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

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Abstract. This paper presents estimates of current and future global anthropogenic methane emissions, their technical mitigation potential and associated costs for the period 2005 to 2030. The analysis uses the GAINS model framework to estimate emissions, mitigation potentials and costs for all major sources of anthropogenic methane for 83 countries/regions, which are aggregated to produce global estimates. Global emissions are estimated at 323 Mt methane in 2005, with an expected increase to 414 Mt methane in 2030. The technical mitigation potential is estimated at 195 Mt methane in 2030, whereof about 80 percent is found attainable at a marginal cost less than 20 Euro t^{-1} CO_2eq when using a social planner cost perspective. With a private investor cost perspective, the corresponding fraction is only 30 percent. Major uncertainty sources in emission estimates are identified and discussed.

1 Introduction

Methane (CH_4) is a greenhouse gas currently contributing to about 15 percent of global anthropogenic greenhouse gases emitted every year when assuming a greenhouse warming potential (GWP) of 25 times carbon dioxide (CO_2) over 100 yr (IPCC, 2007). As CH_4 has a relatively short perturbation lifetime of 12 yr in the atmosphere, the GWP over 20 yr is considerably higher at 72 times that of CO_2 (IPCC, 2007). With this shorter time horizon, CH_4 emissions account for about 35 percent of global anthropogenic greenhouse gas emissions. Hence CH_4 is an important source of anthropogenic greenhouse gas emissions, and its mitigation is especially important for controlling climate change in the near term (Shindell et al., 2012).

This work identifies important sources of global CH_4 emissions, the possibilities for reducing these emissions, and associated mitigation costs. It also points out major sources of uncertainty and highlights critical gaps in knowledge. The presented work is an update and extension of previous work on CH_4 using the GAINS model (Höglund-Isaksson and Mechler, 2005; Cofala et al., 2007; UNEP, 2011), see Sect. 3.2 for a comparison.

Global anthropogenic CH_4 emissions with technical mitigation potentials and costs are estimated for the period 2005 to 2030. Forty source sectors for CH_4 are identified and region-specific estimates for 83 world regions are produced using the Greenhouse gas and Air pollution Interactions and Synergies (GAINS) model (http://gains.iiasa.ac.at/) framework. All major anthropogenic sources of CH_4 are covered, i.e. livestock, rice cultivation, biodegradable solid waste, wastewater, coal mining, oil and gas production, gas transmission pipelines, gas distribution networks and combustion of fuel used for energy consumption and from open burning of agricultural waste residuals. Other types of open burning of biomass for non-energy purposes, e.g. pre-scribed savannah burning or human-induced forest fires, are excluded from the analysis due to lack of systematic information.

Section 2 presents the methodology applied to estimations of emissions and mitigation costs. Results are summarized in Sect. 3 with comparison of results to other studies. A discussion of uncertainty issues is included in Sect. 4, while Sect. 5 concludes the analysis. For more detailed descriptions on emission estimations, mitigation potentials and costs, the reader is referred to the Supplement.

2 Methodology

2.1 CH$_4$ emission estimations in GAINS

2.1.1 General emission estimation methodology

Estimation of CH$_4$ emissions in GAINS follows the methodology recommended by IPCC (2006) as closely as available data allows. With the ambition to produce as consistent estimates across regions as possible, an extensive compilation of country-specific information on parameters with significant effects on emissions was undertaken. This makes it possible to present estimates for several sources that go deeper than what is possible with IPCC Tier 1 methods. It also provides an opportunity to improve the understanding of the consistency and uncertainty in emissions reported by countries to UNFCCC and other inventories. For a detailed description of the estimation methodology applied and the reference sources used for each sector, please consult the Supplement.

