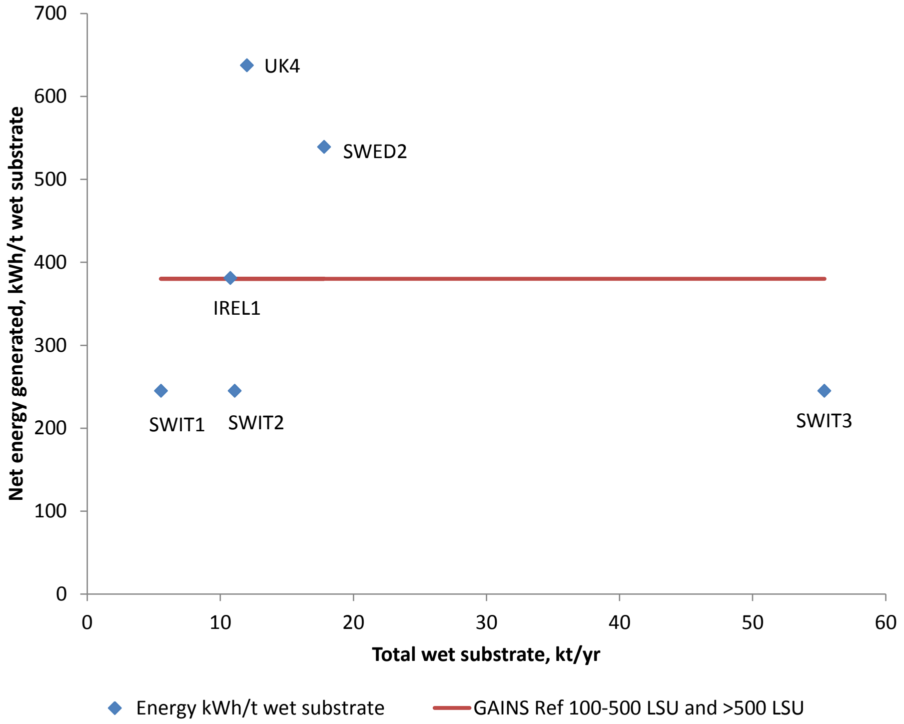

Figure 1: Net energy generation per ton wet substrate loaded for three farm AD installations currently in operation (IREL1, SWED2 and UK4) and for three model simulations (SWIT1, SWIT2, SWIT3) of “typical” Swiss farm AD installations.

Apart from the carbon content of the manure, which has partly been converted into biogas, the nutrients present in the manure feedstock will remain in the digestate after the anaerobic digestion is completed. During digestion, the organic nutrients present in the manure are transformed to inorganic compounds, e.g., organic nitrogen is converted to ammonia. The inorganic compounds can be more readily taken up by the plants than the organic nutrients present in undigested manure (Sommer et al., 2013). The digestate is therefore well suited as organic fertilizer. Table 13 presents typical nutrient contents of animal manure as well as for a few organic waste sources considered suitable as additive organic substrate in co-digestion with manure. The nutrients considered essential as fertilizers are nitrogen (N), phosphorous (P_2O_5), and potassium (K_2O). As shown in Table 13, the range for the nutrient contents is wide. As a conservative assumption, we assume that cattle and pig slurry contains 0.6 percent of nutrients N- P_2O_5- K_2O in the proportions 50-17-33 and that added organic waste contains 2.7 percent of nutrients N- P_2O_5- K_2O in the proportions 55-30-15. The assumptions give us a basis for estimating the amount of nutrients present in the digestate and therefore available for use as organic fertilizer. The value of pure nutrients in the proportions above is set to 1000 Euros per ton N- P_2O_5- K_2O, which would correspond to a price of 500 Euros/ton for an organic fertilizer containing 50 percent pure nutrients.

Table 13: Typical nutrient content in animal waste and some organic waste sources in Europe. % of substrate mass weight.

Substrate source:		unit	Min	Max	Mean
Fresh cattle manure	DS content	% of manure	20	50	n.a.
	N	% of manure	0.55	1.21	n.a.
	P2O5	% of manure	0.1	0.8	n.a.
	K2O	% of manure	0.25	1.2	n.a.
Cattle slurry	Dry solids (DS)	% of slurry	1	18	n.a.
	N	% of slurry	0.26	2.02	n.a.
	P2O5	% of slurry	0.1	1.2	n.a.
	K2O	% of slurry	0.2	1.5	n.a.
Fresh pig manure	Dry solids (DS)	% of manure	n.a.	n.a.	25
	N	% of manure	0.57	0.95	n.a.
	P2O5	% of manure	0.1	0.76	n.a.
	K2O	% of manure	n.a.	n.a.	0.4
Pig slurry	Dry solids (DS)	% of slurry	1	18	n.a.
	N	% of slurry	0.41	1.96	n.a.
	P2O5	% of slurry	0.1	1.2	n.a.
	K2O	% of slurry	0.2	0.9	n.a.
Food & drink industry sludge	Dry solids (DS)	% of sludge	1.3	91	12
	N	% of DS	0.73	16	4
	P2O5	% of DS	0.1	16	2.4
	K2O	% of DS	0.1	16	1.4
Slaughter waste - guts content	Dry solids (DS)	% of waste	2.4	21	n.a.
	N	% of DS	0.2	27.2	n.a.
	P2O5	% of DS	0	3.4	n.a.
	K2O	% of DS	0	1	n.a.
Slaughter waste sludge	Dry solids (DS)	% of sludge	8	25	16
	N	% of DS	2	80	22.1
	P2O5	% of DS	1.7	36	11
	K2O	% of DS	0.8	4.4	1.3
GAINS assumption: cattle & pig slurry	Dry solids (DS)	% of slurry	-	-	15
	N	% of slurry	-	-	0.3
	P2O5	% of slurry	-	-	0.1
	K2O	% of slurry	-	-	0.2
GAINS assumption: Organic waste substrate	Dry solids (DS)	% of waste	-	-	15
	N	% of waste	-	-	1.5
	P2O5	% of waste	-	-	0.8
	K2O	% of waste	-	-	0.4

Source: EC, 2001. Chapter 4: PROPERTIES OF WASTES RELEVANT TO AGRICULTURAL BENEFIT AND ENVIRONMENTAL IMPACT, European Commission-Directorate-General for Environment, Brussels. http://ec.europa.eu/environment/waste/studies/compost/landspreading_4-6.pdf

Figure 2 shows the fixed initial investment cost per ton of wet substrate loaded per year against the wet substrate loading capacity for six anaerobic digestion plants currently in operation and for which information was available on both investment cost and substrate load. In addition to the Swedish and Irish plants presented in Figure 1, these include the Mountstephen farm in Devon UK co-digesting 2373 ton cow slurry and chicken litter with 1095 ton maize and the Langage farm in Devon UK co-digesting 3000 ton cow slurry with 13000 ton food industry waste. Also illustrated in Figure 2 are the assumptions used for model simulations of the potential for farm AD in Switzerland (ETH, 2008). To illustrate the importance of scale for the investment cost of anaerobic digestion plants, Figure 2 also present the investment cost per ton substrate loaded for two large Danish plants co-digesting manure from several farms with organic waste from other sources. For the farm AD plants illustrated, investment costs vary between 75 and 225 Euro/t wet substrate loaded annually over a load range of 3.5 to 55 kt wet substrate per year, while the corresponding costs for the two Danish co-digestion plants are 21 and 37 Euro/t wet substrate for annual loads of 281 and 164 kt wet substrate, respectively. In GAINS the adopted investment cost for AD plants on farms of the size 100-500 LSU is 200 Euro/t wet substrate loaded, while for farms of the size larger than 500 LSU it is 100 Euros/t wet substrate loaded. Because the amount of wet substrate per animal is derived from country-specific volatile excretion rates, the derived investment cost per head is country-specific (see Figure 3). The investment cost is the product of the investment cost per ton wet substrate for farm size s and the country-specific amount of wet substrate loaded per animal head, i.e.,

$$I_{its} = i_s \times m_i \times 1.25.$$

Note that the total amount of wet substrate loaded per head is 1.25 times the manure generated per head as the total substrate contains 80 percent manure and 20 percent other organic substrate.

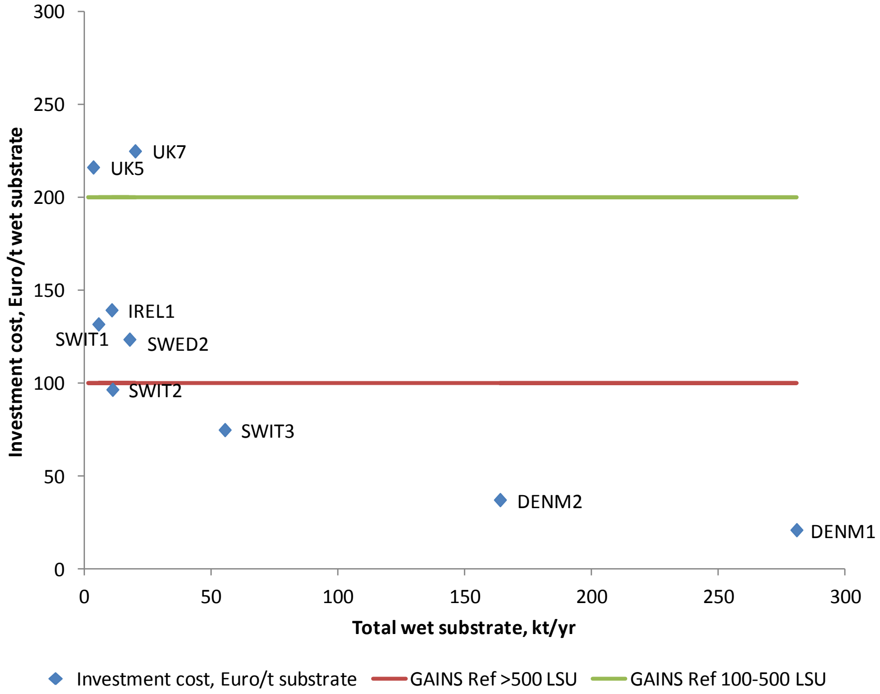

Figure 2: Fixed initial investment cost per ton of wet substrate loaded annually for four currently operating farm AD plants (IREL1, SWED2, UK5, UK7), three model simulation plants (SWIT1, SWIT2, SWIT3) and two large co-digestion plants (DENM1, DENM2) co-digesting manure and industrial organic waste.

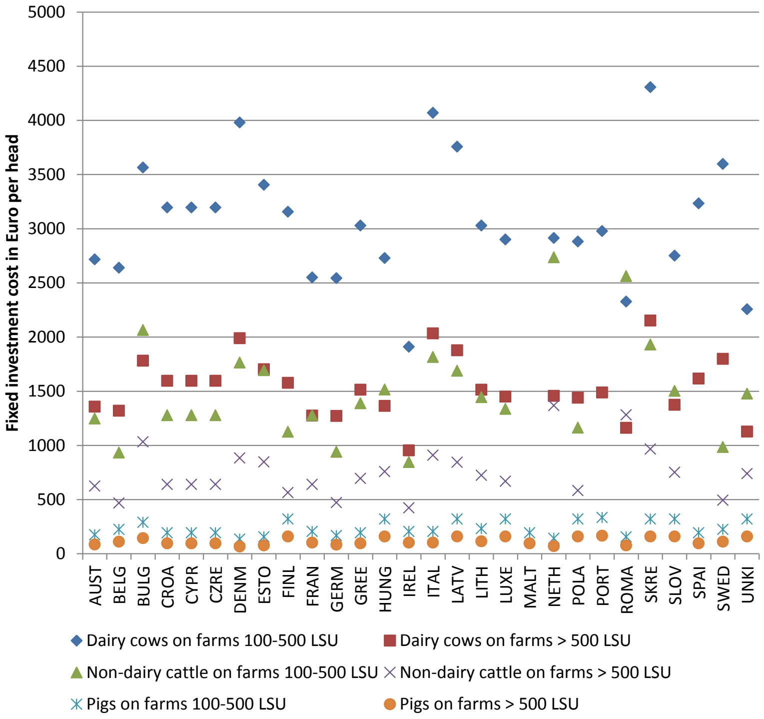

Figure 3: Derived fixed investment cost per animal head.

There are few quantifications of labour costs for the operation of farm AD plants available. There are examples of farmers mentioning high maintenance requirements in particular during the start-up of an AD plant (e.g., Farming Futures, 2010a; Svenska gasföreningen, 2014). When operation and maintenance (O&M) costs are mentioned, these usually reflect the sum of labour costs and the cost of additional organic feedstock, which makes it hard to quantify labour costs separately. Walla (2004) describes two farm AD plants of sizes 100 and 170 kW digesting manure from 140 and 170 LSU dairy cows, respectively. The plants co-digest manure (amount unknown) with 800 and 2300 ton energy crop, respectively, and estimate O&M costs to 34000 and 88000 Euros per year, respectively. USEPA (2014a, 2014b) report O&M costs for two farm AD plants, which only digest manure without adding co-substrate to the process. O&M costs are therefore likely to mainly reflect labour costs. One of the plants has the power 180 kW and digests manure from 8000 pigs and report annual O&M costs corresponding to 19250 Euros or 2.4 Euros per pig. The other farm is a dairy farm with an AD plant of 215 kW and digesting only manure from 900 dairy cows. The latter reports O&M costs corresponding to 38500 Euros per year, i.e., 43 Euros per dairy cow or 3 Euros/ton manure for cows generating 14 tons/head/year. 3 Euros/ton manure convert to about 0.2 work hours per ton manure if assuming an annual wage of 25000 Euros and 1800 working hours per year. We used the assumption of 0.2 work hours per ton substrate digested in GAINS. The cost of labour per ton substrate is estimated by multiplying 0.2 work hours with the average hourly wage rate for the agricultural sector in each member state as reported by ILO (2010) and projected to grow with the growth of value added in the agricultural sector as provided by the PRIMES model (2015).

Measurements of leakage of fugitive methane emissions from farm AD plants suggest leakage rates between 3 and 4 percent of gas produced for well managed installations (Flesch et al., 2011; Groth et al., 2015). Considering that a biodigester enhances the conversion of coal into methane, a leakage rate of a few percent of the total generation of methane should be converted to a higher fraction of the methane generated had the manure not been treated in a digester but been subject to alternative manure management practices. Hristov et al. (2013a) mention removal efficiencies for farm AD plants of about 60 to 70% of methane emissions had the manure been treated in a conventional way. The assumed removal efficiency is in GAINS set to 60 percent of methane released from alternative manure management practices for farms of size 100-500 LSU. The assumed removal efficiency for plants installed on farms with more than 500 LSU is 80 percent as the very large farms are expected to be more efficient in controlling the methane slip throughout the process. Pellerin et al., (2013) estimate a removal efficiency of 88% for farm AD installations treating non-dairy cattle and pig manure in France. It is however not clear from Pellerin et al., (2013) if the 88% removal efficiency refers to the fraction removed of the methane generated in the digester or the methane removed in relation to a manure management system without anaerobic digestion.

Table 14 presents a summary of the assumptions that enter unit cost estimations of farm AD in GAINS.

Table 14: Summary of assumptions entering unit cost estimation for farm anaerobic digestion (AD).

Factors entering unit cost estimation	Unit	Reference scenario assumptions[a]	
		Farms 100-500 LSU (L)	Farms > 500 LSU (XL)
Volatile solids (VS)	% of Total solids (TS) in manure	80%	80%
Total solids	% of manure	15%	15%
Water content of manure	% of manure	85%	85%
Added organic substrate	% of manure	25%	25%
Water content of added organic substrate	% of organic substrate	85%	85%
Total wet substrate (manure+organic substrate)	% of manure	125%	125%
Investment cost -fixed initial investment	Euro per ton wet substrate loaded annually	200	100
Lifetime of investment	years	20	20
Organic substrate price	Euro per ton organic substrate	100	100
Labour hours	work hours per ton wet substrate per year	0.2	0.2
Average wage agricultural sector	Euro per year	Country-specific (ILO, 2010) projected by value added in agricultural sector (PRIMES, 2015)	
Energy generated	kWh per ton wet substrate per year	380	380
whereof electricity supplied at industry electrcity price	kWh per ton wet substrate per year	190	190
whereof heat used on farm	kWh per ton wet substrate per year	152	152
whereof heat used in pasteurization process or lost	kWh per ton wet substrate per year	38	38
Electricity price	Euro per kWh	Industry sector by country (PRIMES, 2015)	
Heat price	Euro per kWh	50% of industry electricity price	
Organic fertilizer generated from slurry	Pure nutrients ($N-P_2O_5-K_2O$) as % of slurry	0.6%	0.6%
Organic fertilizer generated from organic waste	Pure nutrients ($N-P_2O_5-K_2O$) as % of waste	2.7%	2.7%
Organic fertilizer price	Euro per ton pure nutrients ($N-P_2O_5-K_2O$)	1000	1000
Emission removal efficiency	Reduction from no control	60%	80%

[a] Assumptions presented are without effects of technological development (see Section 2.5.1.)

To identify the extent of current adoption of farm AD in different member states, we first derive the maximum technically feasible output of energy from farm AD plants by animal category and farm-size in the respective member states on the basis of the assumptions summarized in Table 14. We then derive the total energy output produced in 2015 from manure-based anaerobic digesters in consistency with the farm-based biogas production as estimated by the PRIMES model for the same year. The conversion efficiency to electricity is assumed 0.375 and to heat 0.7 (and 50% of the energy output generated is in the form of electricity and 50% in the form of heat as specified in Table 14). The source of information for farm-based biogas production in historical years in the PRIMES model is Eur'Observer (2014). By relating the total energy output from manure-based anaerobic digestion in 2015 to the maximum technically feasible output of energy from manure-based systems, we obtain the percentage of the maximum potential currently exhausted. We exhaust the current potential using the same assumed adoption order for all member states, i.e., starting adoption on pig farms greater than 500 LSU. Once the potential in this category is exhausted, we move on to dairy farms greater than 500 LSU, then non-dairy cattle farms greater than 500 LSU, then pig farms 100 to 500 LSU, then dairy farms 100 to 500 LSU, and finally non-dairy cattle farms 100 to 500 LSU. The control strategy for 2015 has been developed in consistency with the PRIMES model and Eur'Observer (2014). The development in implied emission factors for manure management reported by member states to the UNFCCC (2015) for the years 2005 to 2013, was used as an indicator of the development in the uptake of farm AD technology between 2005 and 2015. E.g., if the reported implied emission factor for pigs in 2005 and 2010 is the same as in 2013, then the control in these two years is assumed to be at the same level as in 2015. For future years, the control strategy was developed so as to be in consistent with the growth in farm-based biogas production projected by the PRIMES model (2015).

3.3.2 Rice cultivation

CH_4 emissions from rice cultivation result from anaerobic decomposition of organic material in flooded rice fields. Emissions depend among other factors on the season, soil characteristics, soil texture, use of organic matter and fertilizer, climate, as well as on agricultural practices (IPCC, 2006, Vol.4, p. 5.45). The emission calculation methodology used in GAINS follows the IPCC guidelines (2006, p. 5.49) and adopts IPCC default emission factors for given water management regimes. The IPCC method is based on the annual harvested area with scaling factors for different water regimes. In GAINS, these are translated into three cultivation activities:

- *Continuously flooded cultivation area:* fields have standing water throughout the growing season and only drying out for harvest.
- *Intermittently flooded cultivation area:* fields have at least one aeration period of more than three days during the growing season. Compared with continuously flooded rice fields, IPCC suggests that intermittently flooded rice fields emit 27 to 78 percent of continuously flooded fields, where the range depends on if the fields are rainfed or irrigated. GAINS uses the assumption of 50 percent emissions per hectare from intermittently flooded compared with continuously flooded fields.
- *Upland rice cultivation area:* 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 country *i* in year *t* are calculated as follows:

$$E_{it} = \sum_{sm} A_{it} * ef_{i;\,flood}^{IPCC} * h_i * \beta_s * V_{is} * \left(1 - remeff_{sm}\right) * Appl_{itsm} \ , \qquad (23)$$

where A_{it} is the rice cultivation area in country *i* in year *t*,

$ef_{i;\,flood}^{IPCC}$ is the IPCC default emission factor for CH_4 emissions from flooded rice fields (1.3 kg CH_4 ha^{-1} day^{-1}),

h_i is the duration of the growing season expressed in days per year (=185 days per year),

β_s is an emission scaling factor for water regime *s* (=1 for continuously flooded, =0.5 for intermittently flooded, and =0 for upland rice).

V_{is} is the fraction of rice cultivated land under water regime *s*,

$remeff_{sm}$ is the removal efficiency of technology m when applied to water regime s, and

$Appl_{itsm}$ is the application rate of technology *m* when applied to water regime *s*.

Methane emissions from rice cultivation in Europe are in GAINS accounted for in Bulgaria, France, Greece, Hungary, Italy, Portugal, Romania, and Spain. Activity data for rice cultivation is measured in million hectares of land and is taken from UNFCCC-CRF (2015) with projections based on OECD-FAO (2012) and with information on country-specific application of water regimes taken from UNFCCC-CRF (2015).

Introducing intermittent aeration of continuously flooded rice fields reduces CH_4 emissions, while saving water, but is also likely to increase weed growth in the fields (Barrett et al. 2004, Ferrero and Nguyen 2004). This increases labour costs by an estimated 20 percent (Barrett et al. 2004), which is equivalent to about 60 additional work hours annually per hectare in developing countries (Heytens, 1991) and 12 additional work hours annually per hectare in developed countries, where herbicides are used for controlling weeds (Shibayama, 2001). According to IRRI (2007), intermittent aeration of continuously flooded rice fields may reduce water use by 16 to 24 percent. The mitigation potential of this option is assumed 22 percent, based on the IPCC default emission factor for intermittent aeration of continuously flooded rice fields. Assuming that continuously flooded rice fields need 1000 mm water input per year (Bouman, 2001) and the average cost of irrigated water is 0.02 US$ per m^3 (FAO, 2004), then saving 22 percent of water corresponds to a cost-saving of about 35 Euro per ha.

Certain rice hybrids may affect CH_4 emissions. By careful selection of low CH_4 producing hybrids, emissions can be ten percent lower (ADB 1998). 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. In GAINS is assumed that the potential reduction in CH_4 emissions from switching to alternative rice hybrids is 10 percent with a 3 percent increase in crop yield, when applied as the sole option. When applied in combination with other options, like intermittent aeration of continuously flooded fields, the removal efficiency of this option is set to 5 percent.

Application of sulphate-containing substrates to rice fields reduces CH_4 emissions because CH_4 producing bacteria compete for the same substrate as the sulphate reducing bacteria (van der Gon et al. 2001). The associated costs are the costs of acquiring sulphate containing fertilizers like e.g., ammonium sulphate and spreading them on the fields. In GAINS, this option is assumed to remove 20 percent of emissions when applied as a stand alone option and 10 percent when applied in combination with other options .

3.3.3 Open burning of agricultural waste

This sector refers to open burning of agricultural waste (primarily burning of plant residues) on fields. Activity data used in GAINS is amount of agricultural waste burned and has been revised for most EU countries between the Reference 2013 and 2015 versions of the non-CO_2 scenarios for EU-28. Current data are based on estimates from satellite images by GFED v3.1 (van der Werf et al, 2010) and GFED v4 (Randerson et al., 2015). Furthermore, the estimates taken from satellite images have been reviewed by member state experts during IIASA member state consultations for the proposal of the EU Thematic Strategy for Air Pollution (TSAP) in 2014.

The emission factor used is the IPCC default emission factor for open burning of waste (IPCC, 2006, Vol.5, p.5.20) which corresponds to 6.5 kt CH_4 per Mt waste burned. Any further potential to reduce methane emissions from this source comes from stricter enforcement of the current ban on open burning of field residuals. The cost of mitigating methane through this option is set to zero, assuming stricter enforcement does not incur any additional costs.

3.4 Waste sector

3.4.1 Solid waste

CH_4 from municipal and industrial solid waste is generated when biodegradable matter is digested under anaerobic conditions in landfills or during temporary storage of waste aimed for different types of treatment. CH_4 may also be released during loading or emptying of the reactor when organic waste is treated in anaerobic digesters to produce biogas or during treatment of organic waste in composts. The activity data used in GAINS is the total amount of waste generated before diversion to different types of treatment like recycling, energy recovery or landfill. Amounts of waste generated are first split by municipal or industrial solid waste and then by waste composition for municipal solid waste and by manufacturing industry sub-sector for industrial solid waste.

