Supplementary material to:

Global anthropogenic methane emissions 2005-2030: technical mitigation potentials and costs

Detailed descriptions of estimations by sector

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1 Introduction

This is a description by sector of the estimations of global anthropogenic emissions of methane (CH_4) presented in the paper "Global anthropogenic methane emissions 2005-2030: technical mitigation potentials and costs". It provides further insights into the details of the estimations of emissions, mitigation potentials and associated costs as well as a discussion of the most important sources for uncertainty in the sector estimates.

2 CH_4 emission estimations by sector

2.1 Crude oil and natural gas production

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:

$$E_{its} = E_{its}^{venting} + E_{its}^{flaring} + E_{its}^{leakage} \quad (1)$$

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

$$E_{it;oil}^{venting} = A_{it}^{oil} * 20 * (1 - r_i) * \left(c_i a_i^{conv} v_i^{conv} + (1 - c_i) a_i^{heavy} v_i^{heavy}\right) \quad (2)$$

$$E_{it;gas}^{venting} = A_{it}^{gas} * 20 * a_i^{gas} (1 - r_i) v_i^{gas} \quad (3)$$

where $A_{it}^{oil;gas}$ is energy content of marketable oil or 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 2005,

r_i is the fraction of associated gas recovered for utilization or reinjection in year 2005, 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.,

$$E_{it}^{flaring} = 0.02 * (total - rec - vented) \quad (4)$$

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

Country-specific information for year 2005 on amounts of associated gas and the fraction of associated gas reinjected or recovered are taken from EIA (2010a) International Energy Statistics and used as starting point for emission estimates. From EIA (2010a) 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 applied to developed countries and 0.3 percent for Russia (PFC Energy, 2007), which is applied to developing and transitional countries.

Measurement data published by Johnson and Coderre (2011) for Canadian oil and gas production is used to derive default fractions for the amounts of associated gas vented as opposed to flared for different types of hydrocarbons. Finally, the derived total amount of associated gas flared from both oil and gas production in a country is verified against country-specific satellite images of flares (NOAA, 2011). For a few countries (Mexico, Denmark, China, Columbia) is it necessary to make slight adjustments to the amounts of associated gas reported to EIA (2010a) or to the reported amounts of gas recovered or reinjected in order to match satellite images of flares reasonably well. A summary of the assumptions made for major oil and gas producing countries is presented in Table 1.

Table 1: Assumptions for deriving CH_4 venting and flaring emission factors from oil and gas production in major source countries.

Country	Types of crude oil produced as fraction of total production (EIA, 2010a)		Fraction offshore production (EIA, 2010a)	Assumptions venting from oil production				Assumptions venting from gas production		Derived total estimates of associated gas for 2005			Satellite image flaring 2005 (NOAA, 2010)
				Ass gas as % of crude oil produced[b]	Flaring or venting/ Recovery or reinjection	Venting from conventional oil prod	Venting from heavy oil prod	Ass gas as % of gas produced[b]	Venting as % ass gas flared or vented				
	Conventional oil	Heavy oil[a]		% of oil prod	% of ass gas	venting as % of ass gas flared or vented		% of gas production	% vented	Recov/Reinj	Flared	Vented	Flared
										bcm	bcm	bcm	bcm
Canada	40%	10%[c]	11%	14.5%[efg]	10/90[efg]	29%[f]	88%[f]	0.03%[f]	40%[f]	26.6	2.1	1.0	1.3
Mexico	33%	67%	80%	6.7%[j]	25/75[j]	29%[f]	88%[f]	0.3%[h]	40%[f]	13.4	1.9	2.7	1.9
USA	100%	0%	7%	35.9%[e]	3/97[e]	29%[f]	88%[f]	0.03%[f]	40%[f]	164.9	3.9	1.6	2.8
Brazil	10%	90%	90%	8.1%[e]	45/55[e]	29%[f]	88%[f]	0.3%[h]	40%[f]	6.2	2.0	3.2	1.6
Columbia	5%	95%	0%	22.3%[e]	35/65[j]	29%[f]	88%[f]	0.3%[h]	40%[f]	5.8	0.5	2.6	0.5
Venezuela	100%	0%	0%	20.6%[e]	25/75[e]	29%[f]	88%[f]	0.3%[h]	40%[f]	32.4	1.4	9.6	2.2
Denmark	100%	0%	100%	20%[j]	2/98[j]	10%[j]	88%[f]	0.03%[f]	40%[f]	5.2	0.1	0.0	0.2
Norway	100%	0%	100%	25.7%[e]	1/99[e]	29%[f]	88%[f]	0.03%[f]	40%[f]	51.6	0.6	0.2	0.5
Azerbaijan	100%	0%	80%	19.7%[m]	50/50[k]	29%[f]	88%[f]	0.3%[h]	40%[f]	3.2	2.3	0.9	0.2
Kazakhstan	100%	0%	20%	19.7%[m]	50/50[k]	29%[f]	88%[f]	0.3%[h]	40%[f]	9.6	6.8	2.8	6.2
Russia	100%	0%	0%	20%[h]	50/50[hi]	29%[f]	88%[f]	0.3%[h]	40%[f]	68.7	50.1	21.0	58.3
Iran	100%	0%	33%	18.1%[e]	28/72[e]	29%[f]	88%[f]	0.3%[h]	40%[f]	40.5	11.2	4.7	11.7
Iraq	100%	0%	0%	8.1%[e]	91/9[e]	29%[f]	88%[f]	0.3%[h]	40%[f]	1.0	7.1	2.9	7.0
Kuwait	100%	0%	0%	8.1%[n]	70/30[j]	29%[f]	88%[f]	0.3%[h]	40%[f]	4.7	2.8	8.2	2.3
Oman	100%	0%	0%	6.3%[e]	80/20[j]	29%[f]	88%[f]	0.3%[h]	40%[f]	0.7	2.1	0.9	2.6
Qatar	100%	0%	0%	12.4%[e]	66/34[e]	29%[f]	88%[f]	0.3%[h]	40%[f]	3.1	4.3	1.8	2.3
S. Arabia	85%	15%	20%	1.1%[e]	56/44[e]	29%[f]	88%[f]	0.3%[h]	40%[f]	5.9	3.5	4.2	3.5
UAE	100%	0%	10%	12.2%[e]	5/95[e]	29%[f]	88%[f]	0.3%[h]	40%[f]	23.2	1.0	0.5	0.9
Nigeria	100%	0%	20%	18.8%[e]	77/23[e]	29%[f]	88%[f]	0.3%[h]	40%[f]	8.4	19.7	8.1	21.3
China	100%	0%	15%	16%[q]	10/90[j]	29%[f]	88%[f]	0.3%[h]	40%[f]	38.0	3.1	1.3	3.0
Indonesia	100%	0%	0%	25.9%[e]	27/73[e]	29%[f]	88%[f]	0.3%[h]	40%[f]	15.1	4.1	1.7	3.0
Malaysia	100%	0%	100%	40.6%[e]	11/89[e]	29%[f]	88%[f]	0.3%[h]	40%[f]	18.5	1.7	0.7	1.8
Rest of World										61.5	37.8	18.9	37.1
World total										**608**	**170**	**100**	**172**

[a] API gravity <22.3°; [b] Energy content of associated gas as fraction of PJ crude oil or gas produced (EIA, 2010a) or if data is missing defaults are 5% for heavy crude oil and 35% for conventional oil derived from Johnson and Coderre (2011). CH_4 content of associated gas assumed 86% on average (ERCB, 2010) and 35.9 MJ/m^3 CH_4. ; [c] In addition Canada produces 50% of oil from oil sands.; [d] Information derived from OME (2001) and from Table 4 on existing gas pipelines.; [e] Source: EIA (2011); [f] Source: derived from Johnson and Coderre (2011); [g] Source: ERCB(2010); [h] Source: derived from PFC Energy (2007); [i] Source: Hulbak Røland (2010); [j] Reported value adjusted by author to fit with satellite image of flaring (NOAA, 2011); [k] Assumed same as Russia; [l] Assumed same as Germany; [m] Assumed same as Kazakhstan; [n] Assumed same as Iraq; [o] Assumed same as Qatar; [p] Assumed same as N.Zeeland; [q] Assumed default for Asia when EIA (2010a) data missing; [r] Assumed default for Africa when EIA (2010a) data is missing.