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

$$E_{its} = \sum_m \left[A_{its} \cdot ef_{ism} \cdot \text{Appl}_{itsm} \right], \tag{1}$$

where

$$ef_{ism} = ef_{is}^{NOC} \cdot (1 - \text{remeff}_{sm}) \quad \text{and} \quad \sum_m \text{Appl}_{itsm} = 1, \tag{2}$$

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

Hence, the activity data specified for a particular sector, country and year is allocated to different technology specifications using application rates. The sum of the application rates of all technologies specified for a certain sector, including the application rate for no control, will always be unity. When there are several mitigation technology options available in the same sector, technologies are added sequentially. The most preferred technology (usually the cheapest one) is first adopted to its maximum, thereby removing a fraction of emissions corresponding to its removal efficiency. Then follows adoption of the second preferred technology on the remaining emissions, again removing emissions in correspondence with the removal efficiency of the technology, and so on for each additional technology adopted in the sector.

2.1.2 Activity data

In GAINS, activity drivers for emission projections enter calculations externally and are taken from international sources as presented in Table 1. For the analysis on global CH$_4$, energy and macroeconomic projections are taken from the IEA World Energy Outlook Reference scenario 2009 (IEA-WEO, 2009). Agricultural activities are taken from FAO-STAT (2010) and EUROSTAT (2009) for historical years with projections following FAO (2003) for all world regions except for Europe, where a more recent scenario from the CAPRI model (2009) has been used. The main difference between the FAO and CAPRI projections for Europe, is that FAO projects a slight decline in pig numbers by 4 percent between 2000 and 2030, while the more recent CAPRI scenario projects an increase by 18 percent over the same period. Expected declines in cattle numbers in Europe are comparable in the two scenarios. Figure 1 shows the future development of major external drivers for CH$_4$ emissions on a global scale between 2005 ($=100$) and 2030.

2.1.3 Emission factors

Whenever data availability allows, emission factors have been derived using country-specific information for important parameters. It is however often difficult to bridge all gaps in the country-specific information needed to produce full IPCC Tier 2 emission estimates. These gaps have then been filled with default assumptions taken from IPCC (2006) or other sources. Table 2 presents the basic methodology applied to different emission sources and the country specific and non-country specific information used to produce emission estimates. For a more comprehensive description of the calculation methods applied, the references used and the identified sources of uncertainty in estimations, please refer to the Supplement.

The resulting GAINS emission estimates for 2005 were compared with the emission inventory for countries reporting to UNFCCC (2010) in the Common Reporting Formats (CRFs) and the National Inventory Reports (NIRs). Discrepancies were carefully investigated and adjustments made when appropriate, i.e. to the extent that the consistency in methodology across countries is preserved (Höglund-Isaksson et al., 2009).

2.2 CH$_4$ mitigation and cost estimation in GAINS

2.2.1 Technically feasible CH$_4$ mitigation options

The mitigation potential assessed in this analysis refers to reductions in emissions through application of technologies that are currently commercially available and already implemented at least to a limited extent. Hence, more speculative mitigation options, e.g. large-scale vaccination of livestock or application of propionate precursors to combat enteric fermentation emissions, are not included (Ecofys, 2009;

Table 1. GAINS CH$_4$ emission sources, activity data and drivers.