CH_4 from waste deposited on landfills is formed and released with a time delay of up to several decades. IPCC (2006, Vol. 5, Ch. 3) 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 and garden waste and 20 years for more slowly degrading waste like paper, wood and textile waste. The lags correspond to approximate average half-life values for the respective waste types (IPCC, 2006, Vol.5, Tables 3.3 and 3.4).

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* :

$$E_{it} = \sum_{s} \sum_{m} A_{i;(t-y_s);s} * ef_s * \left(1 - remeff_{sm}\right) * Appl_{itsm} \tag{24}$$

where	$A_{i;(t-y_s);s}$	is amount of waste type (or industry sector) *s* generated in year *t*-y_s, where y_s is the average lag in CH_4 release assumed for waste type (or industry sector) *s*,
	$remeff_{sm}$	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*, and
	ef_s	is the IPCC default emission factor for waste type (or industry sector) *s* deposited in a landfill without recovery of landfill gas.

From IPCC (1997, Vol.3, Ch.6, Equation 1) the following expression for ef_s is obtained:

$$ef_S = DOCm_S * DOCf * MCF * F * 16/12 * (1 - OX), \tag{25}$$

Where

$DOCm_j$	is the fraction of Decomposable Organic Carbon (DOC) in waste type/sector *s*,
DOCf	is the fraction of DOC that can decompose (default used is 0.5),
MCF_i	is the Methane Correction Factor correcting for aerobic decomposition and vary with the management standard of the landfills,
F	is the fraction of CH_4 in generated landfill gas (default used is 0.5),
16/12	is the molecular weight ratio CH_4/C,
OX	is the oxidation factor correcting for increased oxidation from covering of landfills (default used is 0.1).

IPCC (2006, Vol.5, Tables 2.4 and 2.5) default factors are used for the content of decomposable organic carbon (*DOCm*) in different types of biodegradable waste as well as for the Methane Correction Factor (MCF) applied to different management standards of the landfills.

Starting point for emission estimations are historical reported waste generation rates for municipal solid waste and industry reported to EUROSTAT (2015) for the EU countries. Drivers for future generation of municipal solid waste are GDP and urbanization rate, while driver for industrial solid waste is growth in value added in relevant manufacturing industry sectors. Waste generation elasticity parameters were estimated on a dataset comprising historical country-specific waste generation amounts for 31 European countries in 1985-2004 downloaded from EUROSTAT (2005) in 2005. For municipal solid waste, the data set comprise 236 observations in an unbalanced panel. Generation of municipal solid waste (MSW) per capita is estimated as a function of GDP per capita (IMF, 2006) and urbanization rate (UNstat, 2009):

$$\log(MSWcap)_{it} = \alpha + \beta_1 * \log(GDPcap)_{it} + \beta_2 * \log(urbrate)_{it} + \varepsilon_{it}\,, \tag{26}$$

where

$MSWcap$ is kg MSW per capita per year,

$GDPcap$ is the average annual Gross Domestic Product in Euro per capita,

$urbrate$ is the fraction of the total population living in urban areas,

$\varepsilon_{it}=u_i+v_{it}$ is an error term which is separated into an individual effects term and a residual omitted variables term, and

$\varepsilon_{it}\sim IID\left(0,\sigma_\varepsilon^2\right)$ is an error term which is independent and identically distributed.

Estimations are conducted in LIMDEP 8.0 (Greene, 2005) using panel data methods, i.e. estimating OLS, fixed effect and random effect models[3]. A Lagrange multiplier (LM) test of poolability shows that the fixed or random effect models are preferred to the OLS model. A Hausman specification test shows that the fixed effect model is preferred to the random effect model. Results are presented in Table 15 and show that income per capita affects MSW generation per capita with an elasticity of 0.48 (significant at a 1 percent level) on average for the whole sample[4]. The elasticity for the urbanization rate has an expected negative sign (significant at a 5 percent level).

The elasticity for generation of industrial solid waste on a sub-sector level is estimated in response to changes in value added for the industry sub-sector. For the EU, data on value added for manufacturing industry sectors is taken from the PRIMES (2015) model with further sub-sector splits using data from UNIDO (2006):

$$\log(INW)_{it} = \alpha + \beta * \log(VA)_{it} + \varepsilon_{it}\,, \tag{27}$$

where

INW is Mt industrial solid waste per year,

VA is the value added at factor cost in M Euro per year,

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[3] In a fixed effect model the variance within each country is separated out and the regression if performed only on the within variance, while the variance between countries is captured in country-specific constants. This has the advantage that the variance in waste amounts per capita that depends exclusively on country-specific differences is controlled for. In the random effects model estimates are based on a weighted average of the within and between country variances. In the OLS model, the within and between country variances are bluntly added up without using weights (Hsiao, 1986).

[4] Separate models for Western Europe (EU-15 Norway and Switzerland) and Eastern Europe (EU-12, Croatia and Macedonia) were also run, however, with no large differences in parameter estimates compared with the full sample runs.

$\varepsilon_{it}=u_i+v_{it}$ is an error term which is separated into an individual effects term and a residual omitted variables term, and

$\varepsilon_{it}\sim IID\left(0,\sigma_{\varepsilon}^{2}\right)$ is an error term which is independent and identically distributed.

Again panel data methods are used. For industrial solid waste, sample sizes are rather small, less than eighty observations, however as shown in Table 15, in the preferred random effect model the resulting parameter estimates are significant at a 1 percent level and with the expected positive signs. Least elastic to changes in value added to amounts of waste generated is wood and wood products industry (0.3), while pulp and paper has the highest elasticity (1.0).

The elasticity estimates for waste generation are used to calculate predicted future values for generation of solid waste.

Table 15: Results from estimations of elasticity for generation of municipal and industrial solid waste. Values in brackets are t-values. Preferred models in *italics*.

Dependent variable	**Unit**	**No. of obs.**	**Explanatory variable**	**OLS**	**Fixed effect**	**Random effect**	**LM-test**	**Hausman-test**
Municipal solid waste	Mt per capita	236	Constant	4.60 (27.6)	*n.a.*	2.67 (10.5)	235.2	43.6
			GDP per capita	0.17 (10.6)	*0.48 (15.9)*	0.37 (14.6)		
			Urbanization rate	0.05 (0.53)	*-0.17 (1.87)*	0.37 (14.6)		
			R-square	0.39	*0.85*	n.a.		
Food, beverages and tobacco industry waste	Mt	70	Constant	0.77 (0.90)	n.a.	*0.78 (0.72)*	18.7	0.01
			Value added	0.83 (7.73)	0.83 (3.27)	*0.81 (5.82)*		
			R-square	0.47	0.71	*n.a.*		
Pulp and paper industry waste	Mt	70	Constant	-0.12 (0.20)	n.a.	*-1.35 (1.72)*	54.4	0.24
			Value added	0.85 (9.85)	1.07 (7.84)	*1.03 (9.56)*		
			R-square	0.59	0.95	*n.a.*		
Textile, leather and footwear industry waste	Mt	71	Constant	-1.38 (1.99)	n.a.	*-0.53 (0.48)*	67.8	6.4
			Value added	0.88 (9.26)	-0.32 (0.72)	*0.74 (4.74)*		
			R-square	0.55	0.89	*n.a.*		
Wood and wood products industry waste	Mt	71	Constant	3.12 (4.79)	n.a.	*3.64 (2.66)*	173.3	0.78
			Value added	0.47 (4.44)	0.23 (1.39)	*0.33 (4.58)*		
			R-square	0.22	0.83	*n.a.*		

CH_4 emissions from biodegradable solid waste can be controlled by separating out different types of waste treatment for recycling, composting, anaerobic digestion or incineration. Following the EU waste legislation, i.e., the Waste Directive (EC, 2006) and the Landfill Directive (EC, 1999), separation and treatment of biodegradable waste should be preferred to landfill disposal. Landfill disposal of biodegradable waste must be reduced by at least 65 percent between 1995 and 2016 in all EU member states and all landfill sites must have gas recovery facilities installed by 2009.

In GAINS, the maximum feasible reduction of CH_4 emissions in the waste sector is modelled as an "optimal" waste treatment path as defined by the current EU legislation. Source separation of waste for recycling or energy recovery purposes is preferred to landfill disposal with gas recovery. In the optimal case, all biodegradable waste is source separated from the waste stream and none is disposed of to landfills. Some EU member states (Austria, Belgium, Denmark, Germany, Netherlands and Sweden) are close to this optimum and have already a complete ban on landfilling of untreated biodegradable waste in place.

A list of waste treatment options considered in GAINS is presented in Table 16 together with a definition of the optimal control. In reference scenario emissions, the effects of already implemented waste treatment options as well as future effects of adopted legislation are taken into account in the applied control strategies. Information on current adoption of waste treatment in the EU is taken from UNFCCC (2015) CRF tables. All EU member states are assumed to meet the Landfill Directive reduction targets for biodegradable waste by 2020, even though some may not be completely on track for this in 2016.

With the 2015 submission of national inventories to the UNFCCC, countries are expected to report emissions following the IPCC (2006) guidelines. This implies that almost all EU countries now apply a full First-Order-Decay method for estimating methane emissions from landfill of biodegradable waste up to fifty years back in time. This methodological switch has meant that many EU countries report considerably higher (some even the double) methane emissions from solid waste disposal sites in historical years 2005 and 2010 compared to previous versions submitted to the UNFCCC-CRF (2015). As the difference stems from taking a longer historical time perspective into account when estimating emissions from landfills, the GAINS approach has been to apply the simplified GAINS methodology and referring any difference between the GAINS estimate and the landfill emissions reported by countries to the UNFCCC to a separate category reflecting emissions from “Historical solid waste disposal”. The residual is estimated for years 2005, 2010 and 2015, where the reported emissions for year 2013 have been used to estimate the emission residual for year 2015. Considering the progressing decomposition of biodegradable waste landfilled up to fifty years back and that the Landfill Directive is expected to significantly reduce the amount of decomposable biodegradable waste in the landfills in the future, emissions currently released and reported from decomposition of historical disposal of solid waste are assumed phased out linearly until year 2035.

Costs for source separation and treatment of municipal solid waste are taken from various sources. The additional cost of collecting source separated waste compared to mixed waste is derived from Tanskanen (2000) and assumes 33 Euro/t waste for paper waste and 62 Euro/t waste for food and garden waste. The net cost-saving of reducing the amount of waste disposed of and treated in landfills is estimated at 20 Euro/t waste (AEAT, 1998). The cost for upgrading recovered biogas from 60 to 97 percent is taken from Persson (2003). Cost and potential for energy recovery from incineration of waste are taken from IPPC (2006).

Costs for treating household and industry food waste in anaerobic digesters for biogas recovery are taken from AEAT (1998, 2001). The digestion process is assumed to convert 60 percent of the original waste amount to biogas. Half of the rest product is assumed to be compost material which can be given away for free, a quarter is a liquor which needs further treatment at 12 Euro/t liquor, and the last quarter (i.e. 10 percent of the primary waste amount) is a residual which is landfilled at a cost of 20 Euro/t residual (AEAT, 2001).

The cost of recycling wood industry waste into chipboards is taken from Wilson (2003).

The net cost of household paper recycling is defined as the sum of the additional cost of collecting source separated waste compared to mixed waste and of converting paper waste to recycled pulp minus the cost-savings of depositing less waste to landfills and income from selling recycled pulp at a market value . The investment cost is assessed from the cost for a UK deinking plant producing pulp from 0.07 Mt paper waste per year and amounts to 594 Euro per ton paper waste recycled into pulp when expressed in the 2013 price level used here (AEAT, 1998). With a plant lifetime of 15 years and an interest rate of 10%, this means an annualized investment cost of 78 Euro per ton paper waste. From Tanskanen (2000), the additional cost of separate collection of paper waste compared with mixed waste collection is assessed at 36 Euro per ton waste (in 2013 prices). The time lost to households for separation and recycling of paper waste is estimated at 5 minutes per week for every two persons and when about 100 kg paper is recycled per person every year. The loss in time is valued using country-specific average annual wages (ILO, 2010 and projected with PRIMES, 2016). The cost-saving of avoiding landfill disposal is assessed at 24 Euro per ton paper waste (AEAT, 1998). Finally, the cost-saving of selling the recycled pulp on the world market is assessed to 370 Euro per ton recycled pulp (or 330 Euro per ton paper waste recycled), which corresponds to the difference between an average world market price of 645 Euro per ton virgin pulp (FAOSTAT, 2010) and an approximate marginal cost of processing recycled paper into pulp of 275 Euro per ton pulp derived from the cost data provided in AEAT (1998).

When summing up the different cost items described above, the net unit cost will often turn out negative, i.e., with these assumptions there appears to be a relatively large net profit from recycling household paper waste. Why would such opportunities for net profits exist and why have they not been exhausted already in the Reference scenario? We find two possible reasons for why there may still be unexhausted potential for extended paper recycling in the future despite seemingly negative costs. First, the whole recycling chain depends on the willingness of the households to separate the waste and supply it without compensation. Even if there would be profits to be made further down the recycling chain, the initial step of getting the households involved for free may still pose a limitation on the whole chain. Second, the market value of recycled pulp is uncertain and may be distorted upwards due to close integration between primary and secondary markets for pulp, i.e. between virgin and recycled pulp, as such integration has been documented several times (OECD, 2007; Ackerman and Gallagher, 2002). Being close substitutes, it is likely that virgin pulp producers have an interest in keeping the price of recycled pulp at a level where the costs for virgin pulp production are covered. For private investors it may be considered too risky to make investments into recycling infrastructure on the basis of an artificially high price of recycled pulp.

Table 16: CH_4 mitigation options for solid waste in GAINS. Sources: IPCC (2006); AEAT (1998); IPPC (2006); Tanskanen (2000); Persson (2003); Wilson (2003).

Sector	Control options in GAINS	Definition of optimal control
MSW - food and garden	Anaerobic digestion w gas recov. and utiliz. Household composting Large-scale composting Incineration Landfill with gas recovery and flaring Landfill with gas recovery and utilization Landfill without gas recovery	Biodegradable waste currently landfilled is source separated and treated in anaerobic digesters with gas recovery and utilization. Current capacity for composting and mixed incineration remain but without further extensions in the future.
MSW - paper	Paper recycling Incineration Landfill with gas recovery and flaring Landfill with gas recovery and utilization Landfill without gas recovery	90 percent of paper waste source separated for recycling and the rest is incinerated. Current capacity for mixed incineration remains but without further extension in the future.
MSW - wood	Incineration Landfill with gas recovery and flaring Landfill with gas recovery and utilization Landfill without gas recovery	Biodegradable waste currently landfilled is source separated and incinerated for energy recovery.
Food industry	Anaerobic digestion w gas recov. and utiliz. Composting Incineration Landfill with gas recovery and flaring Landfill with gas recovery and utilization Landfill without gas recovery	Biodegradable waste is treated in anaerobic digesters with gas recovery and utilization.
Pulp and paper industry	Incineration Landfill with gas recovery and flaring Landfill with gas recovery and utilization Landfill without gas recovery	All waste (black liqour) recovered and incinerated for energy purposes.
Textile industry	Incineration Landfill with gas recovery and flaring Landfill with gas recovery and utilization Landfill without gas recovery	All waste recovered and incinerated for energy purposes.
Wood industry	Recycling for board production Incineration Landfill with gas recovery and flaring Landfill with gas recovery and utilization Landfill without gas recovery	All waste max recovered and recyled for wood board production, residuals incinerated for energy purposes.

3.4.2 Wastewater

Wastewater treatment plants serve to decompose compounds containing nitrogen and phosphor as well as carbon from the wastewater before discharge. Main gaseous products are CO_2 and molecular nitrogen, but during the process also CH_4 is released. CH_4 is formed whenever wastewater with high organic content is handled under anaerobic conditions.

In the GAINS model, wastewater from households and industry are accounted for separately. The activity data used for estimation of emissions from domestic wastewater is number of people connected to centralized or decentralized collection of wastewater. This basically refers to wastewater from urban and rural population, except for most industrialized countries where wastewater collection services often include some rural areas as well. Country-specific data on fractions of wastewater collected centrally is taken from UNFCCC (submission 2014), EUROSTAT (version as of June 26, 2013) and OECD (2015).

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 limited and to increase for 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 CH_4 emission factors are derived following the IPCC guidelines (2006, Vol.5, Equations 6.1 to 6.3):

$$E_{it} = \sum_{s} A_{it} * h_s * ef_i * (1 - remeff_m) * Appl_{itm} \qquad (28)$$

where A_{it} is total population in country i and year t,

h_s is fraction of total population connected to treatment system s (centralized or decentralized treatment)

$remeff_m$ is the removal efficiency of technology m,

$Appl_{itm}$ is the application of technology m in country i and year t, and

The methanogenic process in the treatment of wastewater is sensitive to daily/seasonal temperature variations as temperature affects the microbiological community and the degradation rate of organic matter (Dhaked, Singh and Singh, 2010). Temperature is therefore a relevant factor for the formation of methane during treatment of domestic wastewater, where the lower the temperature, the lower the methane formation (Luostarinen et al. 2007). In GAINS a country-specific temperature correction factor was included when deriving emission factors for domestic wastewater, i.e.,

$$ef_i = BOD_i * B_0 * MCF_0 * TCF \qquad (29)$$

where BOD is amount of biochemical oxygen demand per person in country $\imath$,

B_0 is maximum CH_4 producing capacity,

MCF_0 is the methane correction factor, i.e. the fraction of BOD converted to CH_4, and

TCF is the temperature correction factor in country i.

The temperature correction factor is derived by weighing the rate of methanogenesis at different temperature intervals with the number of days per year in respective temperature interval, i.e.,

$$TCF_i = \frac{\sum_{j=1}^{4} \alpha_j D_{ij}}{365}, \qquad (29)$$

where α_j are the rates of methanogenesis (0, 0.1, 0.6, and 0.9) at the four respective temperature intervals ≤ 5°C, 5 to 15°C, 15 to 30°C and > 30°C, and

D_{ij} are the average number of days (over years 2000, 2005 and 2010) when the maximum temperature in a country falls within the respective temperature intervals.

Data on the rates of methanogenesis at different temperature intervals is adopted from Lettinga, Rebac, and Zeeman (2001), while daily data of the maximum temperature for years 2000, 2005 and 2010 at 25km resolution was taken from the Agri4 Cast Data Portal (JRC, 2015).

Country-specific values for the biochemical oxygen demand per person (BOD) are used when available from UNFCCC-CRF (2014). When unavailable, an IPCC (2006, Vol.5, Table 6.4) default factor for the EU of 31.0 kt CH_4/million people is used for the maximum CH_4 producing capacity (B_0). Methane correction factors (MCF_0) of 0.1 for uncontrolled decentralized collection and 1 for uncontrolled centralized collection apply.

Industry sectors identified by IPCC (2006, Vol.5, p.6.19) as potential sources for CH_4 emissions from wastewater are food, pulp- and paper industry and other manufacturing industries generating wastewater with an organic content, i.e., textile, leather, organic chemicals etc.

The activity data for estimating methane emissions from industrial wastewater is the amount of COD present in untreated industrial wastewater. These amounts are derived from production volumes combined with COD generation factors as specified in Table 17. Production volumes in ton product are taken from FAOSTAT (2015). Growth in value added by industry is used as driver for future projections.

For pulp- and paper industry, wastewater and COD generation rates reported in literature differ considerably between processes and between developed and developing countries. By comparing reported values from different sources, process specific generation rates are derived as presented in Table 17. For the EU countries, default rates derived for developed countries apply. It should be noted that when using process specific generation rates, the estimated amounts of COD and CH_4 generated from this industry come out several times lower than if using the IPCC default factor (2006, Vol.5, Table 6.9) for some food industries and pulp- and paper industry.

$$E_{it} = \sum_{sm} A_{its} * COD_i * ef_i * (1 - remeff_m) * Appl_{itm} \tag{30}$$

where A_{its} is the amount of product A produced in country i in year t,

COD_i is the chemical oxygen demand in untreated wastewater generated per tonne product produced in country i,

$remeff_m$ is the removal efficiency of technology m,

$Appl_{itm}$ is the application of technology m in country i and year t, and where

$$ef_i = B_0^{COD} * MCF_0, \tag{31}$$

where B_0^{COD} is maximum CH_4 producing capacity,

MCF_0 is the methane correction factor, i.e., the fraction of CH_4 generated which is not oxidized but released as CH_4.

Values for the maximum methane production capacity (Bo^{COD}) of wastewater from different industrial sectors are based on a literature review presented in Table 17. Weighted averages of the values for each process/product for the year 2010 were used to calculate the methane production capacity by sector and country. An IPCC (2006, Vol.5, Table 6.2) default factor of 0.25 kt CH_4/kt COD is applied for the maximum CH_4 producing capacity (B_0^{COD}) when no value was available from literature. A methane correction factor (MCF_0) of 0.5 is applied for the uncontrolled case.

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 (Pohkrel and Viraraghavan, 2004 and Thompson et al., 2001). 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 and CH_4 formation are created. For this type of treatment, the methane correction factor (MCF) used in GAINS is 1. 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. MCF used in GAINS is 0.01 for aerobic treatment and 0.005 for well managed anaerobic treatment. With less well managed systems the occurrence of anaerobic conditions increase as well as CH_4 formation (IPCC 2006, Vol.5, Tables 6.3 and 6.8). Anaerobic treatment has advantages over aerobic treatment like lower costs, smaller volumes of excess sludge produced, and the possibility of recovering useful biogas, which can be upgraded to gas grid quality (Lettinga 1995, Thompson et al. 2001). For industrial wastewater, it is assumed that the most effective way to reduce CH_4 emissions is to apply a two-stage process where the water is treated anaerobically with recovery of the biogas in a first stage, which is then followed by an aerobic treatment in a second stage (Latorre et al., 2007). The assumed MCF for this type of treatment is 0.05. In rural areas, domestic wastewater can be collected and treated in latrines, septic tanks or similar anaerobic treatment (USEPA, 1999).

Current applications of different treatment practices for domestic and industrial wastewater in EU countries are taken from UNFCCC (2014) CRF tables complemented with information from EUROSTAT (version as of June 26, 2013), OECD (data downloaded July 2015) and IPCC (2006, Vol.5, Table 6.5). Investment costs for sewage treatment are taken from EEA (2005) and operation and maintenance costs from Hernandez-Sancho and Sala-Garrido (2008). Rural wastewater treatment costs are from USEPA (1999).

Table 17: Literature review of factors used in calculation of industry wastewater emission factors.