Fugitive CH_4 emissions are usually unintended with irregular occurrence and therefore highly uncertain. In GAINS, fugitive emissions from oil and gas production are calculated as follows:

$$E_{it;oil}^{leakage} = A_{it}^{oil} * \left(\gamma_i ef_{offshore}^{oil} + p_i ef_{oilsand} + (1-\gamma_i - p_i)\left((1-c_i) ef_{onshore}^{heavy} + c_i ef_{onshore}^{conventional}\right)\right) \quad (5)$$

$$E_{it;gas}^{leakage} = A_{it}^{gas} * \left(\gamma_i ef_{offshore}^{gas} + (1-\gamma_i) ef_{onshore}^{gas}\right) \quad (6)$$

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,

$ef_{offshore}^{oil}$ 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,

$ef_{onshore}^{heavy}$ is the IPCC default emission factor for heavy oil production,

$ef_{onshore}^{conv}$ is the IPCC default emission factor for conventional oil production.

$ef_{offshore}^{gas}$ is the IPCC default emission factor for offshore gas production,

$ef_{onshore}^{gas}$ 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 2 by type of hydrocarbon produced and for on-shore/off-shore production.

Table 2: 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

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. Extended recovery and utilization requires infrastructure capacity to transfer the gas from the oil and gas fields to the consumers. As existing pipelines are usually operated close to capacity maximum (EIA, 2010b), additional recovery and utilization of associated gas from major producing regions in the world requires new infrastructure capacity. OME (2001) has analysed the technical possibilities and costs of extending gas supply to the European market from different world regions. Supply costs include production, transportation and transit fees to the EU-15 border and are calculated both for extended gas pipeline capacity and LNG production capacity. In GAINS, transport and transit fee costs from the OME study are used with the exception of the costs for setting up gas processing plants (GPPs) and upgrading the gas. The investment cost of GPPs is set to 0.2 M€/Mm^3 associated gas throughput, which with a 86 percent CH_4 content of associated gas being upgraded to 97 percent, corresponds to a cost of about 3 M€/PJ gas throughput, which falls within the cost range 2.4-3.7 M€/PJ estimated by GGFR (2007) and Persson (2003).

There are several cost-effective and low cost options available for reducing 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 by 50 percent, i.e., from 0.6 to 0.3 PJ gas per PJ conventional oil produced on-shore, and no further mitigation in developed countries. Given the large number of cost-effective measures available (USEPA, 2011a), it is assumed that a 50 percent cut in developing countries is possible at zero mitigation cost and current gas price levels. This corresponds to an investment cost of 6.5 M Euro/PJ gas or oil produced annually or an annualized cost of 0.5 MEuro/PJ production when equipment lifetime is 20 years.

As noted by Buzcu-Guven et al. (2010), the data on flaring and venting volumes of associated gas are highly speculative and "order of magnitude errors are within the realm of possibility". The uncertainty in estimates is both found in the total amount of associated gas generated as well as in the fractions of the gas being recovered, flared or vented. There is a general lack of measurement data to verify assumptions on these fractions. The rare exceptions are the satellite images of flares from NOAA (2010) and the detailed measurement data published by Johnson and Coderre (2011) on amounts of associated gas flared or vented from different types of oil and gas wells in Alberta, Canada. Applying the information from Canadian oil and gas sources to other parts of the world is of course a crude approximation, however, when the derived amounts of flaring are verified against the satellite flaring images there is a reasonably close match for most countries (see Table 1). IPCC (2006, Vol.2, Tables 4.2.4 and 4.2.5) suggests an uncertainty range of ±75 percent for Tier 1 default emission factors for flaring and venting of associated gas. The estimates used here are, however, scaled with a number of country-specific factors and should therefore be lower. When varying the country-specific assumptions about the fractions of associated gas recovered/reinjected or vented as opposed to flared, within reasonable ranges, the resulting uncertainty range falls within ±30 percent on a global scale.

The uncertainty range specified above assumes that reported country-specific data on associated gas is reasonably accurate, in particular for large oil and gas producing countries. If this is not the case, the uncertainty range is higher. As an example, the amount of associated gas as fraction of crude oil produced reported to EIA (2010a) for Saudi Arabia is about 1 percent in 2005. If this were incorrect and the country instead flares at levels comparable with what its neighbours report, e.g., Iraq (8 percent),

Oman (6 percent), Qatar (12 percent), and UAE (12 percent), then Saudi Arabian venting emissions would increase five to ten times, which translates into global anthropogenic CH_4 emissions being four to eight percent higher in 2005.

IPCC (2006, Vol. 2, Tables 4.2.4 and 4.2.5) gives an uncertainty range for unintended leakage from oil production to ± 100 percent for developed countries and -12.5 to +800 percent for developing and transitional countries. Since GAINS weighs in country-specific information about type of oil produced in emission estimates and the emission factor for heavy oil is about three times higher than for conventional oil, the uncertainty range is scaled down three times to ±30 percent for developed countries and -4 to +240 percent for developing and transitional countries. The corresponding IPCC uncertainty ranges for unintended leakage from gas production are ± 100 percent for developed countries and -40 to +250 percent for developing and transitional countries. These ranges are applied here.

A recent study by Howarth et al. (2011) suggests that CH_4 emissions from shale gas is 3.6 to 7.9 percent of the gas produced. This means emissions are at least ten times higher per unit of gas produced than for natural gas production. As both leakage rates as well as the extent of future shale gas extraction are very uncertain, a higher emission factor for shale gas is not assumed in emission estimations. It is, however, still possible to explore what it could mean for future emissions. In the US shale gas production is expected to increase from 5 to 75 percent of total gas production between 2005 and 2035 (Howarth et al., 2011). Using a higher emission factor of five percent for shale gas adds about 1200 kt CH_4 in 2005 and 16641 kt CH_4 in 2030 only for the US. Also Australia, Canada, China, India, Austria, Bulgaria, Germany, Hungary, Ireland and Poland have expressed interests in expanding extraction of shale gas. If these countries extract 10-50 percent of their expected natural gas production in 2030 from shale gas then when added to the emissions from US shale gas extraction this source would add about five percent to global anthropogenic CH_4 emissions.

2.2 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 (IEA-WEO, 2009). 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 oil refined and transported summed up:

$$E_{it} = \sum_{m} \left[A_{it} * \left(ef^{\,refined} + ef^{\,transported} \right) * \left(1 - remeff_{m} \right) * Appl_{itm} \right], \qquad (7)$$

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 3 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 sectors (see Section 2.1). In 2005, developed countries are assumed to have control installed corresponding to between 2/3 of the level considered technically feasible to control (UNFCCC, 2010). Costs for these measures are taken from AEAT (1998).

Table 3: 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

2.3 Natural gas transportation

Loss of natural gas during long-distance transmission is an important source of CH_4 emissions. IPCC guidelines (2006, Vol. 2, p.4.48-4.62) recommend for Tier 1 estimations the use of default emission factors per million m^3 of marketable gas. I 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 and the distance the gas is transported. Instead of using the volume-based IPCC default factors, typical emission factors are derived for a number of countries for which detailed data is available on reported emissions, amounts of gas transported, and km long-distance on-shore gas pipelines. Emissions are measured per unit of a product of the two factors distance (in km) and volume (in bcm). Emissions are estimated as follows:

$$E_{it} = \sum_{m} \left[l_{it} * v_{it} * ef_i * (1 - remeff_{im}) * Appl_{itm} \right], \quad (8)$$

where l_{it} is the length of long-distance on-shore pipelines (in km) in country *i* in year *t*,

v_{it} is the volume of gas transported (in bcm) in country *i* in year *t*,

ef_i is the derived default emission factor in kg CH_4/(km*bcm),

$remeff_{im}$ is the removal efficiency of technology m, which is defined as the quota between the maximum feasible reduction emission factor and the current emission factor ef_i, and

$Appl_{itm}$ is the application rate of technology *m* to emissions in country *i* in year *t*.