Emission source	Historical activity data	Projection driver
Oil and natural gas production – venting of associated gas	Oil and natural gas production (IEA-WEO, 2009)	Future oil and natural gas production (IEA-WEO, 2009)
Oil and natural gas production – unintended leakage	Oil and natural gas production (IEA-WEO, 2009)	Future oil and natural gas production (IEA-WEO, 2009)
Combustion – Flaring of associated gas	Oil and natural gas production (IEA-WEO, 2009)	Future oil and natural gas production (IEA-WEO, 2009)
Long-distance natural gas transmission	Volume transported and length of on-shore pipelines (UNFCCC, 2010; IEA-WEO, 2009; IEA, 2010; Wuppertal Institute, 2005; CIA World Fact book, 2010)	Future gas consumption (IEA-WEO, 2009)
Gas distribution networks	Gas consumption by sector (IEA-WEO, 2009)	Future gas consumption (IEA-WEO, 2009)
Coal mining	Coal production (IEA-WEO, 2009)	Future coal production (IEA-WEO, 2009)
Combustion – fossil and bio fuels	Fuel consumption by sector (IEA-WEO, 2009)	Future fuel consumption (IEA-WEO, 2009)
Livestock	Livestock numbers by animal type (FAOSTAT, 2010; EUROSTAT, 2009; UNFCCC, 2010)	Growth in livestock numbers from FAO (2003), CAPRI model (2009)
Rice cultivation	Land area for rice cultivation (FAOSTAT, 2010)	Growth in land area for rice cultivation (FAO, 2003)
Combustion – agricultural waste burning	Amount of agricultural waste burned (UNFCCC, 2010; Niemi, 2006)	Niemi (2006)
Biodegradable municipal solid waste	MSW generation per capita (EUROSTAT, 2009; Eawag, 2008; IPCC, 1997)	Data from EUROSTAT (2005) used to estimate elasticity for waste generation to growth in GDP per capita and urbanization rate from IEA-WEO (2009)
Biodegradable industrial solid waste	Amounts of waste generated derived from country report to EUROSTAT (2005) and related to sub-industry value added.	Data from EUROSTAT (2005) used to estimate elasticity for waste generation to growth in industry value added from IEA-WEO (2009)
Domestic wastewater	Population connected to centralized wastewater collection (UNFCCC, 2010; FAO, 2009; UN, 2009, 2010)	Population growth from IEA-WEO (2009)
Industrial wastewater	Relevant industry production (FAOSTAT, 2011; USDA, 2011; EC, 2003)	Growth in industry value added from IEA-WEO (2009)

Newbold et al., 2005; Wright et al., 2004). Non-technical mitigation options that involve changes in human behaviour and preferences, e.g. changes in human diets towards consumption of less meat and milk products, are also excluded from the analysis. It should be noted that the technical mitigation potential is different from the politically feasible mitigation potential as the latter also takes into account costs and political barriers for implementation. Because technologies included in the analysis are commercially available and already fairly well developed, significant improvements are not expected over the coming two decades. Hence, no technological development is assumed and mitigation effectiveness and costs per activity unit remain constant over the analyzed period. This assumption together with including only

Table 2. Methodology for CH$_4$ emission estimations in the GAINS model (for references, see Supplement).