Industry	**Product**	**Wastewater genertion in m3/ton. (range over different studies)**	**[COD] in kg/m3 Untreated wastewater. (range over different studies)**	**Maximum CH_4 producing capacity in kg CH_4/kgCOD. (range over different studies)**	**References**
Food	Beer	4.95[a] (1.98 - 7.92)	4[a] (2-6 /1.2 - 125 UK)	0.23 [a] (0.19-0.27)	Debik and Coskun 2009; Kobya, Senturk, and Bayramoglu 2006; Fountoulakis et al. 2008; Şentürk, İnce, and Onkal Engin 2010; AZBAR et al. 2004; Azbar et al. 2009; Healy, Rodgers, and Mulqueen 2007; Brito et al. 2007; Rodgers, Zhan, and Dolan 2004; Sharda, Sharma, and Kumar 2013; Shivayogimath and Jahagirdar 2015; Maya-Altamira et al. 2008.
	Vegetables oils[c]	0.8[a] (0.4 - 1.2)	45.5[a] (5 -804)	0.17[a] (0.11 -0.24	
	Wine	2[b] (0.8-14)	30.4[b] (3.1-150)	0.18[d]	
	Sugar Refining	0.69[a] (0.16-1.0)	6.15 [a] (2.3 -10)	n.a.	
	Meat	13 (IPCC)	5.4 [b] (3 -11)	0.22	
	Dairy Products[e]	3.05[b] [f] (0.19-10)	8.8[b] (0.18 -25.6)	0.22 [b] (0.16 -0.27)	
Pulp	Bleached sulphate pulp	70[a] (30 -110)	1.55[a] (0.10-3.0)	n.a.	Janssen et al. 2009; Ekstrand et al. 2013; Larsson et al. 2015; Karlsson et al. 2011; Tezel et al. 2001; Chaparro and Pires 2011; Dufresne, Liard, and Blum 2001; N H and others 2012; Thompson et al. 2001.
	Unbleached sulphate pulp	50[a] (20 -80)	1.43[b] (1.35 -2.44)	n.a.	
	Bleached sulphite pulp	70[a] (40-100)	2.10[b] (0.62 - 8)	0.22[b] (0.20-0.24)	
	Unbleached sulphite pulp	70[a] (40-100)	0.80[a] (0.20 - 1.4)	n.a.	
	Mechanical wood pulp	20[a] (5-50)	6.9[b] (2.71 - 10.37)	0.19[a] (0.12 - 0.27)	
	Semi-Chemical pulp	50[a] (20-80)	2.19[a] (0.67 -3.71)	0.19[a] (0.11-0.27)	
	Recovered pulp[g]	20	3	n.a.	
	Other fibre pulp	20[g]	8.20[a] (7.7 -8.7)	n.a.	
Paper	Newsprint	9[a] (5-15)	3.5	n.a.	
	Printing and writing paper	60[h] (60-227)	0.81[a] (0.5-1.11)	n.a.	
	Recovered paper	12[a] (8 - 16)	0.51[a] (0.43 -0.58) [i]	0.22[a] (0.16-0.27)	
	Household/sanitary/tissue	8.50[a] (5-12)	1.02[a] (0.05-2)	n.a.	
	Wrapping papers[g]	20	0.08	n.a.	
	Paper and paperboard othe	12[a] (8 - 16)	0.95[b] (0-11)	n.a.	

a Average
b Median
c Olive oil (primarily centrifugation and pressing production processes), sunflower and cotton seed oil
d Based only on one study
e Including milk production, cheese, cheese whey, ice cream and butter
f Most of the data (11 total) are below 4.0 (8)
g based on Höglund-Isaksson, 2012
h 60 m3/ton for UK and 227 m3/ton for Thailand
i Collected after the clarifier

4 N_2O emission sources

4.1 Overview of N_2O emission sources and mitigation options in GAINS

N_2O emission sources in the GAINS model include anthropogenic emissions from agricultural soils, handling of livestock manure, combustion, chemical industry (adipic and nitric acid production, caprolactam production), direct use of N_2O in hospitals and food industry, composting and wastewater treatment. Table 18 provides an overview of the included N_2O emission sources with corresponding mitigation options. Following the requirements of the amendment (EC/29/2009) of the EU-ETS Directive, nitrous oxide emissions from production of nitric acid, adipic acid, glyoxal and glyoxylic acid are included in the EU-ETS emission cap and subject to emission permits under the EU-ETS system (see Table 19). Caprolactam production, which is not part of the EU-ETS, is considered separately.

Table 18: Overview of N_2O emission sources and mitigation options in the GAINS model.

Emission source	GAINS sector	Sector description	GAINS mitigation technology	Technology description
Combustion	CON_COMB -DC/ GSL/ LPG/ MD	Other combustion sources: various fuels	none	No mitigation option identified
	CON_COMB -BC1/ BC2/ HC1/ HC2/ HC3	Other combustion sources: brown coal/hard coal	ISFCSN	NO_X abatement option -*increases* N_2O emissions
	CON_COMB -GAS/HF	Other combustion sources: gas/heavy oil	IOGCSN	NO_X abatement option -*increases* N_2O emissions
	CON_COMB2 -BC1/ BC2/ HC1/ HC2/ HC3	Other combustion sources: fluidized bed -brown coal/hard coal	FBC_CM	Combustion modification in fluidized bed combustion
	DOM -BC1/ BC2/ DC/ GAS/ GSL/ HC1/ HC2/ HF/ LPG/ MD/ OS1/ OS2	Domestic -various fuels	none	No mitigation option identified
	IN_BO -DC/ GSL/ HF/ LPG/ MD/ OS1/ OS2	Industry boilers -various fuels	none	No mitigation option identified
	IN_BO -BC1/HC1/HC2	Industry boilers -brown coal/hard coal	ISFCSN	NO_X abatement option -*increases* N_2O emissions
	IN_BO -GAS	Industry boilers -gas	IOGCSN	NO_X abatement option -*increases* N_2O emissions
	IN_BO -BC1/HC1/HC2/ OS1/ OS2	Industry boilers: solid fuels	FBC	Fluidized bed combustion -*increases* N2O emissions
			FBC_CM	Combustion modification in fluidized bed combustion

Table 18 Cont.: Overview of N_2O emission sources and mitigation options in the GAINS model.

Emission source	GAINS sector	Sector description	GAINS mitigation technology	Technology description
Combustion	IN_OC -DC/ GSL/ HF/ LPG/ MD/ OS1/ OS2	Industry other combustion - various fuels	none	No mitigation option identified
	IN_OC -BC1/HC1	Industry other combustion - brown coal/hard coal	ISFCSN	NO_X abatement option -*increases* N_2O emissions
	IN_OC -GAS	Industry other combustion -gas	IOGCSN	NO_X abatement option -*increases* N_2O emissions
	IN_OC2 -BC1/HC1	Industry other combustion: fluidized bed -brown coal/hard coal	FBC_CM	Combustion modification in fluidized bed combustion
	PP_EX & PP_NEW -DC/ GAS/ GSL/ HF/ MD	Power plants: existing or new - gaseous and liquid fuels	none	No mitigation option identified
	PP_EX & PP_NEW -BC1/ BC2/ HC1/ HC2/ HC3/ OS1/ OS2	Power plants: existing or new - solid fuels	FBC	Fluidized bed combustion -*increases* N2O emissions
			FBC_CM	Combustion modification in fluidized bed combustion
	PP_IGCC, PP_MOD, PP_ENG	Power plants: Integrated Gasification Combined Cycle; Modern (ultra-, supercritical steam of combined cycle); Internal Combustion Engines	none	No mitigation option identified
	TRA_OT_AGR/ AIR_DOM/ CNS/ INW/ LB/ RAI -GSL/MD	Non-road transport: various modes -gasoline/diesel	EU-I to EU-VI	Switching to higher Euro standards
	TRA_RD_HDB/ HDT/ LD4C/ LD4T/ M4 -GSL	Road transport: bus/trucks/cars/vans/two-wheels: gasoline/diesel	EU-I to EU-VI	Switching to higher Euro standards
Industry	PR_ADIP	Adipic acid production	CR	Catalytic or thermal reduction
			TWIN_RED	Twin reduction technology
	PR_NIAC	Nitric acid production	CR	Catalytic or thermal reduction
			BAT	Best available technology
	PR_CAPR	Caprolactam production	CR	Catalytic or thermal reduction
			BAT	Best available technology
Direct N_2O use	N2O_USE	Direct use of N_2O as anaesthetic gas in medicin and as unreactive propellant in food industry	REDUCE	Apply N_2O in combination with other (liquid) anaesthetics
			REDUCE2	Apply even less N_2O in combination with other (liquid) anaesthetics
			REPLACE	Replace N_2O with alternative: e.g., Xe
Waste	COMPOST	Composting	none	No mitigation option identified
Wastewater	WW_DOM	Domestic wastewater handling	OPTIM	Process optimization to increase the N_2/N_2O ratio in effluent gases
Livestock	MANURE-DL/ DS/ OL/ OS/ PL/ PS/ HO/ SH/ LH/ OP	Manure management - solid/liquid systems for various animal categories	none	No mitigation option identified

Table 18 Cont.: Overview of N_2O emission sources and mitigation options in the GAINS model.

Emission source	GAINS sector	Sector description	GAINS mitigation technology	Technology description
Soils	APPLIC - MANURE_N	Application of manure nitrogen on soils	FERT_RED	Set of good practice measures to reduce fertilizer input (note: considered to be covered in fertilier projections)
			FERTTIME	Adjusting fertilizer application to the periods of agricultural demand (note: option superseded by more efficient and cost-effective options)
			VRT_L, VRT_M, VRT_H	Variable rate technology to minimize fertilizer need (three cost levels)
			INHIB_L, INHIB_M, INHIB_H	Nitrification inhibitors to reduce emission rates (three cost levels)
			PRECFARM	Optimization of agricultrual nitrogen efficiency by "precision farming"
	APPLIC - SOIL_N	Application of mineral fertilizer nitrogen on soils, including crop residues	FERT_RED	Set of good practice measures to reduce fertilizer input (note: considered to be covered in fertilier projections)
			FERTTIME	Adjusting fertilizer application to the periods of agricultural demand (note: option superseded by more efficient and cost-effective options)
			VRT_L, VRT_M, VRT_H	Variable rate technology to minimize fertilizer need (three cost levels)
			INHIB_L, INHIB_M, INHIB_H	Nitrification inhibitors to reduce emission rates (three cost levels)
			PRECFARM	Optimization of agricultrual nitrogen efficiency by "precision farming"
	APPLIC - RICE_N	Application of mineral fertilizer nitrogen and crop residues on rice fields	FERT_RED	Set of good practice measures to reduce fertilizer input (note: considered to be covered in fertilier projections)
			FERTTIME	Adjusting fertilizer application to the periods of agricultural demand (note: option superseded by more efficient and cost-effective options)
			VRT_L, VRT_M, VRT_H	Variable rate technology to minimize fertilizer need (three cost levels)
			INHIB_L, INHIB_M, INHIB_H	Nitrification inhibitors to reduce emission rates (three cost levels)
			PRECFARM	Optimization of agricultrual nitrogen efficiency by "precision farming"
	GRAZE - EX_CTTL	Grazing-related emissions from cattle, pigs, poultry excreta	INHIB_L, INHIB_M, INHIB_H	Nitrification inhibitors to reduce emission rates (three cost levels)
	GRAZE - EX_SH	Grazing-related emissions from sheep excreta	none	No mitigation option identified
	HISTOSOLS	Area of organic soils used for agricultural purposes	FALLOW	Abandonment of agricultural use

Table 19: Current legislation affecting N_2O emissions in EU member states.

Emission source	Regulation/ agreement	Region scope	Content that concerns N_2O emissions	Date entering into force
Production of nitric acid, adipic acid, glyoxal and glyoxylic acid	EU ETS Directive (EC/29/2009)	EU-wide	Industry needs to aquire tradable emission permits under the EU emission trading system. With tradable permits control in these sectors is cost-effective.	1 Jan 2012
Soils	EU Nitrate Directive (EEC/676/1991)	EU-wide	Reflected in fertilizer use projections, which GAINS receives from the CAPRI model.	19 Dec 1993
	EU CAP reform (EC/144/2006)	EU-wide	Reflected in animal and fertilizer use projections, which GAINS receives from the CAPRI model.	31 Jan 2009
All non-ETS sectors	EU Effort Sharing Decision (EC/406/2009)	EU-wide	Decision defines legally binding national GHG emission targets for non-ETS sectors. Target year is 2020, but countries need to comply with a linear emission path between 2013 and 2020.	2013

4.2 Energy sector

4.2.1 Combustion in stationary sources

N_2O is formed as a combustion by-product, similar to the formation of NO_x. Available activity data is energy consumption by sector and fuel, which for the EU countries is provided by the PRIMES (2015) model. Stationary combustion sources include emissions from power plants, industry boilers, other combustion in industry, and residential and commercial sector (see Table 18). Emission factors are specified by sector and type of fuel used and taken from IPCC (2006) and de Soete (1993).

No specific mitigation options have been identified for control of N_2O emissions from stationary combustion sources. However, the use of fluidized bed combustion (FBC) and abatement of NO_x (through selective non-catalytic reduction of flue gas) in power plants and industry boilers increases emission factors for N_2O. This may in some cases lead to increasing emissions over time, even if starting from a very low level. For FBC, emission factors used in GAINS have been adopted following Tsupari et al. (2007) and Rentz et al. (2002).

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 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. FBC requires advanced methods to properly regulate combustion air flow and fuel intake to achieve a stable fluidized bed. The GAINS database contains expert estimates of the implementation of FBC, including their future development, in combustion of solid fuels in European countries. This data has been specifically addressed at previous country consultations in order to allow for improvement according to national information. Following information from PRIMES (De Vita, 2013) that FBC is not cost efficient for future power plants, its degree of implementation has been set at the 2005 values for existing power plants and zero for new power plants such that we expect FBC to fade out. In industry, we remain with the GAINS database supplemented with country information.

Methods have been developed and implemented in pilot plants which allow minimizing N_2O formation connected with the use of FBC, i.e., the GAINS technology “combustion modification in fluidized bed combustion”, see Table 18. Data presented by Winiwarter (2005) indicate that 80 percent of N_2O can be removed (Hendriks et al. 2001). Also cost data was taken from this source. No discrimination has been made for applicability or costs in different countries (considered to be 100 percent).

4.2.2 Combustion in mobile sources

N_2O emissions from mobile sources are known to be affected by NO_x abatement applied to the vehicle exhausts. N_2O emissions are linked to the NO_x abatement technology applied in the form of catalytic converters or SCR-technology applied in diesel vehicles. Activity data for the EU countries is adopted from the PRIMES (2015) model. Emission factors depend on several factors like fuel, technology and operating characteristics. GAINS uses default emission factors from the European transport emission database COPERT4 (EMISIA, 2011 http://www.emisia.com/copert/General.html). Emission factors are specified by vehicle category, type of fuel used and the emission control standard of the vehicles (EURO I to EURO VI), while averaging for road types and driving conditions. NO_x abatement may lead to increased N_2O emissions, as were observed in the early generations of catalysts. To reflect this, N_2O emission factors are differentiated by the emission control standard. Apart from this, no N_2O specific mitigation options are identified for mobile combustion sources in GAINS.

4.3 Industry sector

4.3.1 Adipic acid production

The industrial process generating adipic acid (a compound required in the production of Nylon 66 or polyurethane) 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 occurs in only a handful of countries, and since only very few production plants are involved (as of 2010, there were 5 plants operational in EU-28), the CRF tables usually list production data as “confidential”, but the exact sites and production capacities are known (Schneider et al., 2010). Therefore, we supplement activity data with capacity and derive future development by country from PRIMES (2015) model outputs, specifically by scaling according to the value added in chemical industry.

The small number of producers also allows observing general structural changes efficiently. Industry have made voluntary agreements after a cost-efficient method (catalytic reduction) had been developed to take advantage of the high N_2O concentrations in plume to efficiently remove and even convert back into nitric acid (with 95% efficiency). Most plants had been retrofitted by 2000, with the exception of one in Novara, Italy, where this modification started to be fully operative from 2006 only.

As the method in principle is able to reduce 99.9 percent of the emissions, and the remaining emissions are mainly released during operational shutdown of the abatement device, one of the smaller European plants in Krefeld, Germany, recently installed a backup device. This backup device is expected to reduce 80 percent of the remaining emissions (LANXESS, 2008), such that total abatement of 99 percent (95% +80% of 5% remaining) can be achieved, allowing for some system failure still. Costs for the installations have been estimated to be identical to the original system, but the marginal cost of abating the additional 4%-points (considering the much smaller reductions) is of course considerably higher. The option termed "twin reduction technology" is not available in 2015, but with the expected carbon price level of the ETS system (see Section 2.3), we assume full implementation of this option from 2020 onwards.

In this sector, we also cover emissions from Glyoxal/glyoxylic acid production as the underlying chemical process is similar. Glyoxal production employing the nitric acid pathway (thus causing N_2O emissions) is reported from one plant in EU28 only (in France).

4.3.2 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. Nitric acid production occurs in many EU countries, often in several installations, but some countries keep activity data confidential. In such cases, production amounts were inferred using emission results and the default unabated emission factor for the base year. Future production development has been scaled according to the value added in chemical industry, taken from the PRIMES (2015) model outputs.

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 level of production makes this an important emission source. In nitric acid production also 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 (de Soete 1993; de Beer 2001; Kuiper 2001), leading to emission reductions of 80%. The use of information from a demonstration plant in Linz, Austria, as published in the BREF report (EC, 2007) allows for reasonable estimates of the additional costs incurred. Recent information from the same plant (Muik, 2009) demonstrates that a second level of abatement has been made available allowing to reduce emissions by 94%. As the plant operates under commercially favourable conditions, we assume that this more stringent "best available technology" reduction option is available at no extra costs.

As a consequence of the general introduction of emission reduction technologies across EU, between 2007 and 2012 N_2O emissions from nitric acid production have dropped to one quarter (UNFCCC-CRF 2014; 2015), presumably at least in part in connection with introduction of the EU emission trading scheme. We use this UNFCCC data to establish, by country, the respective abated emission factor to assess the level of control already established in a historic year. As the marginal cost of using catalytic reduction to control emissions from nitric acid production is estimated at less than the expected carbon price in the ETS market, thus full adoption of the "best available technology" option seems reasonable in all Member States from 2020.

4.3.3 Caprolactam production

The production of caprolactam, which in a similar manner as adipic acid is used to create the polymer Nylon 6, occurs only in five EU countries at a rather limited scale. As with nitric acid production, nitrous oxide is formed as a by-product during the oxidation of ammonia. Information on abatement technology is scarce, also as the contribution to overall emissions are not large. Only with the decline in emissions from nitric acid production, caprolactam becomes the remaining source of industrial N_2O, in some countries arriving at or even exceeding the emissions of nitric acid production.

Due to the similarities in process, GAINS uses the same control technologies, emission reduction efficiencies and costs as for nitric acid production. Caprolactam is dealt with separately as it is not included in the ETS.

4.3.4 Direct use of N_2O

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 N2O_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 (Spakman et al. 2003; Nakata et al. 1999). While the use of combined anaesthetics to supplement N_2O application can be observed in practice following national sale statistics, data on replacement are highly speculative.

4.4 Waste and wastewater sector

Microbial processes are responsible for conversion of nitrogen compounds contained in waste or wastewater, during which process also N_2O is released. GAINS uses default emission factors derived by IPCC (2006) to quantify these emissions. Specifically, emissions occur during composting and in wastewater treatment. Both emission sources are small sources.

For composting, this default factor refers to the amount of wet waste entering treatment. No differentiation is being made for specific process or type of material. Also, no options are known to mitigate such emissions.

In sewage treatment, the amount of nitrogen added depends on the number of people connected. In consequence, emissions can be estimated by population number on a country scale. GAINS uses a simple emission factor per inhabitant for assessing wastewater related emissions (Behrend et al., 2004). In line with Hendriks et al. (1998), it is assumed that an optimization of process parameters will lead to a decrease of emissions by 40%, without compromising on any of the other operating requirements of the facility, specifically not affecting downstream N content. This measure is assumed to not need any specific investment or operation cost.

4.5 Agriculture sector

4.5.1 Agricultural and grassland soils

4.5.1.1 Emissions of N_2O from 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; Winiwarter and Muik, 2010). Lately there has been some evidence that, averaged over long time periods and large areas, inventories using IPCC methodology provide a very useful tool to understand the real world emissions. On a global scale, Mosier et al. (1998) proved that emissions are in agreement with observed trends of N_2O accumulation in the atmosphere. Using inverse modelling, Bergamaschi et al. (2015) demonstrated in general reasonable agreement between observations on tall towers in Europe, and European inventories. Moreover, assessments of global N_2O developments based on more generic parameters (freshly created reactive nitrogen, or total mineral fertilizers and total manure only) note that the IPCC total “is not inconsistent with the total derived by the top-down methodology” developed therein (Crutzen et al., 2008; Davidson, 2009).

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. Information on mineral fertilizer use and projections till 2050 derive from results of the CAPRI model (2015), which also provides numbers of animals on farms. Assessing the amount of animal manure also requires nitrogen excretion rates, data that are available in the national reports (UNFCCC, 2015) and have been integrated in the GAINS model with the help of national experts during consultations (Amann et al., 2015). The amount of crop residues and their nitrogen content is again taken from national reports (UNFCCC, 2015), with no temporal trend assumed.

As from 2015, countries change reporting methodology in their national greenhouse gas inventory. With completion of the Kyoto period, using the IPCC (2006) guidelines has become mandatory. One major difference for agricultural N_2O emissions is a different treatment of indirect emissions due to nitrate leaching. Nevison (2002) discovered and described in detail these issues that lead to a reevaluation of the situation by IPCC (2006), which under default conditions decreases indirect emissions due to leaching by a factor of more than 3, such that overall soil-related N_2O emissions (direct & indirect) are reduced by about a third.

Consequently, also the algorithm for assessing soil N_2O emissions in GAINS has been updated. As previously, there is no differentiation between direct and indirect emissions. Instead, IPCC default data has been used to assess the level of indirectly produced N_2O (as a result of atmospheric redeposition of ammonia, or nitrate leaching) and aggregated into an overall emission factor. IPCC (2006) reports distinctively different emissions from grazing (of which sheep have distinctively lower emissions than cattle) and from direct application of fertilizers (mineral fertilizers, animal manure and crop residue nitrogen have largely similar impacts) to soils. Wetland rice production is associated with a lower emission factor. Avoiding a category split not supported by data, the following activity clusters having the same emission factor were created in GAINS: grazing (all animals except sheep), sheep grazing and manure application, mineral fertilizer and crop residues application on soil and grassland, and fertilizer application on wetland rice (see Table 20).

Table 20: Emission factors of N_2O from soils as used in GAINS. Default release rate (given in % of N applied), shares of re-emissions and leaching were taken from IPCC (2006), the conversion to total N_2O emitted uses a stoichiometry factor of 1.57

IPCC 2006	manure / grazing (sheep)	grazing (all other animals)	urea	other mineral fertilizer	crop residues	flooded rice
direct soil emissions [%]	1.000	2.000	1.000	1.000	1.000	0.300
indirect / atmos deposition [%]	0.200	0.200	0.150	0.030	0.000	0.150
indirect leaching [%]	0.225	0.225	0.225	0.225	0.225	0.225
Total N_2O-N [%]	1.425	2.425	1.375	1.255	1.225	0.675
Total N_2O [kg N_2O/kg N applied]	0.022	0.038	0.022	0.020	0.019	0.011
GAINS emission factors [kg N_2O/kg N applied]	0.022	0.038	0.020			0.011

Technological options to reduce N_2O emissions may target either on the nitrogen input, or on the release rate of N_2O. Following the tier 1 level of the IPCC (2006) methodology, reducing nitrogen input (increasing NUE) is the only applicable way to get emission reductions accepted, thus the majority of measures available in the literature focusses on reduced inputs. Increased NUE's have been observed over the last years in Europe (OECD, 2008), in part as a consequence of fertilizer savings also triggered by environmental considerations. Further such changes are implemented in the CAPRI (2015) fertilizer projections, improvements deemed technologically possible may in part be factored in already as part of the projections. Using CAPRI's Nitrogen budgets, an improvement of NUE of 6.6% by 2030 compared to the base year 2005 becomes evident. Measures implicitly assumed by CAPRI may in part reflect reduction technologies and need to be accounted for when applying N-input reductions as abatement measures.

Thus, with the update of the algorithm to assess soil N_2O emissions, GAINS also updates abatement technologies. Based on a thorough review of available scientific literature

(Winiwarter and Sajeev, 2015), emission reductions have been reassessed and technologies available in agriculture have been updated. The resulting reduction efficiencies are described in detail below. Using further literature with a specific focus on the European situation (e.g., Tavella et al., 2010, from the "FutureFarm" research project), cost information has been further refined. Cost data are now split into investments, operation costs and (financial) benefits derived from implementing a given technology.

4.5.1.2 Emission abatement technologies for N_2O emissions from soils

As with emissions generally, there are two directions abatement could take: controlling emissions, or reducing activities. In the case of N_2O from soil, lowering fertilization rate (i.e., reducing input activities) is clearly a chance to also reduce emissions wherever the nitrogen use efficiency is low. Obviously such measures would not change the amount of manure or crop residues available to deliver nutrients, but if used more effectively such organic nutrients would be able to further reduce mineral fertilizer application. Further technology options exist to reduce emissions while maintaining fertilizer levels. While combination of both types of technologies is conceivable, evidence seems not to suffice for inclusion in GAINS.

The concept of abatement technology used here basically follows the concept developed by Gale and Freund (2002) and updated for use in GAINS according to Winiwarter (2005). It describes, for the same set of "activity", N application on agricultural soils, subsequent abatement stages of increasing stringency and at the same time increased costs. In addition to the original approach, now also improvements in nitrogen use efficiency are considered, and the cost-dependence ("economy of scale") of the size of farms has been investigated. In this new structure, the three technologies effectively considered are: "variable rate" application of fertilizers, agrochemical "inhibitors" (limiting the microbial processes that release N_2O) and "precision farming" (as a high-tech tool to minimize and optimize agricultural production).