The reason for choosing this particular specification including the chosen scaling of the variables with distance in km and volume in bcm, rests on the observation that for a few number of countries presented in Table 4 and for which there exists reported data on emissions, volume transported and length of onshore gas pipelines, the resulting derived leakage rates fit fairly well for comparable countries and also match measurement results when such are available. E.g., the derived estimate of about 1 percent leakage from Russian gas pipelines is verified by measurement data from Lelieveld et al., 2005 and Lechtenböhmer et al., 2007, who measure ranges of 0.4 to 1.6 percent and 0.5 to 1.5 percent for overall leakages from gas pipelines in Russia. For the US, the derived leakage rate of 0.41 percent is comparable in magnitude to 0.66 percent measured by Kirschgessner et al., 1997 and 0.40 percent reported in USEPA (2006a). Although an approach which regards both volume and distance transported in the emission estimations can be viewed as an improvement over IPCC Tier 1 emission factors, it must still be considered a crude approximation. E.g., most likely the weights given to pipeline length and volume transported in emission estimations differ between pipeline systems. If measurement data on emissions, on-shore pipeline lengths and volume transported were available for a larger number of countries or pipeline systems, it would have been possible and desirable to use statistical methods to empirically determine the functional form for the relationship between distance, volume transported and emissions. With current data availability this is unfortunately not possible.

Data sources for pipeline length and amounts of gas transported are UNFCCC (2010) CRF tables complemented with information from IEA (2010) and CIA World Factbook (2010) as well as country-specific sources (SPP 2007; TAG 2007; EIA 2007; Wuppertal Institute 2005).The derived country-specific factors are presented in Table 4. The factors show close values within groups of similar countries, i.e., a range of 8.9 to 14.7 kg CH_4/(km*bcm) for Western developed countries (Austria, Australia, Canada, Japan and the US) and a range of 37.7 to 97.2 kg CH_4/(km*bcm) for Eastern

European and Central Asian countries (Russia, Slovakia, Ukraine and Kazakhstan). Averages of the emission factors derived for the reference countries are then applied to other countries for which reported emissions are not as complete, see Table 4. For Annex 1 countries, results are verified against reported emissions to UNFCCC (2010). Unless mitigation options apply, current leakage rates remain constant in the future and growth in future emissions is assumed proportional to growth in domestic gas consumption.

Leakage of CH_4 emissions from long-distance gas pipelines arise for several reasons, e.g., untight compressor seals and valves or because pipelines are flushed with gas during start-ups. In the maximum technically feasible reduction case is assumed that all countries are able to reduce emissions from gas pipelines to at least the level currently observed in Western Europe, Japan and North America. On the basis of the derived emission factors in developed countries, it is considered technically possible to reduce emissions in all countries to 10 kg CH_4/(bcm*km). Costs are taken from Ecofys (1998) and reflect costs for a set of measures including electrical start-up with no flushing of natural gas during start-up and inspection and maintenance programs to secure compressor seals and valves.

As mentioned, growth in future emissions assumes no further expansion in pipeline lengths, but a future growth proportional to growth in transported volumes. This assumption is rather crude as future emissions may not grow proportionately with volumes transported but rather result from a combination of extended pipeline capacity and transported volumes. Because of difficulties finding systematic information about unutilized capacity in existing pipelines and the uncertainty surrounding the likelihood that currently planned pipeline extensions will be realized, the transportation capacity assumed reflects the capacity as of 2012 and remains constant throughout future baseline emission estimates. For the uncertainty analysis, the IPCC (2006, Vol.2, Tables 4.2.4 and 4.2.5) default range of ±30 percent for Tier 1 emission factors is adopted for this source.

Table 4: Derivation of reference emission factors for long-distance gas pipelines. Data sources: UNFCCC (2010), IEA (2010), EIA (2010b), Wuppertal Institute (2005), TAG (2007), SPP (2007), CIA World Factbook (2010).

Reference cases in Annex-1 countries	Length of onshore gas pipelines	Gas transported 2005	Energy content of gas transported 2005	Emissions reported for 2005 to UNFCCC (2009)	Derived factors		
					Emission factors		Leakage rate
	km	bcm	PJ	kt CH4	kg CH4/ (bcm*km)	kt CH4/ PJ transport	% of gas transport
Canada	83195	366	13980	270	8.9	0.019	0.10%
Japan	2720	33	1318	1	10.9	0.001	0.00%
USA	278089	589	22591	1862	11.4	0.082	0.41%
Austria	6290	33	1300	3	13.0	0.002	0.01%
Australia	27105	23	915	9	14.7	0.010	0.05%
Slovakia	2270	77	2919	7	37.7	0.002	0.01%
Russia	170000	622	23382	5048	47.7	0.216	1.08%
Kazakhstan	5808	128	4979	63	85.6	0.013	0.06%
Ukraine	37820	60	2349	221	97.2	0.094	0.47%
Assumed emission factors for other country groups	Non-Annex 1				39.0		
	EU-15				13.0		
	EU-10, Turkey, Croatia				37.7		
	N. Zealand				10.9		
	Former Soviet Union				76.9		
Max technically feasible reduction					10.0		
World[a]	**933993**	**2692**	**108374**	**7805**	**24.6**	**0.072**	**0.68%**

[a] World sums when using production quantities reported to UNFCCC, which do not always correspond exactly to quantities in IEA-WEO 2009.

2.4 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 sectors from IEA-WEO (2009) Reference scenario. 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 default factors, country-specific leakage rates are used as reported for year 2005 to UNFCCC (2009) for Annex 1 countries. To split total losses into residential and non-residential users, measurement results from the UK are used (Dennett and Vallender 2011). These measure total gas losses from gas distribution grids in UK to 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 between losses in residential and non-residential sectors is assumed in all countries. For Non-Annex 1 countries the UK leakage rates are used as default except for countries in the Former Soviet Union,

where losses are assumed comparable to levels reported by Russia to UNFCCC (i.e. about three times the UK leakage rate). Uncontrolled emission estimates are the product of the reported emission factors and the amount of gas consumed.

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 baseline, all grey cast iron networks are assumed successively replaced in developed countries, reaching 80 percent replacement in 2030 (from the 1990 level). An alternative option is to increase the control frequency. AEAT assumes a doubling of the control frequency from every fourth (baseline assumption) to every second year removes 50 percent of emissions. In the maximum technically feasible reduction scenario, all grey cast iron networks are replaced by 2030. Costs for these options are taken from AEAT (1998).

As country-specific emission factors reported to UNFCCC are used and a distinction is made between residential and non-residential sectors, the uncertainty range in the GAINS estimate ought to be considerably lower than the range of -2 to +500 percent for IPCC (2006, Vol.2, Tables 4.2.4 and 4.2.5) Tier 1 emission factors. The assumed uncertainty range is 0 to +30 percent on a global scale.

2.5 Fuel combustion for energy purposes in stationary and mobile sources

Apart from leakage in consumer gas distribution networks, CH_4 emissions from energy distribution and use also derive from incomplete combustion of any type of fuel. Emissions are calculated as activity data times a fuel and sector specific emission factor. Activity data is PJ of energy used by fuel and sector as reported and projected by IEA-WEO (2009).

Emissions from incomplete combustion in non-residential stationary sources are estimated using default IPCC emission factors (2006, Vol. 2, pp. 2.16-2.23, p. 3.24). For the residential sector, emission factors specified for different types of boilers and fuels are used as reported by Johansson et al. (2004), Kjällstrand and Olsson (2004), Olsson and Kjällstrand (2006) and Delmas (1994). These emission factors are considerably higher than IPCC default factors in particular for biomass combustion.