| Emission source	Emission calculation method	Country-specific factors used for deriving emission factors	Non-country specific factors used for deriving emission factors
Oil and natural gas production – venting of associated gas	IPCC Tier 2 (2006, Vol. 2, 4.43–4.35)	Types of hydrocarbons produced	Vented associated gas as fraction of gas vented or flared by type of hydrocarbon.
		Fraction offshore production	
		Associated gas as fraction of hydrocarbons produced (by energy content)	Methane content of associated gas is assumed 86 percent.
		Fraction of associated gas reinjected/recovered	
		Fraction of associated gas flared or vented	
		Satellite images of flares	
Oil and natural gas production – unintended leakage	IPCC Tier 1 (2006, Vol. 2, p. 4.41)	No country-specific information used	IPCC Tier 1 default emission factors.
Combustion – Flaring of associated gas	IPCC Tier 2 (2006, Vol. 2, 4.43–4.35)	Country-specific volumes of flared associated gas consistent with derived vented emissions and verified against satellite images of flares.	Combustion efficiency of flares assumed to 98 percent.
Long-distance natural gas transmission	Variant of IPCC Tier 2 (2006, Vol. 2, p. 4.43)	Length of on-shore pipelines	Emission factors in kg CH$_4$ bcm^{-1} km^{-1} derived for nine reference countries, which were applied to comparable world regions.
		Volume of gas transported	
Gas distribution networks	Country reports to UNFCCC (2010)	Country-specific leakage rates for Annex-1 countries.	Split of total losses by residential and non-residential users based on measurement results for the UK.
			UK leakage rates applied to Non-Annex-1 countries, except Former Soviet Union where Russian leakage rates applied.
Coal mining	IPCC Tier 2 (2006, Vol. 2, 4.10–4.20) for pre-mining and mining emissions and IPCC Tier 1 for post-mining emissions.	Methane emissions (mining and post-mining before recovery) per ton coal produced.	IPCC Tier 1 default emission factors for post-mining emissions.
		Fractions brown and hard coal produced.	
		Fraction of hard coal produced underground for Annex-1 countries.	For derivation of emission factors, missing country specific information was replaced by default assumptions.
		VAM and degasification emissions as fractions of total emissions recorded for USA, S Africa, Czech Rep., Germany, Poland, UK, Russia and China.	
		Current recovery of degasification gas.	
Combustion -fossil and bio fuels	IPCC Tier 1–2 (2006, Vol. 2, 2.16–2.23)	GAINS model stores country-specific fuel consumption by detailed sector and fuel type for 162 GAINS regions.	IPCC Tier 1 default emission factors for mobile sources and non-residential stationary sources.
			For residential sources, emission factors specified by fuel and boiler types.
Livestock	Implied ef:s reported to UNFCCC and IPCC Tier 1 (2006, Vol.4, Ch. 10) default factors	Reported country-specific emission factors for Annex-1 countries.	IPCC Tier 1 default emission factors by world region whenever country-specific information is missing.
		Fractions of liquid and solid manure management applied to dairy cows, non-dairy cattle and pigs.	
		Dairy cow emissions linked to country-specific milk yield	
Rice cultivation	IPCC Tier 1–2 (2006, Vol. 4, p. 5.49)	Country-specific data on applied water regimes, i.e. continuously flooded, intermittently flooded or upland.	IPCC default scaling of emission factors for different water regimes
Combustion – agricultural waste burning	IPCC Tier 1 (2006, Vol. 5, p. 5.20)	Country-specific data on amounts of agricultural waste residuals.	IPCC Tier 1 default emission factor
Biodegradable municipal solid waste (MSW)	IPCC Tier 1–2 (2006, Vol. 5, Ch. 2), Variant of First-Order Decay method	Current MSW generated per person	Missing country-specific info replaced by default assumptions
		Current MSW composition	IPCC default Methane Correction Factor (MCF) for landfilled waste is 0.5 for developing countries and 0.8 for developed countries, unless otherwise reported to UNFCCC.
		Current treatment of MSW in Annex-1 countries and for a few non-Annex-1 countries.	
Biodegradable industrial solid waste	IPCC Tier 1–2 (2006, Vol. 5, Ch. 2), Variant of First-Order Decay method	Waste generation rates per value added by industry sector for 31 European countries and European averages as default for other countries.	IPCC default factors for the content of degradable organic carbon (DOCm) in different types of waste.
		Current treatment of industrial solid waste by industry for Annex-1 countries.	IPCC default factor of 0.5 used for fraction of DOCm that decompose.
			IPCC default oxidation factor of 0.1 assumed for covered landfills.
Domestic wastewater	IPCC Tier 1–2 (2006, Vol. 5, Ch. 6)	Fraction of total population connected to centralized or decentralized wastewater collection.	Default MCF assumed for centralized collection is 0.5 and for decentralized collection 0.1.
		Country-specific BOD per person.	
		Current treatment of wastewater (primary/secondary and aerobic/anaerobic).	
Industrial wastewater	IPCC Tier 1–2 (2006, Vol.5, Ch. 6)	Output in tons for relevant food industries, i.e. beer, vegetable oils, wine, sugar, meat and milk.	For relevant food industries, IPCC default rates for COD content in wastewater per ton of product.
		Output by type of production process for pulp and paper industry.	For pulp and paper industry, typical amounts of wastewater generated and COD content for different types of processes.
			For organic chemical industry, typical wastewater generation rates calculated for Europe per value added and extended to rest of the world.
			For organic chemical industry, IPCC default rates for COD content in wastewater.

technologies that are fairly well known makes the assessment of the mitigation potential conservative rather than optimistic.