4.5.1.3 Fertilizer reduction measures and efficiency improvements

The simplest and cheapest form of reducing excess fertilizer application is to reduce its wastage. "Fertilizer reduction" subsumes a set of good practice approaches to avoid fertilizer losses to ditches and to set-asides, or excess application by inappropriate or misadjusted spreaders. Following previous studies, Winiwarter (2005) assumed 6% of fertilizer could be saved this way.

As GAINS obtains external information on future fertilizer application, specifically using the results of the CAPRI model (Britz and Witzke, 2014), it is important to provide consistent assumptions. CAPRI internally estimates fertilizer demand in part from plant requirements, and it also projects agronomic improvements based on past trends. On an EU average, the modelled improvement between 2005 and 2030 amounts to 6.6%, which comes close to the 6% reduction expected from the simple measures to reduce fertilizer application. We thus conclude that improvements expected by CAPRI largely refer to measures defined as simple improvements, and "fertilizer reduction" should therefore be assumed to be already fully implemented without costs in the baseline scenario by 2030. No emission reductions will result as implicitly the reduced fertilizer consumption rates will cover these reductions.

4.5.1.4 Farm sizes

Choosing agronomic practice and developing economically viable strategies for farms will often also depend on the farm size. This is also the case for emission abatement. In the case of air pollutants (ammonia, specifically), an elaborate scheme has been worked out to assess abatement costs on the basis of animal numbers per farm averaged by country (Klimont and Winiwarter, 2015). The same "economy of scale" principle also applies to agronomy, but in contrast to animal husbandry it is the farm area that will determine the scale of activities. Especially for one-time costs that can be distributed over a large area on large economic units, such as investments or one-time training costs, cost advantages may occur for larger units. Smaller units, however, do also have opportunities to take advantage of expensive technology etc., which they can more easily share as needed only for a short time period to cover the smaller area. Traditionally this has been organized in machinery rings or by using the service of a contractor.

We use here farm sizes as collected by EUROSTAT in their agricultural data on farm structure, specifically those for arable crops (Table ef_alarableaa, available at http://ec.europa.eu/eurostat/data/database). For each EU member country, the shares of arable area in a given size class of utilized agricultural area (>150 ha, 30-150 ha, and <30 ha) have been extracted und used for further differentiation. We apply these shares also to grassland and permanent crops as arable land constitutes the largest share of fertilized agricultural area in almost all countries, and we understand that the farm size structure of a country is well represented. An alternative EUROSTAT table (ef_oluaareg) only provides differentiation up to 100 ha utilized agricultural area per farm and was therefore not selected. In contrast to the methods adopted to describe increasing animal numbers per farm (see section 3.3), the agricultural area of 2010 has been used throughout to depict farm sizes, even if data from different years indicate a consistent trend towards increased size could be derived here, too.

4.5.1.5 Variable rate technology

Precision agriculture provides nutrients to plants only to the extent they need it. At high prices of agricultural commodities and technical progress, there is a long-standing discussion (see e.g. Auernhammer, 2001) whether saving fertilizer at a certain point would not compensate any expenditure for technology, such that precision agriculture might become profitable. Looking into the lower-cost options of precision agriculture, here we consider the use of sensors and yield maps to estimate the fertilizer requirements on the scale of square meters, combined with applicators that individually regulate the dose spread according to the locally optimized needs (Variable rate technology, VRT). Winiwarter and Sajeev (2015) compile the results of ten individual studies and reviews which, using sensor technology, on the average allow to reduce nutrient inputs by 24% to arrive at comparable yields. In a situation of 2030, assuming general efficiency improvements having taken place (6%, see above), implementation of such a technology still would decrease application rates by 19%. It is interesting to note that some authors (Sehy et al., 2003) observed N_2O emission reductions clearly higher than the fertilizer application decrease (34% at 18% less fertilizer) which could be explained by less excess nitrogen available – but has not been used here. Instead, emissions remain to be considered proportional to N fertilizer application.

Very little information is available on costs, even while the technology actually exists and is on the market. Cost assessment, in some cases, referred also to different farm sizes, or at least was provided for a given farm size. Operation costs and investment for sensor and spreaders have been made available from U.S. studies (ICF, 2013; Koch et al., 2004). In order to apply instrumentation for a European situation, here we decided to apply the cost estimates of the "FutureFarm" project (Tavella et al., 2010), who (for a 500 ha farm) require one set of sensor & spreader. Moreover, in order to maintain consistency with the emission reductions derived from our literature survey from the sensor system, we include also costs of an "auto guidance" system. This systems provides detailed information on the location of agricultural machinery and allows, by precise GPS guidance, to fully prevent overlaps in spreading. One system is needed per 250 ha (Tavella et al., 2010). Applying this to a 250 ha farm (which we use as representative for all farms at >150 ha), we arrive at total investments of EUR 56000, annualized over ten years, plus 5% maintenance costs and flat costs for the precision GPS signal. Note this investment is about 2-3 times that assumed in U.S. studies (ICF, 2013; Koch et al., 2004). Benefits are fertilizer savings due to a 19% lower application rate, which we estimate at 1.11 €/kg N (following an estimate by KTBL, personal information transmitted to JRC). With costs and benefits closely matching, results are volatile with respect to assumptions taken – i.e., under certain real conditions costs may be higher while for other situations VRT may actually be profitable (see detailed emission factors and cost data provided in Table 21).

Basically the same considerations apply to the use of VRT for manure spreading. As manure cannot be saved, we understand that it can be distributed to a larger area and so save mineral fertilizer elsewhere. Savings, however, are estimated only at 80% of the N content.

For farms smaller than 150ha, investments needed would soon render VRT very costly, while the equipment would remain idle for most of the year. Sharing of equipment, under such conditions, seems a viable option. While some studies (ICF, 2013) have ignored that "because 70–80% of farmers who currently use [a specific VRT] technology purchase it", the current market situation cannot be seen representative for the costs of a future activity. We use the additional costs estimated by Koch et al. (2004) for contracting, scale it by the significantly higher investments assumed for the European situation, and apply the resulting costs to farms between 30 and 150 ha size. For even smaller farms, we understand an organization overhead of 20% is needed in addition. Revenues in both cases are reduced fertilizer application, and again resulting costs reflect an average condition and may be different in individual situations as local variation cannot be adequately modelled here.

4.5.1.6 Inhibitors

Enhanced efficiency fertilizers have been developed to allow a continuous supply of nutrients during the growth phase of plants. As urease inhibitors and nitrification inhibitors, key compounds of the so-called "stabilized fertilizers", prevent processes that release N_2O, we specifically looked into the effect of reduced emissions as a consequence of such inhibitors. Following the literature survey by Winiwarter and Sajeev (2015), 14 studies were evaluated covering different parts of the world and often several types of enhanced efficiency fertilizers. Inhibitors were among the most efficient, by average demonstrating an emission reduction of 38%. Here we do not account for possible simultaneous fertilizer reductions, and we also will not consider the resulting economic benefit – consistent with the way emission reductions are being reported in the background literature. Compared to an improved 2030 situation due to improved nitrogen use efficiency already in the baseline (see above), emission reductions are still as high as 34%.

The effectiveness and considerable achievable emission reductions have been noted before (see e.g. the review by Snyder et al., 2014). However, inhibitors are substances that affect the soil microflora (Freibauer, 2001) and may exhibit possible unintentional side effects, which call for monitoring programs.

Limited information on costs is available, which basically is a consequence of the incremental cost charged to treated fertilizer – inhibitors typically will be applied in combination with or as compounds of fertilizers. Estimates from fertilizer industry indicate costs to be clearly below 10% of the original fertilizer. Costs derived from market prices (Carson and Ozores-Hampton, 2014) matched both the industry quote and the estimate used by Winiwarter (2005). We apply this estimate and add 10% training and other transaction costs (for a 250 ha farm). The same training costs in absolute terms, also applied to smaller far sizes, lead to cost increases for smaller farms, such that the training element for 20ha farms exceed the fertilizer cost increments. Training costs alone have been quoted at 300 GBP per farm every 5 years (Godwin et al., 2003), as annual costs less than an order of magnitude smaller than training and transaction costs of 365 EUR per farm and year which have been derived as above. Resulting emission factors and cost data are provided in Table 21.

Inhibitors can be generally used, also for manure and even animal droppings and urea patches. While use during application is rather straightforward, additional labor is needed to treat animal excreta on pasture. O'Brien et al. (2014b) estimate inhibitors are applicable to urine (60% of N excreted) in 50% of cases, reducing direct & indirect emissions by 50%, while Di and Cameron report reductions of direct emissions by 80%. Here we use 80% generally, applicable to half of the urine excreted, thus total reductions amount to 24% (0.6x0.5x0.8). This reduction applies to pastures and thus is unaffected by the improved nitrogen use efficiency relevant in other cases. Costs were converted from data provided by O'Brien et al. (2014b), reflect the tedious additional work needed and thus represent an upper level of the cost curve (see Table 21).

4.5.1.7 Precision farming

Soil testing, yield mapping, additional sensors including airborne equipment all have been discussed as means to further optimize nutrient supply to plants. Both efficiency in emission reduction and costs exceed those of VRT. While little information is available, we allow abatement marginally higher than inhibitors, and unit costs as already selected by Winiwarter (2005) and Gale and Freund (2002). Precision farming thus appears at the top of the cost curve (Table 21).

4.5.1.8 Cost curve parameters

Resulting from the above assumptions, Table 21 displays the detailed emission factors and cost assumptions used in agriculture, based on IPCC (2006) guidelines and IPCC AR4 global warming potential for N_2O (1 kg N_2O, over 100 years, is assumed to exert the same forcing effect as 298 kg of CO_2).

Table 21: Emission factors and abatement costs in agriculture (except histosols), expressed as € of 2010. Large farms (>150, nominal average set at 250 ha), Medium farms (30-150, nominal average set at 80 ha) and Small farms (<30, nominal average set at 20 ha) are considered separately for some abatement measures. Default fertilizer input used is 170 kg N/ha, the effectiveness of manure as fertilizer has been set to 80%.

Sector	Abatement	Cost structure	Investment [M€/ (kt N/yr)]	Lifetime [yr]	O&M [M€ / kt N]	Savings [M€ / kt N]	Uncontrolled emissions [kt N_2O / kt N]	Controlled emissions [kt N_2O / kt N]
Mineral fertilizer	VRT	Large farms	1.32	10	0.034	0.21	0.020	0.0162
		Medium farms			0.249	0.21	0.020	0.0162
		Small farms			0.299	0.21	0.020	0.0162
	Inhibitors	Large farms			0.095		0.020	0.0132
		Medium farms			0.113		0.020	0.0132
		Small farms			0.194		0.020	0.0132
	Precision Farming				0.302		0.020	0.0132
Manure	VRT	Large farms	1.32	10	0.034	0.17	0.022	0.0178
		Medium farms			0.249	0.17	0.022	0. 0178
		Small farms			0.299	0.17	0.022	0. 0178
	Inhibitors	Large farms			0.095		0.022	0.0145
		Medium farms			0.113		0.022	0.0145
		Small farms			0.194		0.022	0.0145
	Precision Farming				0.302		0.022	0.0140
Grazing (cattle)	Inhibitors	grazing (all except sheep)			0.810		0.038	0.0289

VRT – Variable Rate Technology

O&M – Operation and Maintenance

Note that in GAINS no emission abatement options are foreseen for the categories “grazing sheep” and “flooded rice” production, hence they have been excluded from the table above.

4.5.2 Organic soils

Soil processes in organic soils do not differ from those in other soils, but the larger amount of carbon available provides “feed” for micro-organisms which become more productive. Organic soils (histosols) are thus treated separately in national greenhouse gas inventories (IPCC, 2006). Thus the area of histosols used for agricultural purposes (HISTOSOL, presented in Mha area) is taken from the national submissions to the UNFCCC (UNFCCC 2015).

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. Emission reductions are taken as the difference between natural background and cultivated histosols according to IPCC (2006) which indicate 94% reductions, and costs have been estimated as lost revenues from agricultural production of 500 €/ha (e.g. Riester et al., 2002).

4.5.3 Livestock

When the organic content in livestock manure decomposes, emissions of CH_4 and N_2O are released. While CH_4 release occurs when manure is handled under anaerobic conditions, formation of N_2O occurs during aerobic conditions, i.e., with access to oxygen. Activity data is number of animals by animal category and type of manure management system (solid/liquid). Sources for historical animal numbers are EUROSTAT (2015) for EU countries with projections based on future trends taken from the CAPRI model (2015).

Emissions of N_2O from manure handling 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, 2015), projections of animal numbers are available from the CAPRI model.

For dairy cows, both enteric fermentation emissions and manure management 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 m (13) for milk production exceeding the productivity level 3000 kg per animal per year, i.e.,

$$ef_{it;cow}^{NOC} = ef_i^{animal} + ef_i^{milk} * \left(x_{it} - 3000\right) \tag{32}$$

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*.

Increased nitrogen excretion associated with high milk yields (above 3000 kg/hd) is considered at an increase rate provided by national experts during consultations (Klimont, pers. communication).

While the methodology as such has not been changed in the IPCC (2006) guidelines, different emission factors are now used for manure systems (liquid vs. solid) and for animal categories (poultry). In the Reference 2016 scenario, GAINS applies these default emission factors as in the previous non-CO_2 Reference scenario from 2013 (Capros et al., 2013), just updating from IPCC (1997) to the IPCC (2006) guidelines (Table 22). No emission abatement technologies are considered in GAINS for N_2O emissions from manure handling.

Table 22: Emission factors for manure handling following IPCC (2006), Vol. 4, Table 10.21. The conversion to total N_2O emitted (from originally N_2O-N) uses a stoichiometry factor of 1.57.

GAINS manure system	Emission factor [kg N_2O/kg N excreted]		IPCC characterization
poultry	0.0016		Poultry manure with/without litter
solid manure systems	0.0157		Cattle and Swine deep bedding
liquid manure systems	0.0079		Liquid/slurry with cover

Changes over time occur, however, in terms of the manure systems, with general trends towards an emission reduction due to liquid manure systems becoming more prevalent. Information on such a change over time derived from country experts during consultations (for a few countries only), or from the extrapolated trend in increasing animal numbers per farm (see section 3.3). As large farms (with a high number of animals) tend to be on liquid systems, it is assumed that the separation between liquid and solid systems is strictly along a given number of animals on a farm, and that farms above a certain (country specific) size automatically will use liquid systems. This allows deriving a liquid/solid share for any future scenario, which is applicable for pigs, dairy cows and other cattle, for which such solid/liquid share information is available.

5 F-gas emission sources

5.1 Overview of F-gas emission sources and mitigation options in GAINS

The methodology for inclusion of fluorinated gases (F-gases) in the GAINS model has recently undergone a thorough revision. The starting point for the revisions has been the methodology presented in Tohka (2005), but where Tohka (2005) uses emissions as activity data, the revised GAINS version (Höglund-Isaksson et al., 2013) link emissions to the activity drivers. In addition, recent development in F-gas mitigation options has been updated and included.

F-gas (HFC’s, PFC, SF_6) emissions have increased significantly in recent years and are estimated to rise further in response to phase out ozone-depleting substances (ODS) under the Montreal Protocol (Gschrey et al. 2011, Velders et al. 2015). GAINS accounts for emissions of hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6).

HFCs, PFCs and SF_6 are potent greenhouse gases and therefore regulated under the Kyoto Protocol. Emissions of HCFCs are not regulated under the Kyoto Protocol, but included in GAINS in order to model the transition from HCFCs to HFCs as outlined by the latest revision of the Montreal Protocol (UNEP, 2007). In compliance with the Montreal protocol, many applications that formerly used chlorofluorocarbons (CFCs) for cooling and refrigeration purposes changed rapidly to applications employing HCFCs with lower ozone-depleting effects or to HFCs with no ozone-depleting effects. Later amendments to the Montreal protocol require a complete phase-out of all ozone-depleting substances including HCFCs (UNEP, 2007). In GAINS, all use of CFCs in mobile air conditioners in the EU-28 is assumed phased out by 2005, while in stationary sources about 20 percent of the total demand for HFCs/HCFCs is still covered by HCFCs in 2005 followed by a gradual phase-out completed by 2020.

Table 23 presents the structure of F-gas emission sources (for the Kyoto protocol gases HFCs, PFCs and SF_6) in GAINS with corresponding mitigation options. HFCs are primarily used in cooling and refrigeration appliances, but also as blowing agents in foams or as propellants for aerosols. Emissions of HFCs from these sources can be reduced through good practices like leakage control and end-of-life recollection and recycling. For more substantial removal of emissions, the HFCs need to be replaced by alternative substances with low or no global warming potential. The production of HCFC-22 for feedstock use in industry also gives rise to HFC emissions unless these are controlled through incineration. Sources of PFCs accounted for in the GAINS model are primary aluminium production and the semiconductor industry. The SF_6 sources considered are high and mid- voltage switches, magnesium production and casting, soundproof windows and some small sources like tyres and sports equipment. For more details on activity data, emission factors, mitigation options, and emissions estimation methodology applied in GAINS, see respective sector descriptions below.

Table 23: Overview of F-gas sources and mitigation options in the GAINS model.

Gas	GAINS sector	Sector description	GAINS technology	Technology description
HFCs	CAC_B	Commercial air conditioning, emissions banked in equipment	GP	Good practice: leakage control, improved components
			ALT_HFC	Alternative HFC refrigerant (e.g., HFC-152a)
			ALT_HC	Alternative refrigerant: Propane (HC-290), Iso-butane (HC-600a), propene (HC-1270)
			ALT_CO2	Alternative technology: pressurized CO_2
			LOW_GWP	Placeholder for speculative future HFO alternative refrigerant
	CAC_S	Commercial air conditioning, emissions from scrapped equipment	GP	Good practice: end-of-life recollection
			ALT_HFC	Alternative HFC refrigerant (e.g., HFC-152a)
			ALT_HC	Alternative refrigerant: Propane (HC-290), Iso-butane (HC-600a), propene (HC-1270)
			ALT_CO2	Alternative technology: pressurized CO_2
			LOW_GWP	Placeholder for speculative future HFO alternative refrigerant
	COMM_B	Commercial refrigeration, emissions banked in equipment	GP	Good practice: leakage control, improved components
			ALT_HFC	Alternative HFC refrigerant (e.g., HFC-152a)
			ALT_HC	Alternative refrigerant: Propane (HC-290), Iso-butane (HC-600a), propene (HC-1270)
			ALT_CO2	Alternative technology: pressurized CO_2
	COMM_S	Commercial refrigeration, emissions from scrapped equipment	GP	Good practice: end-of-life recollection
			ALT_HFC	Alternative HFC refrigerant (e.g., HFC-152a)
			ALT_HC	Alternative refrigerant: Propane (HC-290), Iso-butane (HC-600a), propene (HC-1270)
			ALT_CO2	Alternative technology: pressurized CO_2
	DOM_S	Domestic small hermetic refrigerators, emissions from scrapped equipment	GP	Good practice: end-of-life recollection
			ALT_HC	Alternative refrigerant: Iso-butane (HC-600a)
	HFC_OTH	Other	ALT_HFC	Alternative HFC refrigerant (e.g., HFC-152a)
	IND_B	Industrial refrigeration, including food and agricultural sectors, emissions banked in equipment	GP	Good practice: leakage control, improved components
			ALT_HFC	Alternative HFC refrigerant (e.g., HFC-152a)
			ALT_HC	Alternative refrigerant: Propane (HC-290)
			ALT_NH3	Alternative refrigerant NH3
			ALT_CO2	Alternative technology: pressurized CO_2
	IND_S	Industrial refrigeration, including food and agricultural sectors, emissions from scrapped equipment	GP	Good practice: end-of-life recollection
			ALT_HFC	Alternative HFC refrigerant (e.g., HFC-152a)
			ALT_HC	Alternative refrigerant: Propane (HC-290)
			ALT_NH3	Alternative refrigerant NH3
			ALT_CO2	Alternative technology: pressurized CO_2
	RAC_B	Residential air conditioning, emissions banked in equipment	GP	Good practice: leakage control, improved components
			ALT_HFC	Alternative HFC refrigerant (e.g., HFC-152a)
			ALT_HC	Alternative refrigerant: Propane (HC-290), Iso-butane (HC-600a), propene (HC-1270), etc.
			ALT_CO2	Alternative technology: pressurized CO_2
			LOW_GWP	Placeholder for speculative future HFO alternative refrigerant
	RAC_S	Residential air conditioning, emissions from scerapped equipment	GP	Good practice: end-of-life recollection
			ALT_HFC	Alternative HFC refrigerant (e.g., HFC-152a)
			ALT_HC	Alternative refrigerant: Propane (HC-290), Iso-butane (HC-600a), propene (HC-1270), etc.
			ALT_CO2	Alternative technology: pressurized CO_2
			LOW_GWP	Placeholder for speculative future HFO alternative refrigerant
	TRA_REFB	Refrigerated transport, emissions banked in equipment	GP	Good practice: leakage control, improved components
			ALT_HFC	Alternative HFC refrigerant (e.g., HFC-152a)
			ALT_HC	Alternative refrigerant: Propane (HC-290), propene (HC-1270)
			ALT_CO2	Alternative technology: pressurized CO_2
	TRA_REFS	Refrigerated transport, emissions from scrapped equipment	GP	Good practice: end-of-life recollection
			ALT_HFC	Alternative HFC refrigerant (e.g., HFC-152a)
			ALT_HC	Alternative refrigerant: Propane (HC-290), propene (HC-1270)
			ALT_CO2	Alternative technology: pressurized CO_2
	TRA_RD_HDB_B	Mobile air conditioning in buses, emissions banked in equipment	GP	Good practice: leakage control, improved components
			ALT_HFO	Alternative refrigerant: HFO-1234yf
			ALT_CO2	Alternative technology: pressurized CO_2
	TRA_RD_HDB_S	Mobile air conditioning in buses, emissions from scrapped equipment	GP	Good practice: end-of-life recollection
			ALT_HFO	Alternative refrigerant: HFO-1234yf
			ALT_CO2	Alternative technology: pressurized CO_2
	TRA_RD_HDT_B	Mobile air conditioning in heavy duty trucks, emissions banked in equipment	GP	Good practice: end-of-life recollection
			ALT_HFO	Alternative refrigerant: HFO-1234yf
			ALT_CO2	Alternative technology: pressurized CO_2
	TRA_RD_HDT_S	Mobile air conditioning in heavy duty trucks, emissionsfrom scrapped equipment	GP	Good practice: end-of-life recollection
			ALT_HFO	Alternative refrigerant: HFO-1234yf
			ALT_CO2	Alternative technology: pressurized CO_2
	TRA_RD_LD4C_B	Mobile air conditioning in cars, emissions banked in equipment	GP	Good practice: leakage control, improved components
			ALT_HFO	Alternative refrigerant: HFO-1234yf
			ALT_CO2	Alternative technology: pressurized CO_2
	TRA_RD_LD4C_S	Mobile air conditioning in cars, emissions from scrapped equipment	GP	Good practice: end-of-life recollection
			ALT_HFO	Alternative refrigerant: HFO-1234yf
			ALT_CO2	Alternative technology: pressurized CO_2
	TRA_RD_LD4T_B	Mobile air conditioning in light and heavy duty trucks, emissions banked in equipment	GP	Good practice: leakage control, improved components
			ALT_HFO	Alternative refrigerant: HFO-1234yf
			ALT_CO2	Alternative technology: pressurized CO_2
	TRA_RD_LD4T_S	Mobile air conditioning in light and heavy duty trucks, emissions from scrapped equipment	GP	Good practice: end-of-life recollection
			ALT_HFO	Alternative refrigerant: HFO-1234yf
			ALT_CO2	Alternative technology: pressurized CO_2

Continued: Table 23: Overview of F-gas sources and mitigation options in the GAINS model.