Emissions from combustion in mobile sources are estimated using IPCC (2006, p. 3.24) default emission factors. As these are specified per km travelled, they are converted to emissions per energy unit consumed using vehicle specific conversion factors from IEA-WEO (2009). For passenger cars and light duty vehicles, emission factors are specified by fuel and vehicle type and by the emission control standard of the vehicles. For other means of transportation, emission factors are specified only by types of fuel and vehicle, while no default factors by emission control standard are available.

No options for mitigating CH_4 emissions are identified for combustion activities.

If IPCC default emissions factors (2006, Vol. 2, pp. 2.16-2.23, p. 3.24) are applied also to the residential sector, global emissions from incomplete combustion of fuel for energy purposes in stationary and mobile sources would amount to about 3400 kt CH_4 in 2005. This is considerably lower than the estimate of 10800 kt CH_4 when using the Swedish emission factors used in this study. In general, uncertainty is likely to be high in particular for emissions from the residential sector where the variability in emission factors is high between different types of fuels and boilers.

2.6 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 brown and hard coal production are calculated as follows:

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

$$E_{HC;it} = A_{HC;it} \times \left[\gamma_{HC;i}^{undergr} \times \left(ef_{m;i}^{undergr} + ef_{postm;i}^{undergr}\right)\right] +$$

$$+ A_{HC;it} \times \left[\left(1 - \gamma_{HC;i}^{undergr}\right) \times \left(ef_{m;i}^{surface} + ef_{postm;i}^{surface}\right)\right] \quad (10)$$

where

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

$$ef_{m;i}^{undergr} = ef_{m;i;NOC}^{undergr} \times \left[\alpha_{VAM;i} \times \left(1 - r_{VAM}\right) \times CLEappl_{VAM;i}\right]$$

$$+ ef_{m;i;NOC}^{undergr} \times \left[\left(1 - \alpha_{VAM;i}\right) \times \left(1 - r_{dgas}\right) \times CLEappl_{dgas;i}\right] \quad (12)$$

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.

For hard coal, country-specific fractions for surface vs underground mining are derived from UNFCCC (2010) CRF tables for Annex-1 countries, while all hard coal is assumed mined underground in non-Annex-1 countries. Emissions from surface and underground mining are split into mining and post-mining emissions. Mining emission factors are derived from UNFCCC (2010) CRF tables, from a national source for China (China University of Petroleum, 2008) and using IPCC (2006, Vol.2, p.4.12) world low end default factors whenever country-specific information is unavailable. For post-mining emission factors, default IPCC (2006, Vol.2, p.4.12) factors are used specified separately for surface and underground mines. Underground mining emissions derive from emissions during pre-mine degasification (degas) and from CH_4 being released through the ventilation air system (VAM) during mining. Country-specific fractions of VAM emissions to degasification emissions are taken from USEPA (2003) for a selection of countries (see Table 5). For all other countries, the US fraction of 0.6 VAM to 0.4 degasification emissions is assumed.

In 2005, China was mining 38 percent of global coal production and the share is expected to increase in the future. The release of coalbed CH_4 in China is on average assumed to 11 m^3/ton coal. This factor is derived from China University of Petroleum (2008) assuming 41 percent of CH_4 is emitted from coal mines with average release of 15 m^3/t coal, 28 percent from mines releasing 9 m^3/t coal, 18 percent from mines releasing 7 m^3/t coal, and 13 percent from mines releasing 5 m^3/t coal.

As shown in Table 6, the weighted average release of CH_4 from global coal mining in 2005 is 7.8 m^3/t coal produced in GAINS, with on average 1.4 m^3/t coal for brown coal and 9.9 m^3/t coal for hard coal. This can be compared with the weighted global emission factor of 11.9 m^3/t coal when using average default IPCC (2006) emission factors for surface and underground mining in all countries (and applying the same surface/underground split of 2005) and the considerably lower estimates of 6.7 m^3/t by USEPA (2003) and 4.3 m^3/t by GMI (2009).

Emissions from surface mining can be reduced if CH_4 is recovered through pre-mine drainage up to ten years before the surface mining starts (USEPA, 2008). Currently there is only one project known to be recovering and utilizing CH_4 from pre-mine drainage at a surface mine in the US and details about the removal efficiency of this option are uncertain (Sino-US New Energy Sci-Tech Forum, 2009). The CH_4 content of pre-mine drainage gas from surface mines is assumed to 60 percent and it is considered technically possible to recover 90 percent of the drainage gas (USEPA, 2010). Drainage gas is assumed to make up 40 percent of surface mining emissions, while the residual mining emissions are released during mining operations.

Utilization of drained gas requires upgrading to grid quality (from 60 to 97 percent CH_4) and extended transport capacity of gas either by pipeline or liquefied and transported by ship. The same cost assumptions as applied for recovery and utilization of associated gas from oil and gas production are applied here (se Section 2.1).

No mitigation potential is assumed from post-mining emissions.

Currently in the US, at least 90 percent of degasification emissions from underground coal mines are recovered and utilized (USEPA, 2010) and this is assumed technically possible in other countries as well. Costs for degasification are taken from Thakur (2006) and include costs for in-mine drilling, underground pipeline costs, and hydraulic fraction of vertical wells and other gob wells. Costs correspond to 0.023 Euro/ton coal for mildly gassy coal seams containing less than 2.8 m^3 CH_4/ton coal, 0.39 Euro/ton coal for medium gassy coal seams containing 2.8-8.5 m^3 CH_4/ton coal, and 2.74 Euro/ton coal for highly gassy coal seams containing more than 8.5 m^3 CH_4/ton coal. It is assumed that 90 percent of degasification emissions can be recovered and utilized from underground mines. For coal seams exceeding 2.8 m^3 CH_4/ton coal the recovered gas is assumed of a quality high enough (>93 percent) to be injected into natural gas pipelines without further upgrading. Gas recovered from coal seams containing less than 2.8 m^3 CH_4/ton coal is assumed to need upgrading from 60 to 97 percent CH_4. Note that extended pre-mine degasification is also expected to reduce the risk of explosions, which is a major health benefit of this measure. Due to difficulties with assessing the value of this benefit, it has not been regarded in the cost assessment.

Installation of Ventilation Air Methane (VAM) oxidizers is still in a starting phase, with a handful of installations worldwide, e.g., in Australia, China and the UK (Mattus and Källstrand, 2010), however, the technology used is well known and has been applied frequently for controlling 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 the exceptions of South Africa and India, where current VAM concentration rates are on average 0.1 percent USEPA (2003). With better information about the distribution of VAM concentration rates in different countries, this assumption may need to be revised in the future. It is not assumed possible to install VAM oxidizers on surface mines.

Table 5: Assumptions for estimating CH_4 emissions from coal mining in the GAINS model and resulting implied emission factors (for major coal producing countries).