Table 3 presents a list of CH$_4$ mitigation options included in the GAINS model with specifications of how maximum technically feasible applications are defined. For detailed information about the sources and references used for assumptions about removal potentials and costs, please refer to the sector descriptions in the Supplement.

Table 3. CH_4 mitigation measures in the GAINS model.

Emission source sector	Definition of CH_4 mitigation measures for max technically feasible mitigation potential
Oil & gas production	Recovery and utilization of vented associated gas assuming at least 95 % of associated gas now flared or vented can be recovered and utilized. Costs reflect costs for recovery, LNG conversion when needed and transportation by pipeline or ship to EU border.
	Reducing unintended leakage from wells and temporary storage in developing/transitional countries to levels currently observed in developed countries.
Long-distance gas transmission	Reduced leakage rates everywhere to levels currently observed in W Europe, N America and Japan, i.e. about 10 kg CH_4 bcm^{-1} km^{-1}.
Gas distribution networks	Replacement of grey cast iron pipes with PE or PVC networks.
Coal mining	Pre-mine degasification with gas recovery and utilization applicable on both surface and underground coal mines. Up to 90 % of current degasification emissions assumed recoverable. Costs includes recovery of gas, and for surface mines and mildly gassy underground coal seams, upgrading costs are included.
	Oxidation of ventilation air methane (VAM) on underground mines applicable to 50 % of current VAM emissions in all countries except S. Africa and India and with possible extension to 70 % if combined with improved ventilation air systems.
Combustion	Ban on open burning of agricultural waste.
Livestock	Diet changes applicable to indoor fed cows and cattle.
	Farm-scale anaerobic digestion of manure from cows, cattle and pigs on large farms with liquid manure management systems. Household-scale digestors applicable to up to 30 % of manure from cows, cattle and pigs in developing countries.
Rice cultivation	Combined option of intermittent aeration of continuously flooded fields and use of alternative hybrids and sulphate amendments.
Municipal solid waste-food & garden residues, paper, and wood	Full source separation of waste and no future landfill of untreated biodegradable waste.
	Treatment of up to 90 % of household food and garden waste in composts or in anaerobic digesters with biogas recovery and utilization.
	Recycling of up to 90 % of household paper waste.
	Incineration with energy recovery of up to 90 % of household wood waste.
	Landfill gas recovery applied to capture emissions from historical deposition of biodegradable waste.
Industrial solid waste-food, pulp & paper, and wood industry	Food industry: treatment of waste in anaerobic digesters with biogas recovery and utilization.
	Pulp & paper industry: recovery of black liqour for energy utilization.
	Wood industry: max recycling of waste for chipboard production with residuals being incinerated for energy utilization.
Domestic wastewater	Upgrade of current primary treatment systems to anaerobic treatment with biogas recovery and utilization.
Industrial wastewater-food, pulp & paper, and organic chemical industry	Upgrade of current treatment systems to two-stage anaerobic treatment with biogas recovery followed by aerobic treatment.
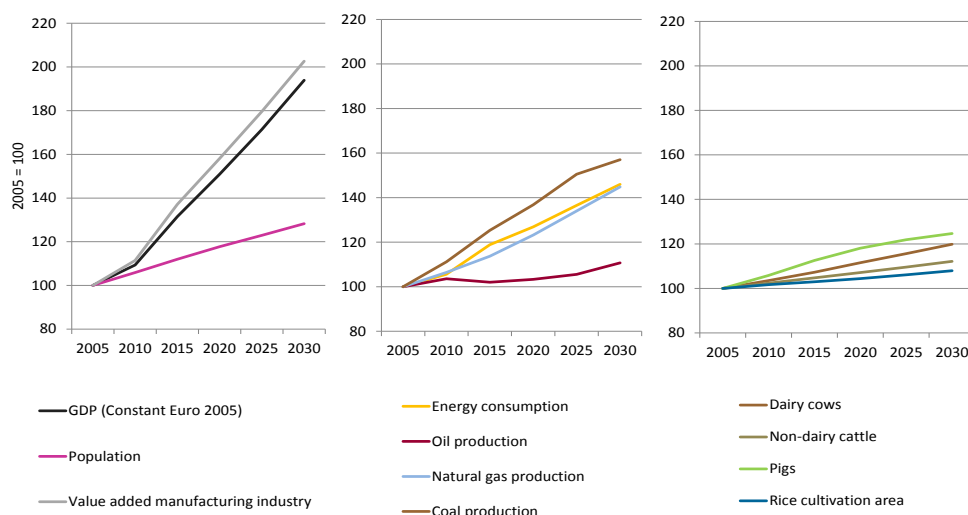
Fig. 1. Global development 2005 to 2030 in major drivers for CH$_4$ emissions entering model estimations from external sources (IEA-WEO, 2009; FAO, 2003; CAPRI model, 2009).