Gas	GAINS sector	Sector description	GAINS technology	Technology description
HFCs	AERO	Aerosols	ALT_HFC	Alternative propellant HFC-152a
			ALT_HC	Alternative refrigerant: Propane (HC-290), Iso-butane (HC-600a), n-propane etc.
			ALT_HFO	Alternative propellant HFO-1234ze
	OC	Polyurethane one component foams	ALT_HFC	Alternative blowing agent: HFC-152a
			ALT_HC	Alternative blowing agent: Iso-butane (HC-600a), Iso-pentane, n-pentane
			ALT_HFO	Alternative blowing agent: HFO-1234ze
			ALT_CO2	Alternative technology: pressurized CO_2
	OF	Other foams	ALT_HFC	Alternative blowing agent: HFC-152a
			ALT_HC	Alternative blowing agent: Iso-butane (HC-600a), Iso-pentane, n-pentane
			ALT_HFO	Alternative blowing agent: HFO-1234ze
			ALT_CO2	Alternative technology: pressurized CO_2
	GSHP_B	Ground source heat pumps, emissions banked in equipment	GP	Good practice: leakage control, improved components
			ALT_HC	Alternative refrigerant: Propane (HC-290), propene (HC-1270)
			ALT_HFC	Alternative HFC refrigerant: HFC-152a
			ALT_CO2	Alternative technology: pressurized CO_2
	GSHP_S	Ground source heat pumps, emissions from scrapped equipment	GP	Good practice: end-of-life recollection
			ALT_HC	Alternative refrigerant: Propane (HC-290), propene (HC-1270)
			ALT_HFC	Alternative HFC refrigerant: HFC-152a
			ALT_CO2	Alternative technology: pressurized CO_2
	FEXT_B	Fire extinguishers, emissions banked in equipment	GP	Good practice: leakage control, improved components
			FK	Alternative agent: Fluoro-ketone (FK-5-1-12)
	FEXT_S	Fire extinguishers, emissions from scrapped equipment	GP	Good practice: end-of-life recollection
			FK	Alternative agent: Fluoro-ketone (FK-5-1-12)
	SOLV_PEM	Solvents	BAN	Ban of use
	HCFC22_E	HCFC-22 production for emissive use	INC_HFC23	Post combustion of HFC-23
	HCFC22_F	HCFC-22 production for feedstock use	INC_HFC23	Post combustion of HFC-23
PFCs	ALU_SWPB	Primary aluminium production using side-worked prebake technology (SWPB)	RETSWPB	Retrofitting SWPB technology
			CONVSWPB	Conversion of SWPB to PFPB technology
			NEWSWPB	Conversion to speculative new technology eliminating emissions[a]
	ALU_VSS	Primary aluminium production using vertical stud Söderberg technology (VSS)	RETVSS	Retrofitting VSS technology
			CONVVSS	Conversion of VSS to PFPB technology
			NEWVSS	Conversion to speculative new technology eliminating emissions[a]
	ALU_CWPB	Primary aluminium production using center-worked prebake technology (CWPB)	RETCWPB	Retrofitting CWPB
			CONVCWPB	Conversion of CWPB to PFPB technology
			NEWCWPB	Conversion to speculative new technology eliminating emissions[a]
	ALU_PFPB	Primary aluminium production using point-feeder prebake technology (PFPB)	NEWPFPB	Conversion to speculative new technology eliminating emissions[a]
	PFC_OTH	Other	BAN	Ban of use
	SEMICOND	Semiconductor industry	NF3	Switch from PFC to NF_3
SF_6	HMVES	High -and mid voltage switches	GP	Good practice: leakage control and end-of-life recollection and recycling
	MAGNPR	Magnesium production and casting	ALT_MAGN	Alternative protection gas: SO_2
	WIND_B	Soundproof windows	BAN	Ban of use
	SF6_OTH	Other SF_6 sources	BAN	Ban of use
FGAS	FGAS_IND	Other F-GAS from industrial processes	NOC	No control

a New technologies refer to either of the following technologies mentioned in IEA's Energy Technology Perspectives 2010 (IEA/OECD 2010): wetted drained cathods, inert anodes, carbothermic reduction or kaolinite reduction.

An overview of the EU legislation currently in place to control the release of F-gas emissions is presented in Table 24. Reference scenario emissions are in GAINS estimated under the assumption that all EU Member States at least meet the requirements of the regulations adopted EU wide. From 1st January 2015 the placing on the market and use of F-gases within the EU has to follow the rules given in Regulation (EU) No 517/2014. This Regulation has repealed Regulation (EC) No 842/2006 with effect from 1st January 2015 and will phase down sales of hydrofluorocarbons (HFCs) to one fifth of the current sales volume by 2030. It introduces bans on the use of F-gases as well as sale-bans of products which contain such gases.

The EU F-gas Regulation (EC 842/2006) was implemented in 2006 to control the release of F-gases from stationary cooling and refrigeration equipment as well as from aerosols, foams and a few other minor sources. Emissions from air conditioners in motor vehicles are regulated in the EU MAC Directive (2006/40/EC) and in the EU Directive on end-of-life vehicles (EC 53/2000). These F-gas regulations stipulate e.g., that good practice measures like leakage control and end-of-life recollection of refrigeration and air-conditioning equipment should be put into place by 2008. Allowing for a certain phase-in period in countries with no prior F-gas regulation, GAINS assumes the full effect of good practice measures is attained from 2015 onwards. From 2011, the use of HFC-134a in mobile air conditioners should be replaced by a cooling agent with a global warming potential (GWP) of less than 150 in all new vehicle models placed on the market. In addition, the EU MAC directive (2006/40/EC) bans the use of HFC-134a in motor vehicle air-conditioners from 2017 and the revised F-gas regulation (EC 517/2014) places bans on the use of certain high-GWP HFCs in other sectors starting in 2015 and also contains a phasedown of HFC consumption from a base level.

The new EU F-gas regulation (517/2014) came into force from 1st January 2015, replacing the previous version (842/2006). Key changes include: product and equipment bans, service and maintenance bans, cap and phase down and responsible supply. The regulation puts restrictions on the placing on the market of certain refrigeration and air conditioning equipment, foams and propellants using F-gases, and of SF_6 in small magnesium foundries. It limits the use of higher GWP gases, such as HFC-404A and HFC-507A, in existing refrigeration equipment from 2020. Further, the new regulation puts a cap on the placing on the market of F-gases and phase down on the supply of HFCs. Only companies with EU quotas will be able to supply HFCs to the EU market. Numerous additional changes include requirements for leakage control, checks and detection systems, end-of-life recovery, training and certification programmes, labelling and reporting (EC 517/2014).

In addition, the new F-gas Regulation requires an increased use of alternative blowing agents for one-component foams, use of alternative propellants for aerosols, leakage control and end-of-life recollection and recycling of high- and mid- voltage switches, SF_6 replaced by SO_2 in magnesium production and casting, and a ban of use of SF_6 in soundproof windows, sports equipment etc. The EU's 2006 regulation only restricted use of SF_6 in magnesium die casting operations. The bans on the use of SF_6 in the recycling of magnesium die casting alloys are new to the 2014 regulation.

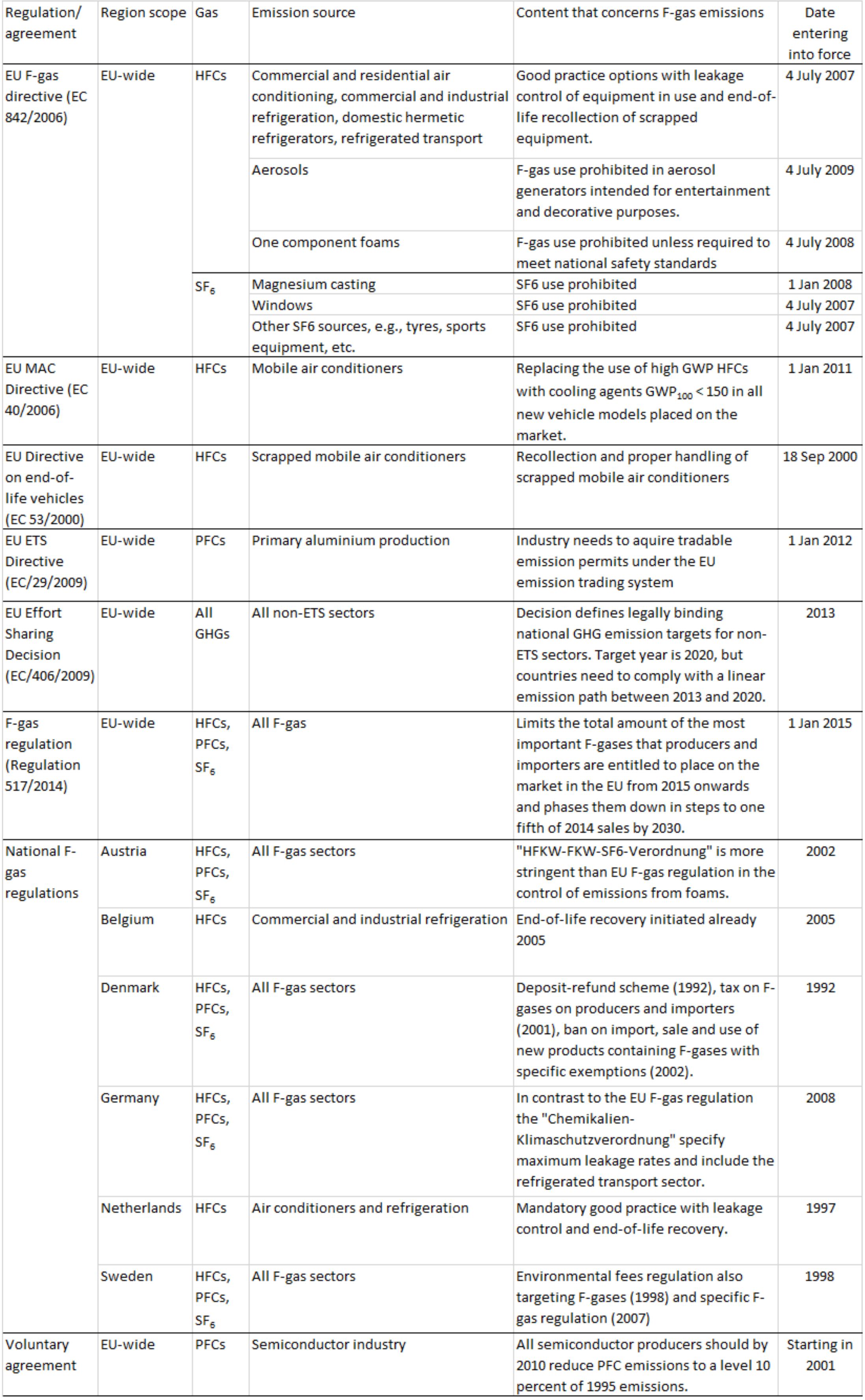
The new EU F-gas regulation (517/2014) phases out the total amount of HFCs that can be sold from 2015 to one fifth of today's sales by 2030. This is expected to reduce the EU's F-gas emissions by some two-thirds in 2030 compared to the 2014 level. Table 25 summarizes how different control options have been implemented in the GAINS Reference scenario in order to meet the F-gas emission reduction target specified in the 2014 F-gas regulation.

Following the requirements of the amendment (EC/29/2009) of the EU-ETS Directive, PFC emissions from the primary aluminium industry are included in the EU-ETS emission cap.

There is a voluntary agreement among semiconductor producers worldwide to reduce release of PFC emissions to 10 percent below the 1995 emission level by 2010 (WSC 2008). The European semiconductor industry has signed up to this agreement (ESIA, 2006). HFCs used in the manufacture of semiconductors are excluded from the phase-down in the new F-gas regulation (EC 517/2014).

In addition to EU wide legislation, there is national legislation targeting F-gases in Austria, Belgium, Denmark, Germany, Netherlands and Sweden. These regulations were put in place earlier, or go further in their stringency or address more sources than the EU wide regulation.

Table 24: Current legislation regulating F-gas emissions in EU member states.



Regulation/ agreement	Region scope	Gas	Emission source	Content that concerns F-gas emissions	Date entering into force
EU F-gas directive (EC 842/2006)	EU-wide	HFCs	Commercial and residential air conditioning, commercial and industrial refrigeration, domestic hermetic refrigerators, refrigerated transport	Good practice options with leakage control of equipment in use and end-of-life recollection of scrapped equipment.	4 July 2007
			Aerosols	F-gas use prohibited in aerosol generators intended for entertainment and decorative purposes.	4 July 2009
			One component foams	F-gas use prohibited unless required to meet national safety standards	4 July 2008
		SF_6	Magnesium casting	SF6 use prohibited	1 Jan 2008
			Windows	SF6 use prohibited	4 July 2007
			Other SF6 sources, e.g., tyres, sports equipment, etc.	SF6 use prohibited	4 July 2007
EU MAC Directive (EC 40/2006)	EU-wide	HFCs	Mobile air conditioners	Replacing the use of high GWP HFCs with cooling agents $GWP_{100} < 150$ in all new vehicle models placed on the market.	1 Jan 2011
EU Directive on end-of-life vehicles (EC 53/2000)	EU-wide	HFCs	Scrapped mobile air conditioners	Recollection and proper handling of scrapped mobile air conditioners	18 Sep 2000
EU ETS Directive (EC/29/2009)	EU-wide	PFCs	Primary aluminium production	Industry needs to aquire tradable emission permits under the EU emission trading system	1 Jan 2012
EU Effort Sharing Decision (EC/406/2009)	EU-wide	All GHGs	All non-ETS sectors	Decision defines legally binding national GHG emission targets for non-ETS sectors. Target year is 2020, but countries need to comply with a linear emission path between 2013 and 2020.	2013
F-gas regulation (Regulation 517/2014)	EU-wide	HFCs, PFCs, SF_6	All F-gas	Limits the total amount of the most important F-gases that producers and importers are entitled to place on the market in the EU from 2015 onwards and phases them down in steps to one fifth of 2014 sales by 2030.	1 Jan 2015
National F-gas regulations	Austria	HFCs, PFCs, SF_6	All F-gas sectors	"HFKW-FKW-SF6-Verordnung" is more stringent than EU F-gas regulation in the control of emissions from foams.	2002
	Belgium	HFCs	Commercial and industrial refrigeration	End-of-life recovery initiated already 2005	2005
	Denmark	HFCs, PFCs, SF_6	All F-gas sectors	Deposit-refund scheme (1992), tax on F-gases on producers and importers (2001), ban on import, sale and use of new products containing F-gases with specific exemptions (2002).	1992
	Germany	HFCs, PFCs, SF_6	All F-gas sectors	In contrast to the EU F-gas regulation the "Chemikalien-Klimaschutzverordnung" specify maximum leakage rates and include the refrigerated transport sector.	2008
	Netherlands	HFCs	Air conditioners and refrigeration	Mandatory good practice with leakage control and end-of-life recovery.	1997
	Sweden	HFCs, PFCs, SF_6	All F-gas sectors	Environmental fees regulation also targeting F-gases (1998) and specific F-gas regulation (2007)	1998
Voluntary agreement	EU-wide	PFCs	Semiconductor industry	All semiconductor producers should by 2010 reduce PFC emissions to a level 10 percent of 1995 emissions.	Starting in 2001

Table 25: Summary of assumptions on the control adopted to meet implemented EU and national F-gas regulations.

Gas	Sector	Control adopted in the Reference scenario to meet implemented F-gas regulations
HFCs	Aerosol	Alternative substance propane (HC-290) implemented to 20% in 2020 and to 60% in 2030 in EU-28, except in the six member countries with national targets/legislations (Austria, Belgium, Denmark, Germany, Netherlands and Sweden), where it is implemented to 20% in 2015 and extended to 80% in 2030.
	Commercial air-conditioning	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10).
		Alternative substance propane (HC-290) implemented to 20% in 2020 and to 70% in 2030 in EU-28, except in the six member countries with national targets/legislations (Austria, Belgium, Denmark, Germany, Netherlands and Sweden), where it is implemented to 40% in 2015 and extended to 80% in 2030.
	Commercial refrigeration	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10).
		Alternative substance propane (HC-290) implemented to 20% in 2005 extending to 70% in 2030 in Denmark and Sweden, while implementation in Austria, Belgium, Germany and Netherlands is 10% in 2030.
		Alternative substance HFC-152a (low-GWP HFCs): 50% in 2005 to 30% in 2030 in Denmark and Sweden; 20% in 2015 to 90% in 2030 in Austria, Belgium, Germany and Netherlands; 20% in 2020 to 80% in 2030 in other EU-28 member countries.
	Domestic refrigerators	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10).
		Alternative substance propane (HC-290) implemented to 20% in 2020 and to 60% in 2030 in EU-28, except in the six member countries with national targets/legislations (Austria, Belgium, Denmark, Germany, Netherlands and Sweden), where it is implemented to 20% in 2005 and extending to 100% in 2025.
	Fire-extinguishers	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10).
		FK's from 37% in 2020 to 79% in 2030 in all EU-28 member States
	Ground source heat pumps	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10).
		Alternative substance propane implemented to 20% in 2020 and extended to 80% in 2030 in all EU-28.
	HCFC-22 production	Post-incineration of HFC-23 100% implemented from 2005 onwards (except Greece but plant has been closed)
	Industrial refrigeration	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10).
		Alternative substance ammonia (NH_3) implemented to 20% in 2020 and to 75% in 2030 in EU-28, except in the six member countries with national targets/legislations (Austria, Belgium, Denmark, Germany, Netherlands and Sweden), where it is implemented to 5% in 2005 and extending to 80% in 2030.
	One component foams	Alternative substance HFC-152a (low-GWP HFCs): Already in-use in Austria, Belgium, Croatia, Denmark, Greece, Luxemburg, Poland, Portugal, Spain and Sweden for 2005/10 as per country reports to UNFCCC (2015). For other EU-28 countries 20% HFC-152a is considered in 2020 and extending to 80% in 2030.
	Other foams	Alternative substance HFC-152a (low-GWP HFCs): Already in-use in Austria, Germany, Estonia and Portugal for 2005/10 as per country reports to UNFCCC (2015). For other EU-28 countries 20% HFC-152a is considered in 2020 and extending to 80% in 2030.
	Residential air-conditioning	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10).
		Alternative substance propane (HC-290) implemented to 20% in 2020 and to 70% in 2030 in EU-28, except in the six member countries with national targets/legislations (Austria, Belgium, Denmark, Germany, Netherlands and Sweden), where it is implemented to 40% in 2020 and extended to 80% in 2030.
	Solvents	Ban implemented to 37% in 2020 extending to 79% in 2030 in EU-28 member states.
	Mobile air-conditioning	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10).
		Alternative substance HFO-1234yf implemented to 20% in 2020 and extending to 90% in 2030 in EU-28 member states.
	Transport refrigeration	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10).
		Alternative substance CO_2 implemented to 20% in 2015 and extending to 80% in 2030 in the six member countries with national targets/legislations (Austria, Belgium, Denmark, Germany, Netherlands and Sweden) and implemented to 20% in 2020 and extending to 75% in 2030 in other EU-28 member states.
PFCs	Primary al production	Only point-feeder prebake (PFPB) technology in use from 2020 onwards.
	Semiconductor industry	Not controlled as reported PFC emissions by MS to UNFCCC (2015) are used as activity data in GAINS.
SF_6	High and mid voltage electrical switches	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10).
	Magnesium production and casting	Alternative gas SO_2 implemented to 100% from 2015 onwards
	Soundproof windows	Soundproof windows with SF_6 phased-out in 2030.

5.2 HFC emission sources

5.2.1 *Air conditioning and refrigeration*

5.2.1.1 Residential air-conditioning

To estimate emissions from stationary air conditioners in the residential sector, we apply a method similar to what has been used in a model described by McNeil and Letschert (2007). HFC use for air conditioning depends both on the average HFC consumption per household using air conditioning (kg HFC/unit) and on the fraction of households who own air conditioners (penetration).

$$HFC\ consumption\ =\ Households\ \times Penetration\ \times\ Average\ charge\ size \tag{33}$$

The number of households was calculated by dividing total population by average household size. Data and scenario values for average household sizes are taken from the UN Global Report on Human Settlements 2005 (UN-HABITAT 2005).

We assume that both energy consumption per appliance and the proportion of households owning air conditioners (penetration) depend on climate and income, being higher in warmer and richer places. Penetration in a certain region is formulated as a function of the climate maximum saturation for that region and of the percentage of the climate maximum saturation achieved at that time in the region (availability).

$$Penetration\ =\ Availability\ \times\ Climate\ Maximum\ Saturation \tag{34}$$

The climate maximum saturation is derived from the assumption that current penetration rates in the USA are the maximum for a climate with a given amount of cooling degree days (CDD's). The relationship between maximum saturation and CDD is exponential, as developed by Sailor and Pavlova (2003) and corrected to give a maximum of 100 percent by McNeil and Letschert (2007) whose equation we have used here. Availability of air conditioners as a function of income is assumed to develop along a logistic function, with a threshold point beyond which ownership increases rapidly. Using data on present day air conditioner penetration in various countries from McNeil and Letschert (2007) we find availability as a function of income

$$Availability = \frac{1}{1+e^{4.152}\times e^{-0.237\times Income/1000}} \tag{35}$$

where income is defined as GDP per capita in purchasing power parity (PPP) and converted to constant Euro 2010.

GDP and population data is taken from the GAINS model in consistency with the relevant external macroeconomic scenario, i.e., EC/DG ECFIN (2012). Data on cooling degree days and household size is taken from Baumert and Selman (2003) and UN-HABITAT (2005), respectively. Once the number of stationary air conditioners is estimated, the HFC consumption is estimated assuming the average size of each appliance is 2.62 kW (Adnot et al. 2003) and the average refrigerant charge is 0.25 kg/kW (UNEP 2011a). An annual leakage rate of 10 percent is assumed from equipment in use mainly due to losses during refill (Schwartz and Harnisch 2003). At the end-of-life the scrapped equipment is assumed to be fully loaded with refrigerant which needs recovery with recycling or destruction.

The control options available for this source are different good practise options including leakage control, improved components and end-of-life recollection. These options are assumed to remove 30 percent of emissions banked in equipment in use and almost 90 percent of scrapping emissions. Good practice options are being implemented in the EU as part of the different regulations controlling F-gases (see Table 24). In countries with no prior national F-gas regulation, full adoption of good practice options is assumed from 2015 onwards. For substantial further emission reductions, the use of HFC-134a (GWP_{100}=1300) and other high GWP blends need to be replaced by an alternative low GWP refrigerant such as HFC-152a (GWP_{100}=140) or pressurized CO_2 (GWP_{100}=1) (Table 23).

A problem with the HFC alternatives with low GWPs is that they often suffer from poorer performance, e.g., in terms of flammability or efficiency (IPCC/TEAP, 2005; USEPA, 2008b; Minjares, 2011). In recent years, companies like Honeywell© and Dupont© have developed and marketed alternative substances with better performances and very short lifetimes of less than a few months. These are known as HFOs (or unsaturated HFCs). E.g. HFO-1234ze with a GWP_{100} of 6 can be used in foam products and HFO-1234yf with a GWP_{100} of 4 can be used in mobile air-conditioners. The suitability of these substances for stationary air conditioners has not yet been confirmed and they are therefore currently not applied in GAINS for this source.

Another option would be to use other non-HFC substances with low or zero GWP like hydrocarbons, CO_2, dimethyl ether and other diverse substances used in various types of foam products, refrigeration, air-conditioning and fire protection systems. Switching to these alternatives is typically costly because it involves process modifications, e.g., changing the process type from ordinary to secondary loop systems (Tohka, 2005; Halkos, 2010). In view of the new EU F-gas regulation (EC517/2014), HFC's with a global warming potential above 750 will be banned from 2025 in 'single split' systems that contain less than 3 kg of refrigerant. Single split systems involve one cooling coil connected to a remote condensing unit. There are no bans for larger air-conditioning or heat pump systems, e.g. chillers or larger split systems.

5.2.1.2 Commercial air-conditioning

The GAINS model store data on commercial floor space area for Annex-1 countries (Cofala et al., 2009). The primary data source for this data is the PRIMES (2015) model. For year 2005 the data on commercial floor space area was correlated with GDP/capita as illustrated in Figure 4.

Fitting a linear trend line, the following relationship was retrieved:

$$\left[\left(\frac{Commercial\ floor\ space}{Capita}\right) = 0.0003\left(\frac{GDP}{Capita}\right) + 7.1984\right] \qquad (R^2 = 0.6737) \qquad (36)$$

Using GDP per capita as driver, projections for future growth in commercial floor space area were obtained for each country. To estimate the HFC consumption in commercial air conditioning, a sector specific HFC consumption value of 0.02 kg/m^2 was applied.