Region	Country	Fraction of coal mined underground (as opposed to surface)	Fraction of mine gas exiting through ventilation shafts as opposed to pre-mining degasification	Average VAM concentr. rate	Implied emission factor coal mining (total surface and underground mining)		
					No control	With current recovery rate maintained	With maximum technically feasible reduction
					kt CH4/Mt coal produced		
Africa	South Africa	88% [a]	90% [f]	0.1% [f]	1.9	1.9	1.8
	Other Africa	100% [b]	60% [b]	0.3% [b]	8.4	8.4	3.3
Asia	Indonesia	100% [b]	60% [b]	0.3% [b]	8.4	8.4	3.3
	Mongolia	1% [d]	60% [b]	0.3% [b]	1.0	1.0	0.6
	North Korea	100% [b]	60% [b]	0.3% [b]	8.4	8.4	3.3
	Thailand	0% [d]	60% [b]	0.3% [b]	0.9	0.9	0.6
	Vietnam	100% [b]	60% [b]	0.3% [b]	8.4	8.4	3.3
Australia and N. Zealand	Australia	19% [c]	60% [b]	0.4% [f]	3.1	2.5	1.5
	New Zealand	14% [c]	60% [b]	0.3% [b]	2.8	2.8	1.1
Canada	Canada	1% [c]	60% [b]	0.3% [b]	0.6	0.6	0.4
Central Asia	Kazakhstan	13% [c]	60% [b]	0.29% [f]	6.6	6.5	3.2
China	China	100% [d]	60% [g]	0.46% [f]	7.9	7.7	3.6
EU-27	Bulgaria	7% [c]	60% [b]	0.3% [b]	0.9	0.9	0.6
	Czech Rep.	23% [c]	73% [f]	0.26% [f]	3.2	2.2	1.4
	Estonia	0% [c]	60% [b]	0.3% [b]	0.9	0.9	0.6
	Germany	12% [c]	61% [f]	0.3% [f]	1.5	1.0	0.5
	Greece	0% [c]	60% [b]	0.3% [b]	1.1	1.1	0.8
	Hungary	0% [c]	60% [b]	0.3% [b]	0.1	0.1	0.1
	Poland	60% [c]	72% [f]	0.26% [f]	3.4	2.9	1.6
	Romania	10% [c]	60% [b]	0.3% [b]	0.8	0.8	0.6
	Spain	44% [c]	60% [b]	0.3% [b]	3.1	3.1	1.6
	United Kingdom	48% [c]	70% [f]	0.3% [b]	12.4	9.9	4.0
Europe -east	Serbia-Monten.	0% [b]	60% [b]	0.3% [b]	0.9	0.9	0.6
	Turkey	4% [c]	60% [b]	0.3% [b]	2.7	2.7	1.5
	Ukraine	99% [c]	60% [b]	0.3% [f]	24.6	23.1	7.6
India	India	93% [e]	60% [b]	0.1% [f]	3.0	3.0	2.3
Latin and Central	Brazil	60% [d]	60% [b]	0.3% [b]	5.4	5.4	2.2
	Mexico	100% [b]	60% [b]	0.5% [f]	8.4	8.4	3.3
	Other L. America	100% [b]	60% [b]	0.3% [b]	8.4	8.4	3.3
Russia	Russia	35% [c]	70% [f]	0.38% [f]	8.3	8.2	4.1
United States	United States	33% [c]	60% [f]	0.39% [f]	3.5	2.8	1.5

Sources: a) UNFCCC (2000), b) Author's assumption, c) UNFCCC (2010), d) IEA-WEO (2009) fraction of hard coal mined, e) UNFCCC (2004), f) USEPA (2003), g) Current VAM fraction reported for China is 88 percent (USEPA, 2003), however, due to an expected increase in degasification (GMI,2011) it is assumed 60 percent also for China.

Table 6: Comparison of implied CH_4 emissions (mining and post-mining) released before recovery per ton coal produced in GAINS and other sources, unit: m^3 CH_4/ton coal produced.

Region	Country	GAINS model	GAINS source	USEPA (2003)	GMI (2009)
Africa	South Africa	2.6	UNFCCC -NIR (2000), IPCC (2006)	2.0	2.1
	Other Africa	11.7	IPCC (2006) low end default factor		
Asia	Indonesia	11.7	IPCC (2006) low end default factor		0.2
	Mongolia	1.4	IPCC (2006) low end default factor		0.5
	North Korea	11.7	IPCC (2006) low end default factor		
	Thailand	1.2	IPCC (2006) low end default factor		
	Vietnam	11.7	IPCC (2006) low end default factor		2.6
Australia and	Australia	4.3	UNFCCC-CRF (2010)	4.1	4.1
N. Zealand	New Zealand	3.9	UNFCCC-CRF (2010)		5.4
Canada	Canada	0.9	UNFCCC-CRF (2010)		1.0
Central Asia	Kazakhstan	9.3	UNFCCC-CRF (2010)	5.9	5.5
China	China	11.0	China University of Petroleum (2008)	9.4	4.7
EU-27	Bulgaria	1.1	UNFCCC-CRF (2010)		3.7
	Czech Rep.	4.4	UNFCCC-CRF (2010)	5.5	5.5
	Estonia	1.2	UNFCCC-CRF (2010)		
	Germany	2.0	UNFCCC-CRF (2010)	5.3	2.9
	Greece	1.6	UNFCCC-CRF (2010)		
	Hungary	0.1	UNFCCC-CRF (2010)		3.6
	Poland	4.8	UNFCCC-CRF (2010)	6.2	5.1
	Romania	0.9	UNFCCC-CRF (2010)		71.1
	Spain	4.3	UNFCCC-CRF (2010)		4.4
	United Kingdom	17.2	UNFCCC-CRF (2010)	11.8	23.8
Europe -east	Serbia Montenegro	1.2	IPCC (2006) low end default factor		
	Turkey	3.7	UNFCCC-CRF (2010)		2.2
	Ukraine	34.2	UNFCCC-CRF (2010)	29.0	30.9
India	India	4.2	UNFCCC -NIR (2004), IPCC (2006)	1.9	3.2
Latin and	Brazil	7.5	IPCC (2006) low end default factor		
Cenral	Mexico	11.7	IPCC (2006) low end default factor	7.7	16.5
America	Other Latin America	11.7	IPCC (2006) low end default factor		
Russia	Russia	11.6	UNFCCC-CRF (2010)	10.2	6.7
United States	United States	4.9	UNFCCC-CRF (2010)	5.1	3.8
World -weighted		**7.8**		**6.7**	**4.3**
World-IPCC (2006)		**11.9**	IPCC *average* default mining+post-mining (surface: 1.2 m3/t, undergr: 19.1 m3/t)		

USEPA (2003, p.30) estimate costs for installing VAM oxidizers without energy recovery on the basis of measured concentrations and flow rates on 58 ventilation shafts at underground coal mines in the US. The resulting curve is adapted to estimate costs in non-US countries. Table 7 shows a comparison between the costs presented by USEPA for different VAM concentration rates and the projected costs as estimated by GMI (2008) for installing 11 sets of VAM oxidizers without energy recovery on the Xiaodongshan Shaft in the Jincheng mining area in China. As shown, cost estimates by USEPA (2003) are considerably lower. The higher costs projected for the

Chinese coal mine are applied here, but adapted to different VAM concentration levels using a scaling proportional to the curve reported by USEPA (2003).

Table 7: Basis for calculation of VAM oxidizer costs, Euro/t CO_2eq (2005 prices).

VAM concentration rate	GAINS model			USEPA (2003, p.30)	
	VAM ox installations on the Xiaodongshan Jingshen Mine (GMI, 2010) scaled to VAM concentr rates as in USEPA (2003)				
	Investment cost	O&M cost	Total cost	Total cost	Total cost
	Lifetime=16 yrs, discount rate=4%	Lifetime=16 yrs, discount rate=4%	Lifetime=16 yrs, discount rate=4%	Lifetime=16 yrs, discount rate=15%	Lifetime=16 yrs, discount rate=4%[a]
<0.2%	VAM oxidation not possible				
0.20%	2.67	2.52	5.19	2.85	2.16
0.30%	2.53	2.39	4.92	2.7	2.04
0.40%	2.39	2.25	4.64	2.55	1.93
0.50%	2.25	2.12	4.37	2.4	1.81
1.00%	1.54	1.46	3.00	1.65	1.25

[a] Author assumes 50% investment cost and 50% O&M costs.

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. An improved ventilation system is assumed to double the ventilation capacity of the mine compared with a conventional system, which would double the amount of electricity used for ventilation. Unruh (2002) estimates the total energy consumption by the US coal mining industry in 1998 to 25.5 billion kWh. According to Papar et al. (1999), the energy use of the entire US mining industry is 44 billion kWh in 1998 whereof 12 billion kWh (27 percent) is used for mine ventilation. If this fraction is applied to the coal mining industry, the energy consumption for coal mine ventilation in the US is 6.9 billion kWh in 1998. With a total production of 1117.5 Mt coal in 1998 (whereof 63 percent surface and 37 percent underground mined), then current use of electricity for mine ventilation per ton coal produced is 6.2 kWh (EIA, 2010c). The total cost for this option is the sum of the cost for improved ventilation and the installation of VAM oxidizers. Just like the degasification options, upgraded ventilation in coal mines is likely to reduce the risk of explosions, which is a major health benefit of this measure. Due to difficulties assessing the value of this benefit, it has not been regarded in the analysis. 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 (except S Africa and India).