Table 4. Gas prices in the IEA-WEO (2009) Reference scenario in Euro GJ^{-1}.

	2005	2010	2015	2020	2025	2030
Europe	3.95	5.29	7.20	8.32	9.01	9.64
North America	5.94	3.73	5.02	6.10	6.90	7.81
Pacific	4.50	6.23	8.19	9.46	10.20	10.91

2.2.2 Mitigation costs

CH$_4$ mitigation costs per unit of activity are in GAINS calculated as the sum of investment costs, labour costs, non-labour operation and maintenance costs, cost-savings due to gas or energy recovery, and non-energy cost savings. The annual cost per unit of activity of applying technology m in country i and year t is defined as:

$$C_{itm} = I_{im} \left[\frac{(1+r)^{T_m} \times r}{(1+r)^{T_m} - 1} \right] + M_{im} + (L_{im} \times W_{it} \times w_{is})$$
$$- S_{im} - 0.75 \left(E_{im} \times p_{it}^{\text{electr}} \right) - \left(G_{im} \times p_{it}^{\text{gas}} \right) \quad (3)$$

where I_{im} is the non-annualized investment cost for technology m in country i, i.e. the upfront investment cost, $\left[\frac{(1+r)^{T_m} \times r}{(1+r)^{T_m} - 1} \right]$ is the factor by which investment costs are annualized using discount rate r and a technology-specific lifetime of T_m years, M_{im} is the annual operation and maintenance cost for technology m, L_{im} is the fraction of annual work hours for operating technology m, W_{it} is the annual average wage in country i in year t, w_{is} is a country-specific wage adjustment factor for type of sector s (agriculture or manufacturing industry), S_{im} is the sum of non-energy annual cost-savings, E_{im} is the amount of energy recovered and utilized as electricity or heat, p_{it}^{electr} is the electricity price in country i in year t, G_{im} is the amount of gas recovered, and p_{it}^{gas} is the gas price in country i in year t.

The unit costs are expressed in constant 2005 Euros per unit of activity. Depending on the sector, the unit mitigation cost is expressed in e.g. Euro per cow, Euro per GJ oil produced or Euro per ton waste generated.

Country and sector specific annual average wages are taken from LABORSTA (ILO, 2010) for historical years. Agriculture and manufacturing industry wages as fractions of the average annual wage were derived on a country-specific basis taking the average for 2005–2008 and keeping the fractions constant for future years. Projections for agriculture and manufacturing industry wages are assumed to follow growth in value added in respective sector (IEA-WEO, 2009).

In the GAINS estimation of CH$_4$ mitigation costs, energy recovery with utilization assumes half of recovered energy is utilized as heat and half converted to electricity. The price of heat is taken to be half the electricity price, i.e. the opportunity cost saving of recovering energy is multiplied by a factor 0.75.

Gas recovery refers to recovered gas of an upgraded quality of 97 percent CH$_4$. For some mitigation options, e.g. when biogas is recovered from anaerobic digestion or landfills, upgrading from 60 to 97 percent CH$_4$ is necessary for supplying the gas to the grid (Persson, 2003). Costs for upgrading gas have been included in investment costs.