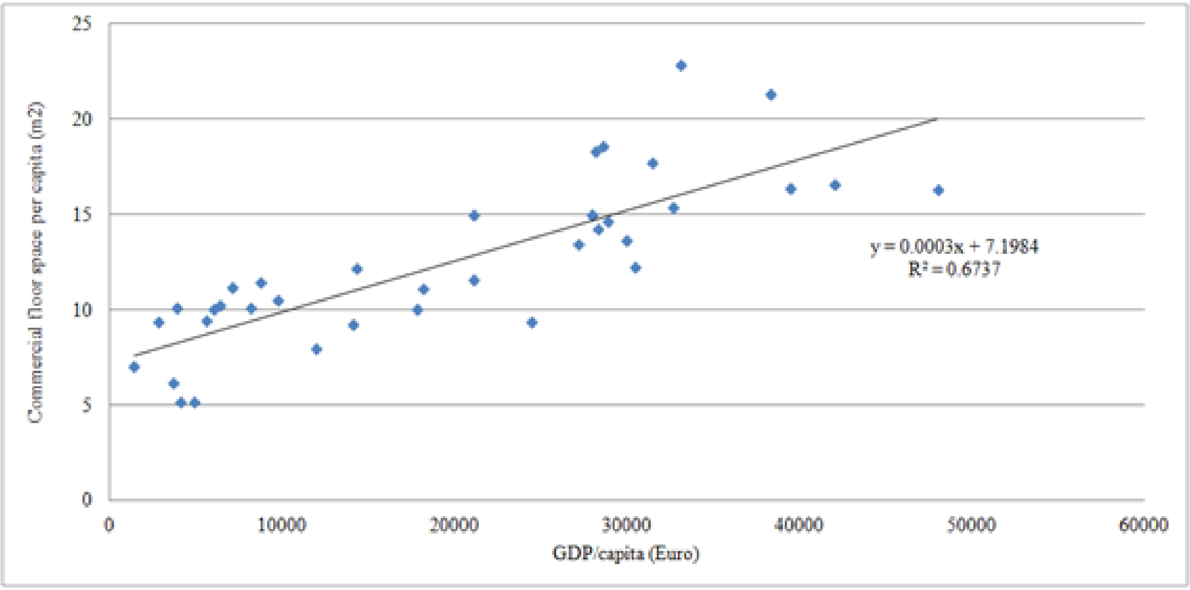


Figure 4: Variation of commercial floor space per capita w.r.t. GDP per capita in year 2005. Source: PRIMES model (2015).

An annual leakage rate of 10 percent is assumed from equipment in use mainly due to losses during refill (Schwartz and Harnisch, 2003). Figure 5 shows the default GAINS leakage rate applied to all EU-28 countries in comparison to the different leakage rates reported by member states to UNFCCC (2015) for years 2005 and 2010. At the end-of-life the scrapped equipment is assumed to be fully loaded with refrigerant which needs recovery, recycling or destruction.

Control options available for this source are similar to the options discussed for residential air conditioning (previous section).

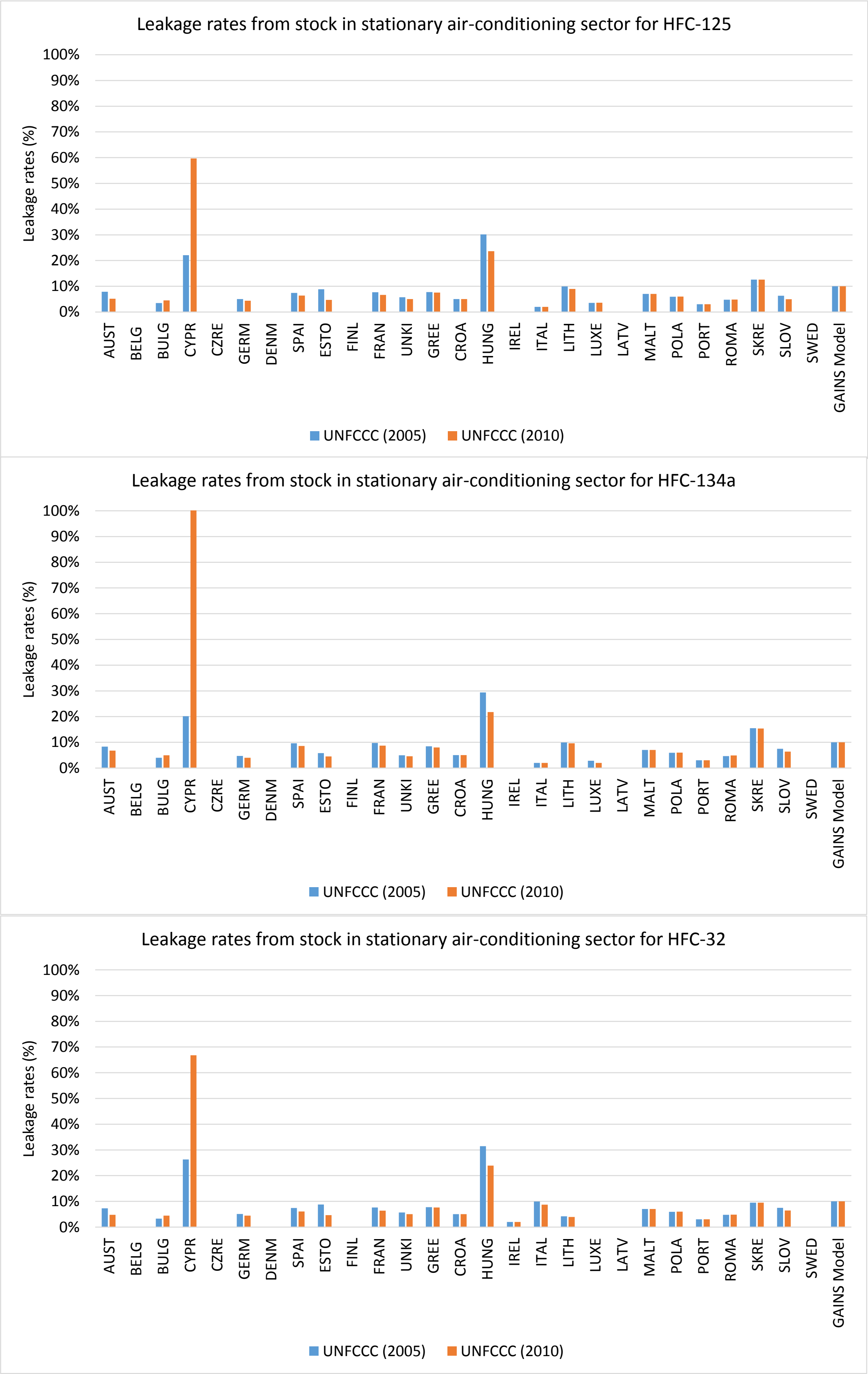


Figure 5: Leakage rates from stock in stationary (residential and commercial) refrigeration in years 2005 and 2010 for different HFCs as reported to UNFCCC (2015) and assumption adopted in GAINS.

5.2.1.3 Domestic refrigeration

The activity data for refrigeration in the domestic sector is number of refrigerators owned by households. The rate of ownership of refrigerator(s) per household is derived using a function estimated by the PAMS model (2012). The general form of the function for the rate of refrigerator ownership per household is given by:

$$Sat_{DOM} = (K \times I_t)^{\lambda_a} \times \left[1 - e^{-\left(bE_t{}^{\lambda_b} + cU_t{}^{\lambda_c}\right)}\right]^a \tag{37}$$

where Sat_{DOM} represents the saturation (rate) of domestic refrigerator ownership, I is the monthly household income given by GDP per household in the country, U is the national urbanization rate, E is the national electrification rate, and t is the year of the projected saturation. The econometric parameter estimates from the PAMS model were applied to derive the rate of refrigerator ownership per household in GAINS. The number of refrigerators in a country was calculated by multiplying the ownership rate by the number of households in a country (UN-HABITAT, 2005). Growth in number of refrigerators is driven by population growth and trends in appliance ownership as estimated above. Once the number of refrigerators is estimated, an average refrigerant charge of 0.25 kg HFC per unit (USEPA, 2010a) is used to estimate the HFC consumption in domestic refrigerators.

As domestic refrigerators are hermetic there is no risk of leakage during use, but there is a risk of emission release during the scrapping phase. At the end-of-life, the scrapped equipment is assumed to be fully loaded with refrigerant which needs recovery with recycling or destruction.

The control option available for this source is good practice during end-of-life scrapping, which is assumed to remove 85 percent of emissions. The option is already in place in the EU through the F-gas Regulation 2006 (see Table 24). For substantial further emission reductions, the use of HFC-134a (GWP_{100}=1300) need to be replaced by alternative low GWP refrigerants such as propane (GWP_{100}=3). HFCs with global warming potentials above 150 are banned in domestic fridges and freezers as per new F-gas regulation (EC 517/2014).

5.2.1.4 Commercial refrigeration

Commercial refrigeration includes refrigerated equipment found in supermarkets, convenience stores, restaurants, and other food service establishments (Girotto et al. 2004). Equipment in this end-use typically lasts approximately 15–20 years. At present, the commercial refrigeration sector accounts for approximately 32 percent of global HFC consumption, or 40 percent of HFC consumption in the refrigeration/AC sector (USEPA 2010b).

Starting point for the estimation of emissions from commercial refrigeration in EU-28 in GAINS is the HFC consumption reported by member states to the UNFCCC for this sector for the years 2005 and 2010. As we are not able to fully explain the variations in the reported consumption, e.g., by having access to information on consumption patterns for refrigerated goods, we adopt HFC consumption as reported. Projections for future HFC consumption are driven by growth in service sector value added. For countries not reporting HFC consumption in this sector, the German consumption per service sector value added has been adopted as default. Projections for service sector value added are adopted from the macroeconomic scenario by EC/DG ECFIN (2015).

An annual leakage rate of 18 percent from equipment in use is applied consistently across all member states (Gschrey et al., 2011) since no evidence has been found available from direct measurements which would suggest that leakage rates differ substantially between EU countries for this source sector. The leakage from this source mainly reflects losses during refill (Schwartz and Harnisch 2003) Figure 6 shows the default GAINS leakage rate applied to all EU-28 countries in comparison to the different leakage rates reported by member states to UNFCCC (2015) for years 2005 and 2010. At the end-of-life the scrapped equipment is assumed to be fully loaded with refrigerant which needs recovery, recycling or destruction.

The control options available for this source are different good practise options including leakage control, improved components and end-of-life recollection. These options are assumed to remove 42 percent of emissions banked in equipment in use and almost 90 percent of scrapping emissions (Tohka, 2005). Good practice options are already implemented in the EU as part of the different regulations controlling F-gases (see Table 24). For substantial further emission reductions, the use of HFC-134a (GWP_{100}=1300), HFC-125 (GWP_{100}=2800), HFC-143a (GWP_{100}=3800) and other high GWP blends need to be replaced by alternative low GWP refrigerants such as HFC-152a (GWP_{100}=140), HC-290 (GWP = 3) or pressurized CO_2 (GWP_{100}=1) (see Table 20). HFCs with global warming potentials of more than 2,500 will be banned in commercial refrigeration systems as per new F-gas regulation (EC 517/2014).

Figure 6: Leakage rates from stock in commercial refrigeration in years 2005 and 2010 for different HFCs as reported to UNFCCC (2015) and assumption adopted in GAINS.

5.2.1.5 Industrial refrigeration

Food processing and cold storage is an important application of industrial refrigeration used for preservation and distribution of food while keeping nutrients intact. On a global scale this application is very significant in size and economic importance (Mohanraj et al. 2009). The application includes cold storage (at temperatures from −1°C to 10°C), freezing (−30°C to −35°C) and the long-term storage of frozen products (−20°C to −30°C). The preferred HFCs used are HFC-134a and HFC blends with a small temperature glide such as HFC-404A, HFC-507A and HFC-410A. Ammonia/CO_2 cascade systems are also being used, as are hydrocarbons as primary refrigerants in indirect systems (IPCC/TEAP 2005).

Starting point for the estimation of emissions from industrial refrigeration in EU-28 in GAINS is the HFC consumption reported for this source by member states to the UNFCCC for the years 2005 and 2010. As we are not able to explain the variations in the reported consumption, we adopt it as activity data as reported. Projections for future HFC consumption are driven by growth in value added for manufacturing industry. For countries not reporting HFC consumption in this sector, the German consumption per value added has been adopted as default. Projections for manufacturing industry value added are adopted from the macroeconomic scenario by EC/DG ECFIN (2015).

An annual leakage rate of 11 percent is applied consistently across member states (Gschrey et al., 2011) from equipment in use mainly due to losses during refill (Schwartz and Harnisch 2003). No evidence has been found available from direct measurements which would suggest that leakage rates differ substantially between EU countries for this source sector. Figure 7 shows the default GAINS leakage rate applied to all EU-28 countries in comparison to the different leakage rates reported by member states to UNFCCC (2015) for years 2005 and 2010. At the end-of-life the scrapped equipment is assumed to be fully loaded with refrigerant which needs recovery with recycling or destruction.

The control options available for this source are different good practise options including leakage control, improved components and end-of-life recollection. These options are assumed to remove 42 percent of emissions banked in equipment in use and almost 90 percent of scrapping emissions (Tohka, 2005). Good practice options are already implemented in the EU as part of the different regulations controlling F-gases (see Table 24). For substantial further emission reductions, the use of HFC-134a (GWP_{100}=1300), HFC-125 (GWP_{100}=2800) and other high GWP blends need to be replaced by alternative low GWP refrigerants such as ammonia (NH_3), HFC-152a (GWP_{100}=140) or pressurized CO_2 (GWP_{100}=1) (see Table 20).

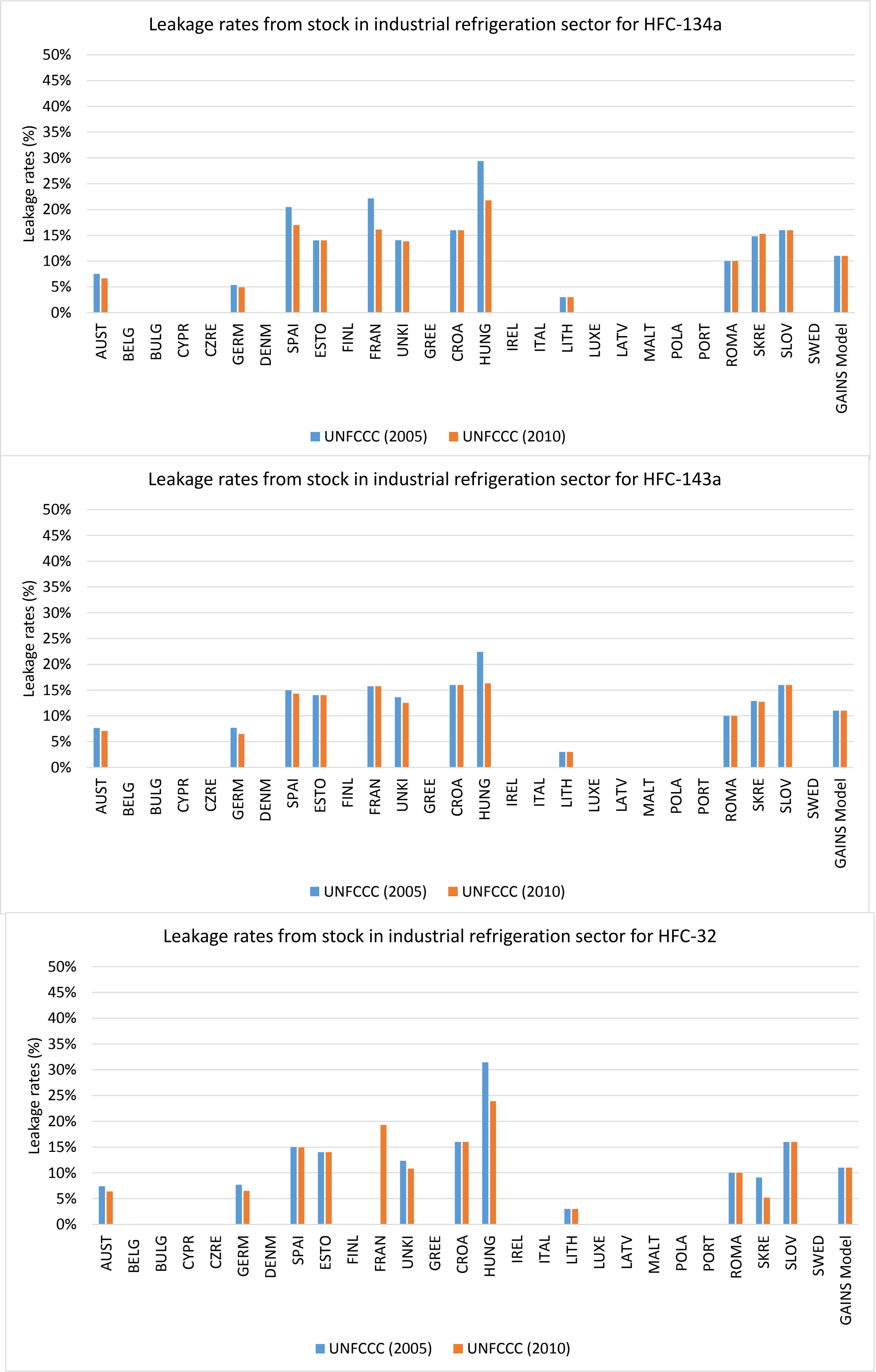


Figure 7: Leakage rates from stock in industrial refrigeration in years 2005 and 2010 for different HFCs as reported to UNFCCC (2015) and assumption adopted in GAINS

5.2.1.6 Refrigerated transport

Refrigerated road transport includes transportation of food products (fresh, frozen or chilled), pharmaceutical products, and plants/flowers. The type of vehicles used for such transportations are trailers, heavy and small trucks, and vans. Refrigerated road transport vehicles have different capacities; vans are typically below 3.5 tonnes, small trucks and trailers vary between 3.5 to 7.5 tonnes, and heavy trucks have a capacity of more than 7.5 tonnes.

Approximately 650000 refrigerated road vehicles were used within the EU during 2003-04 (Tassou et al. 2009; 2010). These units predominantly use HFC-404A and HFC-410A as refrigerants. HFC-134a is also used for chilled distribution only vehicles. It is reported that the emission leakages from transport refrigeration systems are higher than those from stationary refrigeration because the former operate under more severe conditions (IIR 2003). The operating environment involves vibration, which will depend on road surface and a wide range of weather conditions and operating temperatures. Annual leakage figures reported are 10–37 percent of the refrigerant charge (IPCC/TEAP 2005). A study reported by Koehler et al. (2003), which assumed a 10 percent leakage rate showed the direct emissions (refrigerant leakage) from the refrigeration system to be 21 percent of indirect emissions (engine fuel consumption) for HFC-404A and 13 percent for HFC-410A.

Due to the country-specific variation in the amount of freight transported as well as the type of vehicles used (see UNECE 2010; Eurostat 2010; OECD 2010; USDOT 2010), GAINS derive HFC consumption per unit of freight transportation in 2005 based on the consumption reported by countries for this source to the UNFCCC. For countries not reporting HFC consumption specific for this sector, the rate reported for Germany (0.40 and 0.51 kg HFC per unit GDP for 2005 and 2010 respectively) is adopted as default. Projections of HFC consumption in refrigerated transport have been assumed to follow proportionately the growth in GDP (EC/DG ECFIN, 2015).

An annual leakage rate of 25 percent from equipment in use is adopted consistently across all member states (Gschrey et al., 2011). This leakage is mainly due to losses during refill (Schwartz and Harnisch 2003). No evidence has been found available from direct measurements which would suggest that leakage rates differ substantially between EU countries for this source sector. Figure 8 shows the default GAINS leakage rate applied to all EU-28 countries in comparison to the different leakage rates reported by member states to UNFCCC (2015) for years 2005 and 2010. At the end-of-life the scrapped equipment is assumed to be fully loaded with refrigerant which needs recovery, recycling or destruction.

The control options available for this source are different good practise options including leakage control, improved components and end-of-life recollection. These options are assumed to remove 33 percent of emissions banked in equipment in use and 80 percent of scrapping emissions. The latter emissions are controlled in the EU through the end-of-life vehicles Directive (see Table 24). Control of leakage from equipment in use for refrigerated transport was not part of the EU F-gas regulation, but assumed to be adopted with full effect from 2015 in Germany, Denmark and the Netherlands due to national F-gas regulations. Further emission reductions from this source can be achieved through switches to alternative refrigerants like HFC-152a or pressurized CO_2 (see Table 20). HFCs with global warming potentials of more than 2,500 will be banned in transport refrigeration systems as per new F-gas regulation (EC 517/2014).

Figure 8: Leakage rates from stock in refrigerated transport in years 2005 and 2010 for different HFCs as reported to UNFCCC (2015) and assumption adopted in GAINS.

5.2.1.7 Mobile air-conditioning

A major source of F-gas emissions from the transport sector is emissions from mobile air-conditioners (MAC). Air conditioning in cars became common in the United States in the 1960s. Mass installation in Europe and developing countries started only later, around 1995. The refrigerant currently used in MACs in the EU is HFC-134a. The emissions of HFC-134a take place during accidents, through leakage and servicing and at disposal. Global recovery rates are generally low (DeAngelo et al. 2006), except for the EU where end-of-life recollection has been mandatory since 2000 due to the Directive on end-of-life vehicles (EC 53/2000).

In the GAINS model, emissions from MAC are accounted for in cars, light and heavy duty trucks, and buses, as shown in Table 20. The number of vehicle types in different GAINS regions is extracted from the GAINS model and for EU member states consistent with transport fuel use in the PRIMES (2015) model. The penetration rates for air-conditioners in different vehicle types were derived from a literature survey (IPCC/TEAP 2005; Kanwar 2004; Hu et al. 2004; CSI 2009; Uherek et al. 2010). The adopted penetration rates for MAC in EU-28 in 2005 are applied consistently across all member states assuming 75 percent in cars and 60 percent in buses, light and heavy duty trucks. By 2020 all vehicles are assumed equipped with MAC. Using the average charge size for different vehicle types, the HFC consumption from MACs is estimated (Repice and Schultz 2004; Tohka 2005). Average charge sizes used are 0.63 kg for cars, 1.2 kg for light and heavy duty trucks and 12 kg for buses (Schwarz et al., 2011). The leakage rate assumed from MAC in use is 10 percent and at the end-of-life the scrapped MAC is assumed to be fully loaded with coolant which needs recovery, recycling or destruction. Figure 9 shows the default GAINS leakage rate from equipment in use applied to all EU-28 countries in comparison to the different leakage rates reported by member states to UNFCCC (2015) for years 2005 and 2010. No evidence has been found available from direct measurements which would suggest that leakage rates differ substantially between EU countries for this source sector.

Following adherence to the MAC Directive (see Table 24), HFC-134a is expected to be replaced by a low GWP substance ($GWP_{100} < 150$) in all new models put on the market from January 2011 onwards. Moreover, new vehicles fitted with air conditioning cannot be manufactured with fluorinated greenhouse gases having global warming potentials (GWP) greater than 150 from January 2017 onwards. There are a few possible alternatives to HFC-134a including replacement with CO_2, HFO-1234yf (GWP_{100} is 4) or HFC-152a (GWP_{100} is 140). Until today, no new car models have been put on the market and therefore there is still uncertainty concerning which alternative cooling agent car manufacturers will choose to meet the MAC Directive. In absence of further information, GAINS assumes car manufacturers will switch to HFO-1234yf in all new car models placed on the EU market from 2015 onwards.

CO_2 is considered safe, reliable and efficient, but the cost is relatively high. Evidence for mobile air conditioners from the B-COOL (2011) project funded by the EU Sixth Framework Program suggests that the cost of a CO_2-based AC system is between 1.5 to 2 times the cost of a HFC-134a system. This finding is adopted as an approximation for the cost of switching from conventional HFCs to CO_2-based systems for mobile air conditioners. Moreover, CO_2-based systems show slightly higher fuel consumption at higher thermal load (35 °C) as compared to the HFC-134a system. This is in contrast to the fuel (diesel/gasoline) savings claimed by some CO_2 promoters (e.g., www.r744.com). As a compromise we do not assume any effect on energy consumption when switching to a CO_2 based system in stationary or mobile air conditioners. The modelling of additional future potential for adoption of CO_2-based systems versus the use of HFO-1234yf in mobile air conditioners, depends in GAINS on the marginal cost of the respective alternatives when implemented in different types of vehicles.