IPCC (2006, Vol. 2, p. 4.12) define an uncertainty range for underground coal mining emission factors of ±40 percent with the low-end estimate for mining depths < 200 m

and the high-end estimate for depths > 400 m. Taking several country-specific factors into account, including effects of mine depths in major producer countries, the uncertainty range for the GAINS estimate is evaluated at ±20 percent on a global scale. For surface mining GAINS adopts the uncertainty range of a factor two suggested by IPCC (2006, Vol.2, Table 4.1.4). For post-mining emission factors, IPCC (2006, Vol.2, pp. 4.12, 4.19) provide uncertainty ranges of ±100 percent for surface mining and ±60 percent for underground mining.

Uncertainty is also present in the fixed assumptions about removal efficiencies. E.g., country- and site-specific obstacles for implementation of VAM oxidizers have not been fully explored due to lack of site-specific information.

Including emissions from abandoned coal mines in the analysis would increase CH_4 emissions from this sector. Currently, CH_4 emissions from abandoned coal mines in the US correspond to about 9 percent of VAM emissions (UNFCCC, 2011). If this factor is applied worldwide, the global release is in 2005 is 1400 kt and growing to 2400 kt CH_4 in 2030.

2.7 Livestock

CH_4 emissions from livestock emerge from enteric fermentation during the digestive process in the stomachs of ruminants as well as from manure management. GAINS estimate CH_4 emissions separately for the animal types dairy cows, non-dairy cattle, pigs, sheep and goats, camels, buffalo, and horses. For dairy cows, non-dairy cattle and pigs, animal types are further split by whether animals are subject to liquid or solid manure management. CH_4 emissions from livestock are estimated as the sum of the two emission types *n* (enteric fermentation and manure management) for a certain animal type *s* in country *i* and year *t*:

$$E_{its} = \sum_{lmns} \left[A_{itls} * ef_{ilns}^{NOC} * (1 - remeff_{mns} * h_{itsm}) * Appl_{itslm} \right], \qquad (13)$$

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*.

Activity data is number of animals by type. Sources for historical and current animal numbers are EUROSTAT (2009) for EU countries, UNFCCC (2010) CRF tables for other Annex 1 countries, and FAOSTAT (2010) for non-Annex1 countries. Projections for EU are taken from the CAPRI Model (2009) to be consistent with the EU effort sharing agreement (EC, 2009). For other world regions, future drivers are based on forecasts by major world regions as developed by FAO (2003).

Implied emission factors reported by countries to UNFCCC (2010) are used when available, complemented with regional specific IPCC (2006, Vol.4, Tables 10.10, 10.11, 10.14 and 10.15) default emission factors.

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

$$ef_{it;cow}^{NOC} = ef_i^{animal} + ef_i^{milk} * (x_{it} - 3000) \quad (14)$$

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*.

CH_4 emissions from enteric fermentation in cows and non-dairy cattle can be reduced by changing animal diets, e.g., by replacing roughage with concentrates or introducing more fat in the diet. As feed changes require control over what animals eat, they are only assumed applicable to animals when these are kept indoor. Removal efficiency for this option is five to ten percent when applied (Ecofys 2009, ECCP 2003, Lovett et al. 2006, Boadi et al. 2004). Costs for feed changes refer to the cost of replacing 6 percent of the daily dry matter intake (DMI) by soy oil (Ecofys, 2009). Indoor housing rates are taken from Klimont and Brink (2003) for European countries and extended to other countries by applying European rates in countries with similar livestock structure. No indoor housing of cows and cattle is assumed for Africa, Central Asia and Latin America.

CH_4 emissions from liquid manure management from cows, non-dairy cattle and pigs can be reduced by treating the manure in anaerobic digesters (AD) (Ecofys 2009, AEAT 2001). AD plants produce biogas, which can be recovered and utilized for energy purposes. Three scales of AD installations for treatment of manure are considered in GAINS: farm-, household-, and community- scale digesters. Farm scale AD is assumed economically feasible for handling manure from all large farms, i.e., farms with a minimum size of 100 dairy cows, 200 beef cattle or 1000 pigs. Large farm fractions are taken from EUROSTAT (2008) and European rates are applied to other countries with similar agricultural structures. Removal efficiency for farm-scale AD is assumed 80 percent (Ecofys 2009). For developing countries, GAINS also include the option of treating manure in household-scale ADs (An et al. 1997; Dhingra et al. 2011). These are common in some developing countries and digest manure and other organic waste material from farm households. The generated biogas is recovered and utilized by the households, e.g., to fuel cooking stoves. The digesters are cheap to install but labour intensive to operate effectively (An et al. 1997), which make application limited to developing countries with low average wage rates in agriculture[1]. Household size digesters are currently assumed to treat 5 to 10 percent of cattle manure in India (MNRE, 2006) with an assumed possible extension to 30

[1] Afghanistan, Armenia, Azerbaijan, Bangladesh, Bhutan, Cambodia, China, Egypt, Turkmenistan, Tadjikistan, Uzbekistan, Indonesia, Kazakhstan, Georgia, North Korea, Kyrgizistan, Laos, Malaysia, Mongolia, Myanmar, Nepal, Pakistan, Philippines, Sri Lanka, Thailand and all African countries except South Africa.

percent of livestock manure in all developing countries. Community-scale AD plants receive manure from several farms in the vicinity of the plant. Transportation of manure for long distances is costly and increase emissions of both CH_4 and carbon dioxide. This option is therefore only applied in GAINS to countries with intensive pig farming (more than 200 pigs per m^2), which is Belgium, Denmark, the Netherlands and Malta, and in India to the extent that current use of village size digesters has been documented (MNRE, 2006). Costs for farm-scale and community-scale AD installations are taken from Ecofys (2009). Cost for household-scale ADs is taken from An et al. (1997).

Uncertainty in baseline emission estimates is primarily linked to difficulties with measuring emissions from a large number of point sources (animals) and to convert highly variable measurement results to default emission factors. Comparability of results also suffers from a large variation in the measurement techniques used (Iqbal et al. 2008). GAINS adopts the IPCC (2006, Vol.4, p.10.33) uncertainty range of ± 30 percent for enteric fermentation emissions and ± 25 percent for manure emissions when assessed on a global scale.

Uncertainty about the future mitigation potential is particularly present for emissions from enteric fermentation and linked to both the selection of mitigation options included in the model and to highly uncertain removal efficiencies. This is an area of intensive research and several options show promising results, however, widespread adoption appears slow. These include the use of vaccination against methanogenic bacteria in the rumen (Wright et al., 2004; Ecofys 2009) and the use of propionate precursors as feed additive or through genetic engineering of feed plants for grazing animals (Newbold et al. 2005, Ecofys 2009). As these options are not yet in commercial use, they have not been considered feasible as mitigation options in the 2030 timeframe in GAINS.

General productivity increases in milk and meat production through genetic engineering is sometimes mentioned as a possible CH_4 mitigation option with the assumption that a cut in animal stocks can outweigh increases in emissions per animal. Lovett et al (2006) show that general productivity increases tend to increase system emissions because of negative effects on animal health, which increase the fraction of non-productive (young) animals in the stock. General productivity increases is therefore not regarded as a viable CH_4 mitigation option in this study.

Although the current technical mitigation potential for enteric fermentation in GAINS is limited to a few percent on a global scale, it may grow suddenly in response to new developments in mitigation options and their commercial availability.

2.8 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 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 unless country-specific factors have been reported to UNFCCC (2009). 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 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:

$$E_{it} = \sum_{sm} A_{it} * ef_{i;\,flood}^{IPCC} * h_i * \beta_s * V_{is} * (1 - remeff_{sm}) * Appl_{itsm} , \qquad (15)$$

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*.