Gas prices with projections are taken from the IEA-WEO (2009) Reference scenario as presented in Table 4. The price of electricity has been derived from the price of natural gas using the investment and operation costs of converting gas to electricity in a natural gas combined cycle power plant taken from OECD/IEA (2005). From this cost and when expressing the prices of electricity and gas in per unit of GJ, the

Table 5. Regional aggregations of CH_4 emission estimates in GAINS.

World region	GAINS CH_4 regions
Africa	Egypt, South Africa, North Africa (includes Algeria, Morocco, Libya, Tunisia, Sudan), and Other Africa (includes all other African countries)
China	China
India	India
Asia -rest	Afghanistan, Armenia, Azerbaijan, Bangladesh, Bhutan, Brunei, Cambodia, Former Soviet Union States (includes Tadjikistan, Turkmenistan and Uzbekistan), Gerogia, Indonesia, Japan, Kazakhstan, Kyrgizistan, Nepal, North Korea, Laos, Malaysia, Mongolia, Myanmar, Pakistan, Philippines, Singapore, South Korea, Sri Lanka, Taiwan, Thailand and Vietnam
Australia&NZ	Australia and New Zeeland
US&Canada	Canada and United States
L. America	Argentina, Brazil, Chile, Mexico, Other Latin America (includes all other countries in Central- and Latin America and the Caribbean)
EU-27	Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom
Europe – rest	Albania, Belarus, Bosnia-Herzegovina, Croatia, Iceland, Macedonia, Moldova, Norway, Serbia-Montenegro, Switzerland, Turkey, Ukraine
Middle East	Middle East (includes Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, UAE, Yemen, Gaza, Israel, Iran Iraq, Jordan, Lebanon and Syria)
Russia	Russian Federation

following general approximation of the link between the gas and the electricity prices was constructed:

$$p_{it}^{\text{electr}} = 3 + 2 p_{it}^{\text{gas}}. \tag{4}$$

The total mitigation cost in sector s in country i and year t when technology m is applied to application rate Appl_{itsm} is defined as:

$$\text{TC}_{its} = \sum_m \left[A_{its} \cdot C_{itm} \cdot \text{Appl}_{itsm} \right], \tag{5}$$

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

The average cost of mitigation when applying technology m on sector s in country i and year t, is defined as the additional cost imposed on the sector in comparison with the cost already invested on mitigation in the baseline. The additional cost is then divided by the additional emission reduction attained when applying technology m in sector s, i.e.

$$\text{AC}_{its} = \frac{\text{TC}_{its}^{\text{Max}} - \text{TC}_{its}^{\text{Baseline}}}{E_{its}^{\text{Max}} - E_{its}^{\text{Baseline}}}. \tag{6}$$

Hence, if mitigation has already been adopted in the baseline in response to current legislation, the average cost reflects the

additional cost of extending mitigation beyond current legislation. When no mitigation has been adopted in the baseline, the average cost reflects the cost of moving from no control to maximum mitigation in the sector.

The marginal mitigation cost curve on a global or world region scale is built up by the country and year-specific average cost estimates for extending adoption of mitigation technology in each sector.

2.2.3 Social and private cost perspectives

An important feature of splitting the unit mitigation costs for CH_4 in GAINS into different cost items is that it allows for specifying costs from different investor perspectives. From an investor's point of view, costs are not absolute but relative to a set of alternative costs and benefits available to the investor in a certain moment in time. The subjective perspective of the investor is therefore decisive for investment decisions in general as well as for mitigation investments. To reflect some of the effects of differences in investor perspectives, two different cost perspectives are defined: a "social" and a "private".