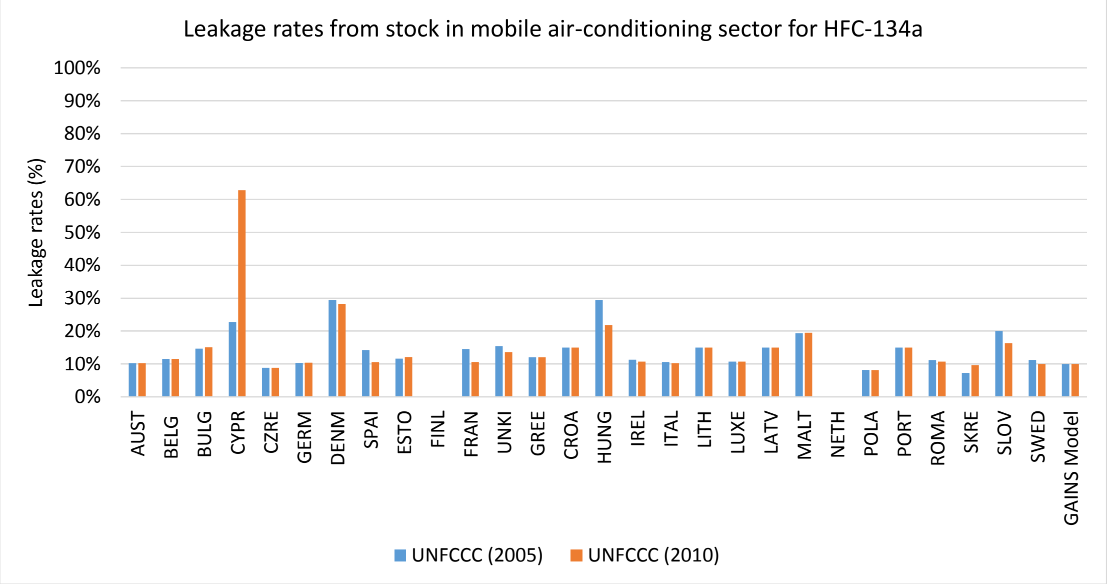


Figure 9: Leakage rates from stock in mobile air-conditioning in years 2005 and 2010 for HFC-134a as reported to UNFCCC (2015) and assumption adopted in GAINS

5.2.2 Foams

5.2.2.1 Polyurethane one component foams

Foams became a significant application for HFCs as part of the phasing-out of CFCs under the Montreal Protocol. HFCs are used as blowing agents in a solidifying matrix of a polymer (UNEP, 2006). The main application of polyurethane (PU) one component (OC) foam is to fill cavities and joints when installing inner fixtures in housing constructions. Since one component foams come in pressurized canisters and cylinders, they are also called aerosol foams. One component blowing agents are typically gaseous and function as propellant for the foam. They volatilize upon application, except for small residues that remain for at most one year in the hardened foam (Schwarz and Leisewitz 1999).

To estimate emissions from one component foams we adopt HFC consumption in one component foams as reported by member states to the UNFCCC (2015) for years 2005 and 2010. When reporting is missing for this source, an EU-28 average consumption per GDP (2.75 tonne HFC per billion Euro GDP) is adopted as default. Projections of blowing agents for the one component foam sector follow growth in GDP (EC/DG ECFIN, 2015). The annual release of HFCs from foams is assumed 15 percent of the stock banked in foams.

Emissions from foams can be controlled by replacing HFC-134a and other high GWP blends with alternative low GWP blowing agents, like HCs or CO_2. A recent mitigation option for applications where high pressure is essential is the replacement with HFO-1234ze (GWP_{100} of 6). According to the manufacturer Honeywell© it is already available for use as blowing agent for one component foams (http://www51.honeywell.com/sm/lgwp-uk/applications.html) however the cost is unclear.

The F-gas Regulation (see Table 24) requires that all EU member states from 2008 stop using HFCs in one component foams unless this is required to meet national safety standards. According to Kaschl (2012) the most common current replacement options for HFCs in foams is CO_2. For some applications the performance of CO_2 in foam blowing is limited (UNEP/TEAP 2010). In GAINS the options considered available for replacement of HFCs in one component foams are CO_2, different hydrocarbons like propane and butane, and HFO-1234ze.

5.2.2.2 Other foams

The sector for other foams (OF) in the GAINS model includes about 10 different polyurethane foam types (viz. PU appliances, PU/PIR/Phen laminates, PU disc panel, PU cont panel, PU blocks, PU spray, PU pipe, XPS) and extruded polystyrene (XPS). It is difficult to estimate product life emissions and lifetime of the foam product. End of life emissions depend greatly on the end of life treatment. If the product is land filled, the emission factor depends mainly on the properties of the plastic. If the product is recycled, all gases can be emitted into the atmosphere if fugitive emissions during the recycling process are not incinerated or collected. If the product is incinerated, the emission factor can be close to zero, depending on the incineration temperature. To estimate emissions from the other foam sector we adopt HFC consumption in other foams as reported by member states to the UNFCCC for years 2005 and 2010. For countries not reporting HFC consumption from this source, an EU-28 average of 1.44 tonne HFC per billion Euro GDP is adopted as default. Projections of refrigerants for one component foam sector follow GDP as taken from (EC/DG ECFIN, 2015). The annual release of HFCs from foams is assumed 15 percent of the stock banked in foams.

Emissions from foams can be controlled by replacing HFC-134a and other high GWP blends with an alternative blowing agent like CO_2 or hydrocarbons like propane or butane. According to Harvey (2007) a water/CO_2 mixture has been used in Europe (with a 10 to 20 percent market share by 2000) for solid PU in building applications. The use of HFO-1234ze (GWP_{100} of 6) is according to the manufacturer Honeywell© available for use as blowing agent for one component foams (http://www51.honeywell.com/sm/lgwp-uk/applications.html), but as the manufacturer does not mention other types of foams than one component foams as a possible application, GAINS currently does not assume HFO technology to be available for the other foam sector.

According to Kaschl (2012) 80 percent of XPS board foams in the EU use CO_2. However, CO_2 has some limitations with respect to thermal resistance and product thickness (UNEP/TEAP 2010). The remaining 20 percent will therefore need to use some other alternative, e.g., a mix of HFCs, HCs and water could be possible, but also HFO-1234ze is an interesting possible option (UNEP/TEAP 2010). In GAINS the options considered available for replacement of HFCs in one component foams are CO_2, different hydrocarbons like propane and butane, and HFO-1234ze.

All F gases with global warming potentials of more than 150 will be banned as the refrigerant or foam blowing agent in any hermetically sealed system. This will mainly affect the use of HFC-134a as a refrigerant and HFCs-245fa and HFC-365mfc as foam blowing agents (EC 517/2014). From 2020, HFCs with global warming potentials of more than 150 will be banned in extruded polystyrene foam (XPS). From 2023 HFCs with global warming potentials of more than 150 will be banned in all other foams, including polyurethane.

5.2.2.3 Summary HFC emissions from foams in the GAINS model

Figure 10 presents a comparison of HFC emissions (in CO_2-equivalents) from the foam sector reported by countries to UNFCCC for years 2005 and 2010 in comparison to emissions estimated in the GAINS model using consistent assumptions on leakage rates and global warming potential.

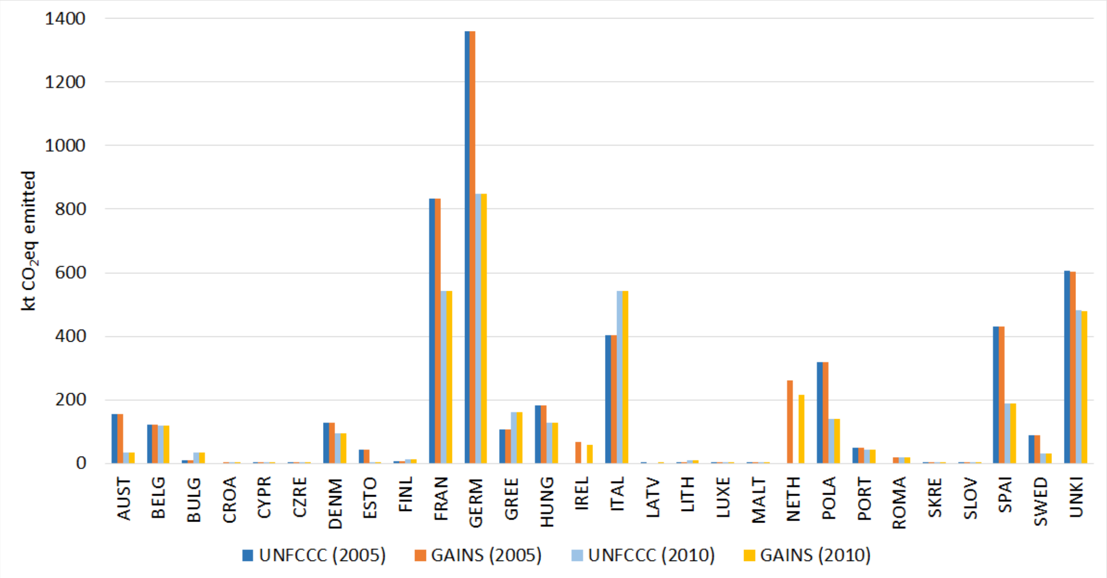


Figure 10: Emissions from foams in 2005 and 2010 as reported by UNFCCC (2015) and as estimated in GAINS.

5.2.3 *Aerosols*

HFC is used as propellant for aerosols released from cans and metered dose inhalers, e.g., medical asthma inhalers. In the EU, the use of HFCs as propellant for aerosols in all applications for entertainment and decorative purposes has been prohibited since 2008 (see Table 24). From 2018 HFCs with a global warming potential above 150 will be banned in technical aerosols (EC 517/2014). The release from this source is therefore mainly from medical dose inhalers (MDIs), where high pressure is essential and the approval of new medical drugs is very expensive and time-consuming (UNEP/TEAP 2010). We assume that for the EU, the current use of HFCs in MDIs is limited to severe cases and that the primary gases used are HFC-134a with some use of HFC-152a (Schwarz et al., 2011). To estimate HFC consumption in aerosols, we adopt the HFC consumption reported by member states to the UNFCCC for years 2005 and 2010. When reporting is missing for this source, an EU-28 average consumption per capita (0.1 kg HFC per person) is adopted as default. Population growth is used as driver for future HFC use in aerosols.

Figure 11 provides an overview of HFC emissions from aerosols in 2005 and 2010 as represented in the GAINS model and in comparison with emissions reported by member states to the UNFCCC (2015).

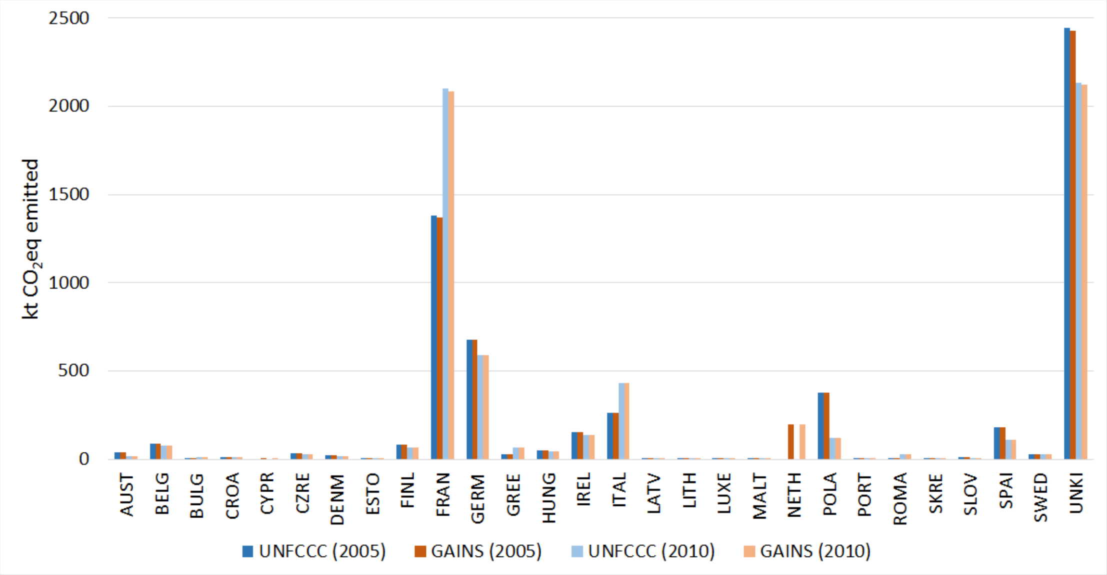


Figure 11: Historical HFC emissions from aerosols in GAINS and as reported to UNFCCC (2015).

The primary alternatives to HFC-134a as propellant in medical dose inhalers are dry powder inhalers (DPI) or HFC-152a, which has a GWP_{100} of about 140. The relative cost of these options is similar to the cost of MDIs in developed countries (UNEP/TEAP 2010), however, for medical reasons MDIs are still preferred in severe cases.

For severe cases, where high pressure is essential, there is the option to replace HFC-134a with HFO-1234ze (GWP_{100} of 6), which according to the manufacturer Honeywell© is already available for use as propellant for aerosols (http://www51.honeywell.com/sm/lgwp-uk/applications.html). As no cost information is available for this option, GAINS assumes that the cost is about 50 percent higher than the cost of using HFCs.

5.2.4 HCFC-22 production

HCFC-22 (chlorodifluoromethane) is a gas used in refrigeration and air-conditioning systems, in foam manufacturing as a blend component of blowing agents, and in the manufacturing of synthetic polymers. Since it is an ozone-depleting substance its release is regulated in the Montreal Protocol (MP). The phase-out schedule of HCFCs in the latest revision of the MP (UNEP, 2007) is presented in Table 23 for Article 5 (developing) and non-Article 5 (developed) countries. In addition to the phase-out of the use of HCFCs, the MP also requires the production and sales of HCFC-22 for emissive use to end completely after 2040.

In contrast to production of HCFC-22 for emissive use, the production and use of HCFC-22 as feedstock in industry is not regulated in the MP as it does not contribute to emissions of HCFCs. Production of HCFC-22 is however a source of HFC-23 emissions, which is a strong greenhouse gas with GWP_{100} of 14800 times that of CO_2 (IPCC, 2007).

Table 26: Phase-out schedule of HCFCs for emissive use in the Montreal protocol (UNEP 2007).

	Article 5 (developing countries)		**non-Article 5 (developed countries)**
	Pre 2007 revision of MP	**Post 2007 revision of MP**	**Pre- and post 2007 revision of MP**
1996			freeze in emissions
2004			-35%
2010			-75%
2013		freeze at average of 2009 & 2010 levels	
2015	freeze in emissions	-10%	-90%
2020	-35%	-35%	-99.50%
2025		-67.5%	
2030		-97.5%	-100%
2035			
2040	-100%	-100%	

To calculate HFC-23 emissions from HCFC-22 production in the EU, GAINS applies an IPCC default emission factor of 3 percent related to the volume of HCFC-22 production for emissive (HCFC22_E) and feedstock (HCFC22_F) applications (IPCC, 2005). Activity data are based on reported production levels for historic years (UNEP, 2011) and UNEP's phase out schedule for HCFC products for future years (UNEP, 2007). Projections of HCFC-22 production for feedstock use are assumed to grow proportionately with value added in manufacturing industry with a levelling off after 2030 due to an assumed saturation in demand.

HFC-23 emissions from HCFC-22 production can be almost eliminated through post combustion during which HFC-23 is oxidized to carbon dioxide, hydrogen fluoride (HF) and water. The marginal abatement cost for destruction of HFC-23 emissions from HCFC-22 production is very low, less than 1 Euro/tCO_2eq (Schneider 2011; IPCC/TEAP 2005).

HCFC-22 production in the EU is recorded in the emission inventories submitted to the UNFCCC and takes place in France, Germany, Greece, Italy, Netherlands and United Kingdom. All countries except Greece are in the reference scenario assumed to have full post-incineration of emissions in place already in 2005. Greece has full control from 2010 onwards.

5.2.5 Ground source heat pumps

Geothermal heat pumps or ground source heat pumps (GSHP) are systems combining a heat pump with a ground heat exchanger (closed loop systems) or being fed by ground water from a well (open loop systems). The earth is used as a heat source when operated in heating mode, with a fluid as the medium which transfers the heat from the earth to the evaporator of the heat pump, thus utilizing geothermal energy (Sanner et al., 2003). In cooling mode, heat pumps use the earth as a heat sink. With borehole heat exchangers (BHE), geothermal heat pumps can offer both heating and cooling at virtually any location, with great flexibility to meet demands.

The growth in Europe's GSHP systems has been accelerated by national policies[5] stimulating installation, e.g., through subsidies, efficiency standards to new buildings and heating demand mandates for heat pumps (EurObserv'ER, 2009). Many European countries have identified barriers that mirror those seen in the United States, namely higher investment costs, lack of knowledge and awareness among end users, and underdeveloped institutional and financial support (EHPA, 2008). In the EU, Sweden (>320,000) and Germany (>150,000) today show the highest absolute numbers of GSHPs as shown in Figure 12.

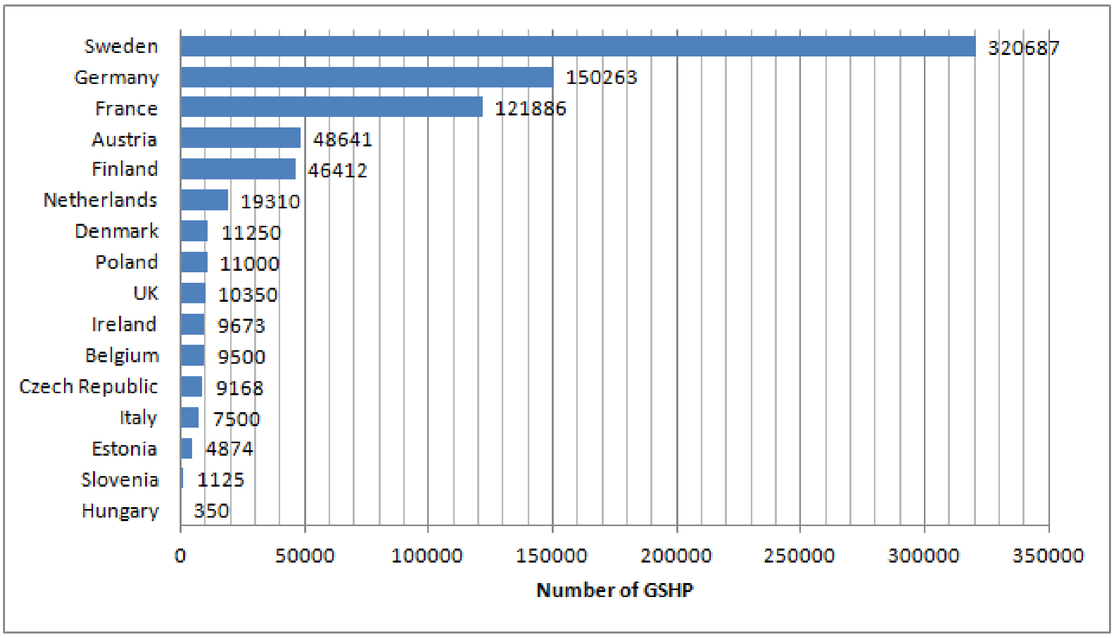


Figure 12: Number of existing GSHPs (with more than 10 MW heat capacity) in 2008. Source: EGEC (2009).

Lund et al. (2011) estimated installed capacity of direct use geothermal in 2009 at 51 GWth, distributed in 78 countries, while Goldstein et al. (2011) estimated direct use at 60 GWth at the end of 2009. Direst use (ranging from 60 to 120°C) by type and relative estimates as given by Lund et al. (2011) were space heating (63%), bathing and balneology (25%), process heating and agricultural drying (3%), aquaculture (fish farming) (3%) and snow melting (1%). GSHP contributed to 70% (35.2 GWth) of the global installed geothermal heating capacity in 2009 (Ogola et al., 2012) and is the fastest growing of all forms of geothermal direct use since

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[5] Heat pumps are considered a renewable energy technology in EU, where they are expected to account for between 5% and 20% of the EU's renewable energy target for 2020. For example, the revised National Renewable Energy Action Plan (NREAP) of Malta listed that 1.6% of heat pumps is required in order to reach the RES target by technology.

1995 (Rybach 2005; Blum et al., 2010; Thorsteinsson and Tester, 2010; Lund et al. 2011; Schimschar et al. 2011). Although, most of the installations occur in North America, Europe, and China, the number of countries with installation increased from 33 in 2005 to 43 in 2010. The equivalent number of installed 12 kW units (typical of US and Western European homes) is approximately 2.76 million (Lund et al., 2011).

To estimate HFC consumption in the GSHP sector in the GAINS model we have taken the GSHP installed capacity from Lund et al. (2005, 2011), EurObserv'ER (2009), EHPA (2010) and Bayer et al. (2012). For projections, it is assumed that the annual growth in GSHPs using HFCs follows the growth in GDP (EC/DG ECFIN, 2015). Based on available technical information, the current fluid/refrigerant used in GSHP is most likely HFC-410a (IPCC/TEAP, 2005; Johnson, 2011). An average refrigerant charge of 0.22 kg HFC per kW installed capacity (Schwartz et al., 2011) is used to estimate the HFC consumption in GSHP sector. Annual leakage from equipment is assumed 2.5 percent per year. Emissions can be controlled through good practice options and switching to alternative substances. In the near future, the key alternatives for HFC-410a use in GSHP are assumed to be HC-290 direct, CO_2 and HFO-1234yf (Schwarz et al., 2011).

Figure 13 presents the current emissions of HFCs from GSHP as estimated in the GAINS model.

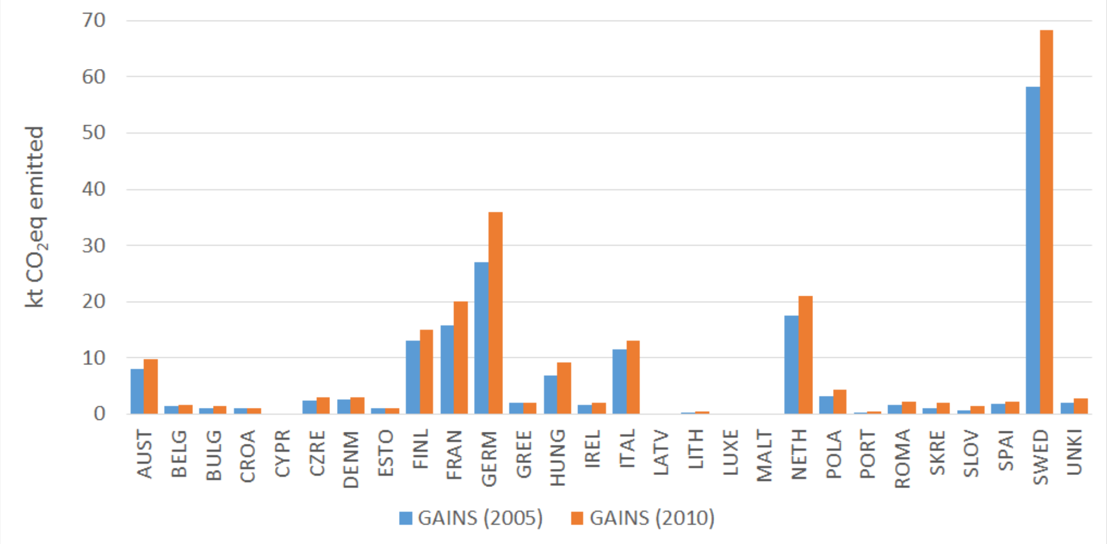

Figure 13: HFC emissions from ground source heat pumps for 2005 and 2010 in the GAINS model.

5.2.6 *Other HFC emission sources*

GAINS includes two additional HFC emission sources: fire extinguishers and solvents. Emissions from fire extinguishers are derived from the HFC consumption in fire extinguishers per unit GDP as reported for some EU countries to UNFCCC (2015) for year 2005/10. We adopt reported values when available and derive a default factor per GDP for countries not reporting consumption from this source. Emissions from solvents are only included for those countries reporting emissions from this source to UNFCCC (2015) for year 2005/10. For projections, emissions from both sources are assumed to grow proportional to GDP. Control options identified for these sources are good practice during scrapping and switching to alternative HFCs with low GWP. PFCs have been banned in fire protection systems since 2007. From 2016, HFC-23 are banned in new fire protection systems (EC 517/2014).