Activity data for rice cultivation is measured in million hectares of land and is taken from FAOSTAT (2008) with projections based on FAO (2003). Data on country-specific water regimes is taken from IRRI (2007).

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 reduce 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 sole option and 10 percent when applied in combination with other options.

Estimation of emissions from soils belong to one of the most uncertain estimates in emission inventories in general (Winiwarter and Rypdal 2001, Winiwarter and Muik 2010). In GAINS, baseline emission estimates are scaled for different water regimes, however, IPCC (2006, Vol. 4, p. 5.44) recommends in addition to scale with the application of organic amendments. As it was not possible to collect country-specific data for organic amendments, variation in this factor is not regarded in estimations. IPCC (p. 5.52) provide a default value for the uncertainty in scaling fraction estimates of ± 20 percent, which is adopted in this study.

2.9 Open burning of agricultural waste residues

This sector refers to open burning of agricultural waste, e.g., burning of plant residues on fields. Activity data is amount of agricultural waste burned, which is taken from UNFCCC (2009) for Annex-1 countries and from Niemi (2006) for countries without reporting to UNFCCC. A few countries (France, Germany, Ireland, Luxembourg, Netherlands, Sweden and the UK) report no generation of agricultural waste for open burning and hence these countries have no emissions at all from this source. The uncontrolled 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.

The maximum technically feasible reduction of emissions from introducing a ban on agricultural waste burning is set to 3 kt CH_4 per Mt waste. Due to enforcement problems, it is not assumed that all of emissions from this source can be controlled with a ban. The cost of mitigating methane through this option is set to zero, because it is assumed that this is a measure that would be implemented primarily to control other types of airborne emissions like VOCs and black carbon. CH_4 control would come as a co-benefit.

IPCC (2006, Vol. 5, p.5.23) estimate uncertainty in default emission factors for combustion of solid waste to an order of magnitude.

It should be noted that due to lack of systematic information, GAINS does not cover emissions from pre-scribed burning of savannahs and human-induced forest fires. Estimates by USEPA (2011b) suggest that a more complete coverage of emissions from open biomass burning would add considerably to emissions. USEPA estimates global emissions from all three sources to about 20 000 kt CH_4 per year, to be compared with about 3000 kt CH_4 per year estimated in GAINS for burning of agricultural waste residues only.

2.10 Biodegradable 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 energy. The activity data used in GAINS is the total amount of waste generated before it is disposed of to landfills or other types of treatment. Amounts of waste generated are first split into 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* :

$$E_{it} = \sum_s \sum_m A_{i;(t-y_s);s} * ef_s * (1 - remeff_{sm}) * Appl_{itsm} \quad (16)$$

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:

$$ef_S = DOCm_S * DOCf * MCF * F * 16/12 * (1 - OX), \quad (17)$$

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.

Activity data used is country-specific amounts of waste generated from 1980 onwards. Historical reported waste generation rates are taken from various sources as presented in Table 8 together with approximations made for countries where data is missing. While data on MSW generation is available for most parts of the world, generation rates for industrial solid waste are rare. It has only been possible to find European data (EUROSTAT, 2005) on industrial waste generation. The European rates per value added are used to extend the data to other world regions as shown in Table 8. This is of course a very crude assumption, as both differences in production technologies used as well as barriers in global markets are likely to affect amounts of waste generated and the relative value of the product in the market, which in turn affects the amount of waste generated per value added. It would have been desirable to relate industrial waste amounts to physical rather than monetary units in order to at least control for differences in product market values, however, data on physical production units coupled with associated waste amounts is not readily available.

The historical waste generation rates are used as basis for future projections. Waste generation elasticity estimates are produced using a detailed data set from EUROSTAT (2005) covering 31 European countries with annual data from 1985 to 2003. 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):

$$\log(MSWcap)_{it} = \alpha + \beta_1 * \log(GDPcap)_{it} + \beta_2 * \log(urbrate)_{it} + \varepsilon_{it}, \qquad (18)$$

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[2]. A Lagrange multiplier (LM) test of poolability show 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 9 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[3]. 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 (UNIDO 2006):

$$\log(INW)_{it} = \alpha + \beta * \log(VA)_{it} + \varepsilon_{it}, \qquad (19)$$

where

INW is Mt industrial solid waste per year,

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

$\varepsilon_{it}=u_i+v_{it}$ 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 9, 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

[2] 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).

[3] 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.

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 8: Baseline assumptions for solid waste amounts generated.

Sector	World region	Basis for future projections	Annual waste generated	Source
Municipal solid waste (MSW)				
	EU-27, Iceland, Norway, Switzerland, Turkey	MSW in kg/person 2005	300 to 793	EUROSTAT 2009
	USA	MSW in kg/person 1996	453	IPCC (1997, Vol.2, p.6.6-6.7); Eawag (2008)
	Canada		493	
	Australia		460	
	New Zealand		485	
	Russia		318	
	Japan		157	
	India		73	
	China		307	
	Indonesia		186	
	Brazil		168	
	Chile		537	
	Peru		360	
	Guatemala		215	
	Egypt		146	
	Nigeria		146	
	Rest of Africa	MSW in kg/person 1996	146	Author's assumptions
	Rest of Former Soviet Union and Eastern Europe		318	
	Rest of Latin America		360	
	Rest of South Asia		186	
Industrial solid waste				
Food, beverages and tobacco	EU-15	industrial solid waste per value added in 2000, ton/M Euro value added	390	EUROSTAT 2005
	EU-10 (New Member States)		724	
Pulp and paper	EU-15		271	
	EU-10 (New Member States)		542	
Textile, footwear and leather	EU-15		105	
	EU-10 (New Member States)		154	
Wood and wood products	EU-15		963	
	EU-10 (New Member States)		1544	
Rubber and plastics	EU-15		86	
	EU-10 (New Member States)		106	
Other manufacturing	EU-15		244	
	EU-10 (New Member States)		1331	
	Other industrialized countries		like EU-15	Author's assumptions
	Other transitional or developing countries		like EU-10 (New Member States)	

Table 9: 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 (Denmark, Germany and Sweden) are close to this optimum and have since 2005 introduced a complete ban on landfilling of biodegradable waste.

A list of waste treatment options considered in GAINS are presented in Table 10 together with a definition of the optimal control. In baseline emissions, the effects of

already implemented waste treatment options as well as future effects of adopted legislation are taken into account in applied control strategies. Information on current adoption of waste treatment are taken from UNFCCC (2009) CRF and NIR and complemented with other sources (IPCC 2006, Vol.5, ch.2; Sakai, 1997; USEPA, 2006b). Data on collection and treatment rates of MSW in developing countries is difficult to obtain or verify. IPCC (2006, Vol.5, Ch.2) and Eawag (2008) provide guiding information for a few developing countries, which is used to make general assumptions for developing countries. It is assumed that about half of household food waste is centrally collected and deposited to an unmanaged landfill, while the other half ends up in household composts. Household paper waste ends up in an unmanaged landfills and household wood waste is to fifty percent burnt and to fifty percent deposited to an unmanaged landfill. These assumptions are of course very crude and the picture may change with better information about the situation in developing countries.

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 (Tanskanen, 2000) and of converting paper waste to recycled pulp (AEAT, 1998) minus the cost-savings of depositing less waste to landfills (AEAT, 1998) and income from selling recycled pulp at a market value (FAOSTAT, 2010). When summing up the different cost items the net unit cost turns out negative, i.e., with these assumptions there appears to be a relatively large net profit from recycling household paper waste. I find two possible reasons for the negative cost estimates for this mitigation measure. First, the market value of recycled pulp 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. Second, costs for separate collection may be higher than assumed in particular in countries currently lacking infrastructure and institutions for mixed collection of household waste. Initial costs for setting these up and educating the public on how to use them are likely to be considerable. Because of difficulties with guessing the non-distorted market value of recycled pulp and lack of information about costs for setting up basic infrastructure for waste collection in developing countries, the cost estimates for the municipal solid waste sector should be treated with caution until further verification is possible.

Crude approximations of the amounts of waste generated and the application of different treatment options, in particular for developing countries, contribute to uncertainty in estimated emissions. The effect on emissions from the combined uncertainty for activity data and treatment rates is estimated at ±50 percent on a global scale.

Table 10: 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.	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.
	Household composting	
	Large-scale composting	
	Incineration	
	Landfill with gas recovery and flaring	
	Landfill with gas recovery and utilization	
	Landfill without gas recovery	
MSW - paper	Paper recycling	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.
	Incineration	
	Landfill with gas recovery and flaring	
	Landfill with gas recovery and utilization	
	Landfill without gas recovery	
MSW - wood	Incineration	Biodegradable waste currently landfilled is source separated and incinerated for energy recovery.
	Landfill with gas recovery and flaring	
	Landfill with gas recovery and utilization	
	Landfill without gas recovery	
Food industry	Anaerobic digestion w gas recov. and utiliz.	Biodegradable waste is treated in anaerobic digesters with gas recovery and utilization.
	Composting	
	Incineration	
	Landfill with gas recovery and flaring	
	Landfill with gas recovery and utilization	
	Landfill without gas recovery	
Pulp and paper industry	Incineration	All waste (black liqour) recovered and incinerated for energy purposes.
	Landfill with gas recovery and flaring	
	Landfill with gas recovery and utilization	
	Landfill without gas recovery	
Textile industry	Incineration	All waste recovered and incinerated for energy purposes.
	Landfill with gas recovery and flaring	
	Landfill with gas recovery and utilization	
	Landfill without gas recovery	
Wood industry	Recycling for board production	All waste max recovered and recyled for wood board production, residuals incinerated for energy purposes.
	Incineration	
	Landfill with gas recovery and flaring	
	Landfill with gas recovery and utilization	
	Landfill without gas recovery	

2.11 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, domestic and industrial wastewater are accounted for separately. Domestic wastewater is split into centralized and decentralized collection, basically referring to wastewater from urban and rural population, except for industrialized countries where wastewater collection services often include some rural areas as well. Fractions of wastewater collected centrally are taken from UNFCCC (2010), FAO (2009) and UNstat (2010).

Uncontrolled emissions are defined as emissions when wastewater is emitted directly to a water body without prior collection and treatment. As anaerobic conditions are formed when large quantities of wastewater are collected and stored, CH_4 formation in the uncontrolled case are likely to be very limited 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):

$$E_{it} = \sum_{s} A_{it} * h_s * ef_i * (1 - remeff_m) * Appl_{itm} \quad (20)$$

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

$$ef_i = BOD_i * B_0 * MCF_0, \quad (21)$$

where *BOD* is amount of biochemical oxygen demand per person in country *i*,

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.

Country-specific IPCC (2006, Vol.5, Table 6.4) default factors for the amount of biochemical oxygen demand per person (*BOD*) are used with a range from 12.4 to 31.0 kt CH_4/M people. A IPCC (2006, Vol.5, Table 6.2) default factor of 0.6 kt CH_4/kt BOD is used for the maximum CH_4 producing capacity (B_0). Methane correction factors (MCF_0) of 0.1 for uncontrolled decentralized collection and 0.5 for uncontrolled centralized collection apply.

Industry sectors identified by IPCC (2006, Vol.5, p.6.19) as potential sources for wastewater CH_4 emissions are food, organic chemical, and pulp- and paper industry. Emissions are calculated as:

$$E_{it} = \sum_{sm} A_{its} * COD_i * ef_i * (1 - remeff_m) * Appl_{itm} \quad (22)$$

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

$$ef_i = B_0^{COD} * MCF_0, \quad (23)$$

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 oxidised but released as CH_4.

A 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}). A methane correction factor (MCF_0) of 0.5 is applied for the uncontrolled case.

Activity data is the amount of COD in untreated industrial wastewater. These amounts are derived from production volumes combined with COD generation factors as

specified in Table 11. Production volumes in tonne product are taken from FAOSTAT (2011), USDA (2011), and EC (2003). Future production volumes are projected proportional to growth in value added in each industry sector (food, organic chemical, and pulp- and paper). 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 11. 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 pulp- and paper industry, which amounts to 162 m^3 wastewater per ton product and 9 kg COD per m^3 wastewater.

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. 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. 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). 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 are taken from UNFCCC (2009) CRF tables and NIRs for Annex 1 and non-Annex 1 countries complemented with information from FAO (2009) wastewater

database, IPCC (2006, Vol.5, Table 6.5), USDC (2005), and Pokhrel and Viraraghavan (2004). 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).

IPCC (2006, Vol. 5, p.6.17) estimates the uncertainty range for both maximum CH_4 producing capacity (B_0) and BOD per person to ± 30 percent.

A major uncertainty source in the estimation of CH_4 emissions from wastewater are amounts and COD content in industry wastewater. Reported data is rare and anecdotal and the water efficiency in industry is likely to fluctuate widely with the chosen production technology as well as access to quality water and local water price. IPCC (2006, Vol. 5, p.6.23) provides a general uncertainty range for amount of COD per ton product of -50 to +100 percent, which is applied here.

1 Table 11: Assumptions for estimation of amounts of pre-treatment COD (chemical oxygen demand) in industry wastewater.

Industry	Product/production process	Wastewater generation		COD content pre-treatment		COD concentration in untreated wastewater		Sources
		developed countries	developing/ transitional	developed countries	developing/ transitional	developed countries	developing/ transitional	
		m3/t dry product		kg COD/ton dry product		kg COD/m3 wwater		
Food	Beer of barley	6.3	6.3	18.3	18.3	2.9	2.9	IPCC (2006, Vol.5, Table 6.9)
	Vegetable oils	3.1	3.1	3.1	3.1	1	1	
	Wine	23	23	34.5	34.5	1.5	1.5	
	Sugar (centrifugal)	9	9	28.8	28.8	3.2	3.2	
	Meat (total)	13	13	53.3	53.3	4.1	4.1	
	Milk (total)	7	7	18.9	18.9	2.7	2.7	
Organic chemical	Organic chemicals[a]	9 m3/ Euro value added	9 m3/ Euro value added	27 kg COD/ Euro value added	27 kg COD/ Euro value added	3	3	EUROSTAT (2005), IPCC (2006, Vol.5, Table 6.9)
Pulp	Bleached sulphate pulp	70	200	150	500[b]	2.14	2.50	Judd and Jefferson (2003), Pokhrel and Viraraghavan (2004), Khansorthong and Hunsom (2009), Buzzini and Pires (2002), Thompson et al. (2001), Latorre et al. (2007)
	Unbleached sulphate pulp	50	100	60	200[b]	1.20	2.00	
	Bleached sulphite pulp	150	200	160	500[b]	1.07	2.50	
	Unbleached sulphite pulp	70	200	100	300[b]	1.43	1.50	
	Mechanical wood pulp	20	100	60	300[b]	3.00	3.00	
	Semi-chemical wood pulp	30	100	140	600[b]	4.67	6.00	
	Other fibre pulp	20	100	60	300[b]	3.00	3.00	
	Recovered pulp	20	100	60	300[b]	3.00	3.00	
Paper	Newsprint	25	50	1.5	5	0.06	0.10	
	Printing&writing paper	29	60	1.5	5	0.05	0.08	
	Recovered paper	20	40	1	5	0.05	0.13	
	Household/sanitary/tissue	15	30	1.5	5	0.10	0.17	
	Wrapping papers	20	40	1.5	5	0.08	0.13	
	Paper&paperboard-other	8	20	1.5	5	0.19	0.25	

[a] Production volumes not available. Amounts refer to average wastewater generation rates for organic chemical industry in Europe (EUROSTAT, 2005)

2 [b]COD content in effluent wastewater when recovered black liqour has been removed, i.e. COD generated in the digester house not included.

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