5.3 PFC emission sources

5.3.1 Primary aluminium production

Primary aluminium production has been identified as a major emission source of the two PFCs tetrafluoromethane (CF_4) with GWP_{100} 6,500 and hexafluoroethane (C_2F_6) with GWP_{100} 9,200 times that of CO_2. During normal operating conditions, an electrolytic cell used to produce aluminium does not generate measurable amounts of PFC. PFC is only 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 cell 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.

For EU-28, the GAINS model uses the production volumes of primary aluminium as the activity driver for calculating emissions from this source. Primary aluminium production data for historical years (2005 and 2010) and projections are taken from the PRIMES (2016) reference projection for the EU. Four different types of activities are distinguished based on the technology used; point-feeder prebake (PFPB), side-worked prebake (SWPB), vertical stud söderberg (VSS), and center-worked prebake (CWPB) technology. As per the information provided by the MS, there was a significant reduction of primary aluminium production in Slovenia due to economic crisis in 2010 as the new electrolysis unit operated less than half of its capacity. According to most recent data submitted in Slovenia’s National Inventory Report 2015, primary aluminium production amounted to 84 kt in 2013, which is close to maximal capacity of 85 kt per year of the existing plant. Therefore, we have used primary aluminium production of 85 kt per year in Slovenia for 2015. Shares of different primary aluminium production technologies were adopted from the aluminium industry website and from national communications to the UNFCCC (2015). 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).

Conversion of SWPB, VSS or CWPB technology to PFPB technology removes over 90 percent of PFC emissions, while retrofitting of the three technologies would remove about a quarter of emissions (Harnisch and Hendricks 2000). Data on mitigation costs is taken from the same source. As emissions from the primary aluminium production is regulated under the EU-ETS system, control options with marginal costs falling below the expected ETS carbon price in the reference scenario (projected with PRIMES) are adopted in the reference scenario.

This means that with the natural turn-over of capital, all EU member states will have phased-in PFPB technology by 2020.

The development of inert anodes is sometimes promoted as a promising mitigation option, which could eliminate emissions of PFCs from the electrolysis process (Bernstein et al., 2007). In the Energy Technology Perspective (ETP) 2010 by the International Energy Agency (IEA/OECD, 2010), deployment of inert anode technologies is expected to start in 2015-2020 with full commercialization by 2030. If realized, inert anode technology would have significant energy, cost, productivity, and environmental benefits for the aluminium industry worldwide (Inert Anode Roadmap, 1998; RUSAL, 2010). The technology is expected to eliminate PFC emissions from primary aluminium production altogether. However, the commercial aspects of inert anodes have not yet been proven (Kvande and Drabløs, 2014). Despite promising initial results, the technology still needs further development before it can be introduced as a viable alternative to PFPB technology. In GAINS, inert anode technology is assumed available as a mitigation option from 2035 onwards, however, no adoption in the reference scenario is assumed.

Figure 14 shows PFC emissions from primary aluminium production in EU-28 as estimated by the GAINS model and in comparison with emissions reported to UNFCCC for years 2005 and 2010.

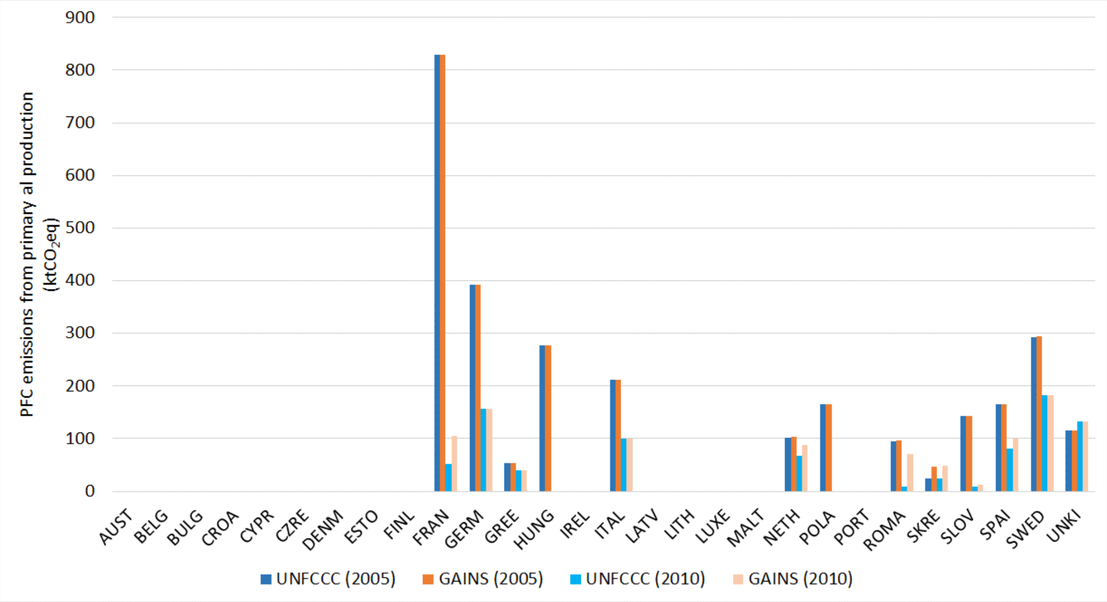

Figure 14: PFC emissions (in kt CO_2eq) from primary aluminium production in the GAINS model and as reported to UNFCCC for years 2005 and 2010.

5.3.2 Semiconductor industry

The semiconductor industry uses HFC-23, CF_4, C_2F_6, octafluoropropane (C_3F_8), carbon tetrafluoride (c-C_4F_8), sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3) in two production processes: plasma etching thin films (etch) and plasma cleaning chemical vapour deposition (CVD) tool chambers (IPCC, 2000a). Both the PFCs (GWP_{100}=6500) and NF_3 are potent greenhouse gases (GWP_{100}=17200). PFCs have been regulated under the Kyoto Protocol, while NF_3 is added to the 'basket' of six greenhouse gases (covered by the KP in the first commitment period) with effect from 2013 and the commencement of the second commitment period of the protocol. The semiconductor industry has been switching from PFCs to NF_3 as part of a voluntary agreement to reduce PFCs. The commitment has been to reduce PFC emissions to ten percent below the 1995 baseline level by 2010 (ESIA 2006; WSC 2008). In 2008 the industry was close to reaching this target (WSC 2008). Under well managed conditions and certainly in the EU and the US, a switch from PFC to NF_3 reduces the net global warming effect because about 98 percent of NF_3 is destroyed by industry in the process (UNFCCC 2012b). With a release of about 60 percent of the PFCs used in the industry, the switch to NF_3 contributes to a net reduction in greenhouse gas emissions by about 85 percent. As the proposal to include NF_3 among the Kyoto gases has not yet been ratified, the global warming effect of NF_3 emissions is currently not accounted for in the estimation of non-CO_2 emissions from EU countries.

As PFC is only used by a few companies in a country and because the amount of PFC use allows deriving production volumes, data on the use is often confidential. The activity variable used in GAINS for this sector is the volume of PFC emissions as reported by member states to UNFCCC (2015). We use the reported emissions for the years 2005 and 2010 while future projections follow growth in value added for manufacturing industry.

The European semiconductor manufacturers have been part of the voluntary commitment to reduce PFC emissions from this source (ESIA, 2006). We assume that the reduction attained by the industry in 2005 will continue into the future. This corresponds to an application of control to 86 percent of the production from 2010 onwards. Costs for switching to NF_3 use were taken from Harnisch et al. (2000), Harnisch and Hendriks (2000) and Tohka (2005).

Figure 15 shows the GAINS model estimates of current future emissions of PFC from semiconductor industry in EU member states.

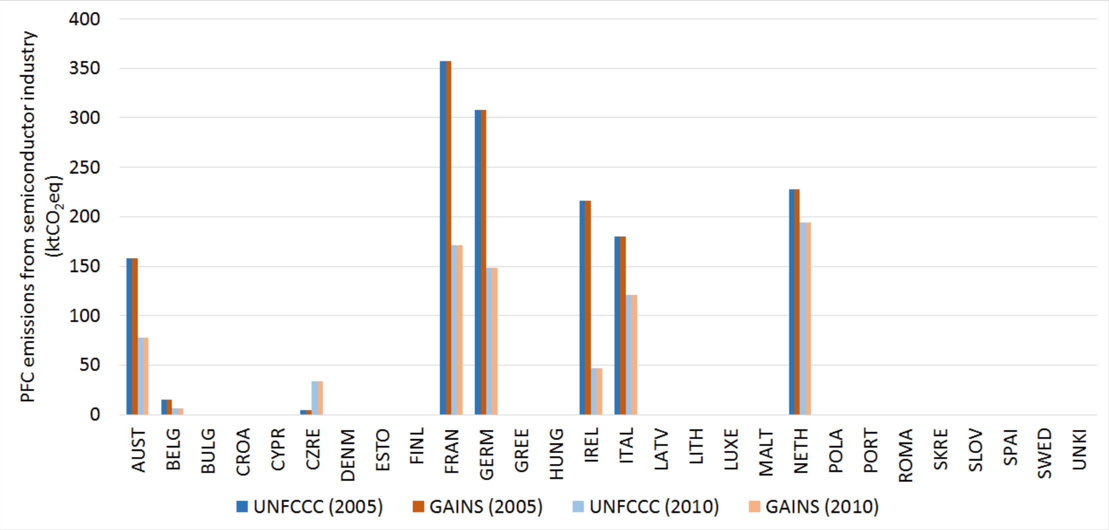

Figure 15: PFC emissions (in kt CO_2eq) from semiconductor industry in the GAINS model and as reported to UNFCCC for years 2005 and 2010.

5.4 SF_6 emission sources

Sulphur hexafluoride (SF_6) emissions are released from high- and mid-voltage switches, magnesium production and casting and a variety of other applications e.g., soundproof windows or sports equipment. SF_6 has a very high global warming potential of 23,900 times that of CO_2 over a 100 year time horizon.

5.4.1 High and mid voltage switches

SF_6 is used as an electrical insulator in the transmission and distribution equipment of electric systems. Most of the SF_6 is stored in gas-insulated switchgears for high and mid-voltage electric networks. Emissions of SF_6 depend on the age of the gas insulated switchgear (GIS) since older models leak more than newer ones, as well as on the size of the transmission network and on recycling practises of the old equipment. The GAINS model uses electricity consumption as activity variable for this sector. The emission factor for SF_6 in electricity transmission per unit of electricity consumed is taken from the GHG inventory of California (CEPA, 2010) and applied in a consistent manner to all EU member states.

Suitable alternatives to SF_6 do not exist for these applications as the oil and compressed air systems, which were used previously, suffer from safety and reliability problems (AEAT, 2003). Emissions can be reduced through the adoption of recycling practices of used SF_6 switchgears. The EU F-gas Regulation requires end-of-life recollection and recycling from 2010 onwards. Full compliance with this regulation is assumed in GAINS to apply in all EU countries. Figure 16 shows GAINS emission estimates for this sector in comparison to emissions reported to UNFCCC (2015) for years 2005 and 2010.

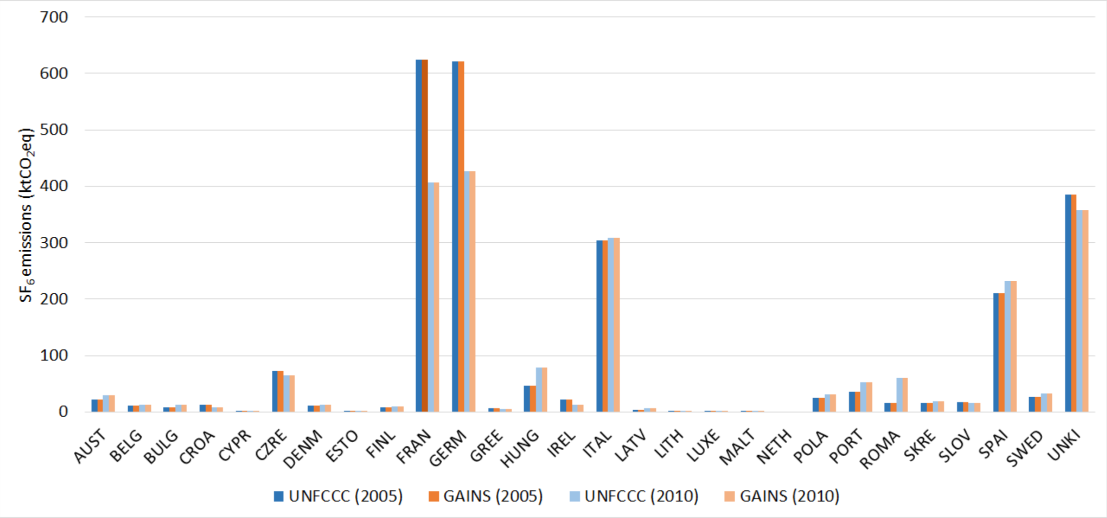

Figure 16: Historical SF_6 emissions from high and mid voltage electrical switches in the GAINS model and as reported to UNFCCC (2015).

5.4.2 Magnesium production and casting

Casting and production of primary and secondary magnesium are well known sources of atmospheric emissions of SF_6. The gas is used as a shielding gas in magnesium foundries to protect the molten magnesium from re-oxidizing whilst it is running to best casting ingots (IPCC, 2000b). GAINS use the reported SF_6 emissions for the years 2005 and 2010 while future projections follow growth in value added for manufacturing industry. Activity data on historic volumes of processed magnesium in the EU countries is taken from national communications to UNFCCC (2015). An emission factor of one kg SF_6 per ton processed metal is taken from Schwartz and Leisewitz (1999) and Tohka (2005). The EU's 2006 regulation only restricted use of SF_6 in die casting operations. The bans on the use of SF_6 in the recycling of magnesium die casting alloys are new to the 2014 regulation (DEFRA, 2014). SF_6 emissions in magnesium production and casting can be substituted by using sulphur dioxide (SO_2) as alternative gas.

5.4.3 Soundproof windows

Some European countries used significant amounts of SF_6 in soundproof windows. From 2006, the F-gas Regulation (EC 842/2006) bans the use of SF_6 soundproof windows. Soundproof windows have a relatively long life-time and it is therefore expected that the stock of SF_6 found in such windows in 2005 will be successively phased-out over a period of 25 years. The available stock of SF_6 in soundproof windows in 2005 in EU countries is estimated at 288 t SF_6 in Austria, 75 t SF_6 in Belgium, 86 t SF_6 in Denmark, 1764 t SF_6 in Germany, 1.78 t SF_6 in Slovenia, and 11.1 t SF_6 in Sweden. These estimates were verified in national communications between IIASA and country experts as part of review processes of baseline non-CO_2 GHGs organized by the European Commission in 2009 and 2012. With an assumed leakage/refill rate of 1 percent per year for windows still in use and a linear phase-out of emissions, annual emissions from this source until 2030 (when phase-out is completed) are estimated as:

$$E_t^{SF_6} = \frac{Stock_{2005}}{25} + Stock_t \; * 0.01, \tag{38}$$

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

No further mitigation options beyond the ban included in the F-gas Regulation are considered necessary to control emissions from soundproof windows.

5.4.4 Other SF_6 sources

SF_6 has been used in tyres, 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 (2015). From 2006, the EU F-gas Regulation (EC 842/2006) bans the use of SF_6 in sports equipment and tyres. GAINS assumes that all EU countries adhere fully to this ban.

6 Comparison of GAINS draft estimates to UNFCCC inventory

Table 24 presents the deviation of GAINS final emission estimates (final version of April 1, 2016) from emissions reported by member states to the UNFCCC (versions available on 17 November 2015). The GAINS estimates for year 2005 for overall non-CO_2 GHGs deviate within ten percent from the emissions reported by countries to UNFCCC for 22 of the 28 countries. For Austria, Belgium, Cyprus, Estonia, Malta, Romania, and Sweden the deviations are larger than ten percent. At the level of individual gases emissions may deviate more.

The principal difference between GAINS model estimates and those reported by member states to the UNFCCC is that GAINS applies a consistent methodology across all countries, whereas estimation methodologies applied by countries tend to differ in key assumptions. Another reason for differences is that member states sometimes report emissions for minor sources which the GAINS model structure does not capture, e.g., CH_4 emissions from thermal baths or rabbits.

As 2005 is used as a starting point for the mitigation efforts analysed within the EUCLIMIT2 project, the GAINS estimate for year 2005 is aligned with the emissions reported to UNFCCC for 2005 by introducing a calibration residual for the pollutants CH_4 and N_2O. The level of the calibration residuals for year 2005 is carried over as a constant to all future years. No calibration was conducted for the F-gas emissions, because of large unexplained variations in leakage rates between countries and in the completeness of the sector emissions reported for F-gases.

Table 27: Deviation of GAINS Final Reference scenario from UNFCCC (2015).

		Deviation of Final GAINS from CRF Nov 2015 (Mt CO_2eq.)		% deviation of Final GAINS from CRF Nov 2015	
Country	**Gas**	**2005**	**2010**	**2005**	**2010**
Austria	CH4	-1.040	-0.510	14%	7%
	N_2O	-0.512	-0.703	15%	22%
	F-gases	-0.281	-0.327	16%	17%
	Sum non-CO_2	**-1.832**	**-1.540**	**14%**	**13%**
Belgium	CH4	-0.209	-0.014	2%	0%
	N_2O	-1.088	-0.953	13%	13%
	F-gases	-0.863	-1.250	43%	48%
	Sum non-CO_2	**-2.160**	**-2.218**	**11%**	**11%**
Bulgaria	CH4	0.620	0.921	-7%	-11%
	N_2O	0.164	0.090	-4%	-3%
	F-gases	-0.498	0.174	300%	-28%
	Sum non-CO_2	**0.286**	**1.185**	**-2%**	**-9%**
Croatia	CH4	0.676	0.824	-16%	-20%
	N_2O	-0.052	-0.117	2%	5%
	F-gases	-0.418	-0.466	105%	84%
	Sum non-CO_2	**0.206**	**0.241**	**-3%**	**-3%**
Cyprus	CH4	-0.057	0.021	7%	-2%
	N_2O	0.270	0.181	-48%	-38%
	F-gases	0.072	0.323	-29%	-63%
	Sum non-CO_2	**0.285**	**0.525**	**-18%**	**-28%**
Czech Republic	CH4	-0.693	-0.308	5%	2%
	N_2O	0.329	0.389	-5%	-7%
	F-gases	-0.639	-1.347	77%	67%
	Sum non-CO_2	**-1.003**	**-1.266**	**5%**	**6%**
Denmark	CH4	-0.092	-0.135	1%	2%
	N_2O	-0.241	-0.467	4%	9%
	F-gases	0.051	0.058	-5%	-6%
	Sum non-CO_2	**-0.283**	**-0.544**	**2%**	**4%**
Estonia	CH4	-0.203	-0.186	17%	16%
	N_2O	-0.177	-0.146	28%	20%
	F-gases	0.016	0.054	-12%	-30%
	Sum non-CO_2	**-0.364**	**-0.279**	**19%**	**13%**
Finland	CH4	-0.472	-0.261	8%	5%
	N_2O	-0.756	-0.853	13%	18%
	F-gases	0.356	1.140	-38%	-62%
	Sum non-CO_2	**-0.872**	**0.027**	**7%**	**0%**
France	CH4	2.939	1.942	-5%	-3%
	N_2O	2.591	0.967	-5%	-2%
	F-gases	3.001	4.718	-18%	-24%
	Sum non-CO_2	**8.531**	**7.627**	**-6%**	**-6%**
Germany	CH4	1.391	0.866	-2%	-1%
	N_2O	-6.214	-6.410	14%	18%
	F-gases	-3.076	-3.851	24%	29%
	Sum non-CO_2	**-7.898**	**-9.395**	**6%**	**9%**
Greece	CH4	-0.767	-1.105	6%	9%
	N_2O	0.375	0.321	-6%	-6%
	F-gases	-0.411	-0.081	8%	2%
	Sum non-CO_2	**-0.803**	**-0.865**	**3%**	**4%**
Hungary	CH4	0.427	0.157	-5%	-2%
	N_2O	-1.061	-2.637	18%	69%
	F-gases	0.124	0.266	-11%	-20%
	Sum non-CO_2	**-0.509**	**-2.214**	**3%**	**17%**
Ireland	CH4	0.654	0.533	-5%	-4%
	N_2O	-0.415	-0.876	5%	12%
	F-gases	0.281	0.366	-22%	-30%
	Sum non-CO_2	**0.520**	**0.023**	**-2%**	**0%**
Italy	CH4	-0.275	-0.070	1%	0%
	N_2O	1.883	1.871	-7%	-10%
	F-gases	-4.050	-4.241	48%	36%
	Sum non-CO_2	**-2.441**	**-2.440**	**3%**	**3%**

Cont.Table 27: Deviation of GAINS Final Reference scenario from UNFCCC (2015).

		Deviation of Final GAINS from CRF Nov 2015 (Mt CO_2eq.)		% deviation of Final GAINS from CRF Nov 2015	
Country	**Gas**	**2005**	**2010**	**2005**	**2010**
Latvia	CH4	0.097	0.109	-5%	-6%
	N_2O	-0.073	-0.040	6%	3%
	F-gases	-0.024	-0.048	83%	55%
	Sum non-CO_2	**0.000**	**0.021**	**0%**	**-1%**
Lithuania	CH4	0.008	-0.298	0%	8%
	N_2O	-0.776	-1.036	15%	31%
	F-gases	-0.072	-0.089	86%	38%
	Sum non-CO_2	**-0.840**	**-1.423**	**9%**	**20%**
Luxembourg	CH4	0.002	0.007	0%	-1%
	N_2O	-0.011	-0.031	4%	10%
	F-gases	-0.002	-0.003	4%	5%
	Sum non-CO_2	**-0.011**	**-0.028**	**1%**	**3%**
Malta	CH4	-0.001	0.057	0%	-27%
	N_2O	-0.016	-0.023	28%	49%
	F-gases	-0.022	0.021	53%	-14%
	Sum non-CO_2	**-0.039**	**0.054**	**15%**	**-14%**
Netherlands	CH4	1.073	0.205	-5%	-1%
	N_2O	-2.008	-3.497	15%	44%
	F-gases	-0.490	0.102	22%	-3%
	Sum non-CO_2	**-1.425**	**-3.190**	**4%**	**10%**
Poland	CH4	6.812	6.772	-15%	-16%
	N_2O	-3.298	-3.430	15%	18%
	F-gases	-0.062	0.544	1%	-7%
	Sum non-CO_2	**3.452**	**3.886**	**-5%**	**-5%**
Portugal	CH4	-0.659	-1.142	5%	9%
	N_2O	0.207	0.222	-5%	-6%
	F-gases	-0.061	0.158	7%	-10%
	Sum non-CO_2	**-0.512**	**-0.762**	**3%**	**4%**
Romania	CH4	11.322	9.282	-32%	-32%
	N_2O	-0.848	-2.032	8%	27%
	F-gases	-0.296	0.266	39%	-25%
	Sum non-CO_2	**10.178**	**7.516**	**-22%**	**-20%**
Slovakia	CH4	0.254	0.083	-5%	-2%
	N_2O	0.319	0.131	-9%	-4%
	F-gases	-0.022	0.078	8%	-14%
	Sum non-CO_2	**0.550**	**0.291**	**-6%**	**-3%**
Slovenia	CH4	-0.162	-0.118	7%	6%
	N_2O	-0.025	-0.053	3%	7%
	F-gases	0.033	0.065	-11%	-23%
	Sum non-CO_2	**-0.155**	**-0.106**	**4%**	**3%**
Spain	CH4	-0.599	-0.431	2%	1%
	N_2O	5.608	6.361	-22%	-26%
	F-gases	1.363	2.865	-18%	-28%
	Sum non-CO_2	**6.372**	**8.795**	**-9%**	**-12%**
Sweden	CH4	-0.640	-0.348	10%	6%
	N_2O	-0.809	-0.817	16%	16%
	F-gases	-0.643	-0.730	49%	60%
	Sum non-CO_2	**-2.091**	**-1.896**	**16%**	**16%**
United Kingdom	CH4	-9.006	-6.273	10%	9%
	N_2O	-0.726	-0.237	2%	1%
	F-gases	5.091	6.426	-35%	-38%
	Sum non-CO_2	**-4.641**	**-0.083**	**3%**	**0%**
EU-28	CH4	11.400	10.581	-2%	-2%
	N_2O	-7.358	-13.827	2%	5%
	F-gases	-1.541	5.189	2%	-5%
	Sum non-CO_2	**2.502**	**1.943**	**0%**	**0%**

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