The social cost perspective refers to a social planner or public investor, who optimizes costs and benefits over a longer future time horizon and is able to accommodate risks better than a private investor. The social investor is assumed
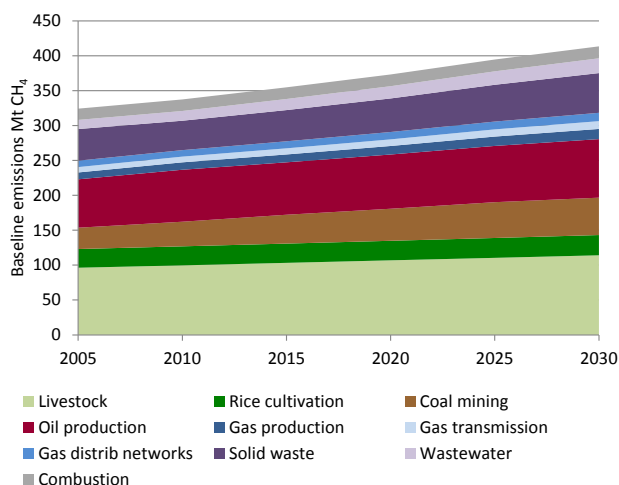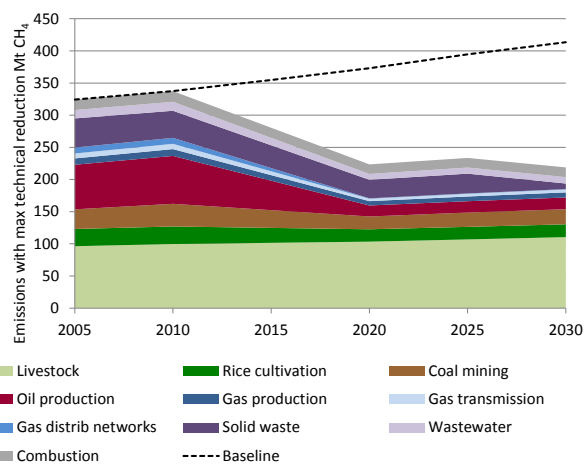
Fig. 2. Global anthropogenic CH$_4$ baseline emissions 2005 to 2030.

Fig. 3. Global anthropogenic CH$_4$ emissions with max implementation of available mitigation technology 2005 to 2030.

to apply a discount rate of four percent as a reflection of the long-term social opportunity cost of capital. The entire lifetime of installed mitigation technology, which for CH$_4$ mitigation technology included in GAINS varies from two to twenty years, is regarded in the cost analysis. Finally, the expected increase in the future gas price, here foreseen by the IEA-WEO (2009) Reference scenario, is assumed fully anticipated in the social planner's investment decision.

The private investor is assumed to have an interest in short-term profits at a minimum of uncertainty. In this cost perspective, the discount rate reflecting the private opportunity cost of capital is taken to be ten percent and the equipment lifetime is only considered up to maximum ten years. Due to high uncertainty about the future gas price level, investors are expected to heavily discount potential future gains from increases in the gas price to the extent that only observed fuel price levels are anticipated in the investment decisions today. The same type of unwillingness to invest in mitigation under uncertainty is in the economics literature often regarded as the expected response of rational investors to uncertainty in future carbon price levels (Brunner et al., 2012).

2.3 Geographic coverage of CH$_4$ in GAINS

The geographic coverage of CH$_4$ emission estimates in the GAINS model is global with the world divided into 83 regions as specified in Table 5. Emissions, mitigation potentials and costs are calculated for each of the 83 regions, however to display results, the regions are aggregated into ten world regions as shown in Table 5.

3 Results

3.1 Global CH$_4$ emissions and mitigation potentials

Global anthropogenic emissions of CH$_4$ are estimated at 323 Mt in 2005 and expected to increase by 28 percent to 414 Mt in 2030 when assuming no further implementation of control measures than those currently adopted or prescribed by implemented legislation. Figure 2 illustrates the expected development in global baseline emissions and Table 6 summarizes the findings quantitatively. Fossil fuel extraction and use contribute 131 Mt CH$_4$ or 41 percent of global CH$_4$ emissions in 2005. Until 2030 emissions from this sector are expected to grow by 37 percent, primarily due to an expected increase in production and use of coal in China. Agriculture sources contribute 126 Mt in 2005 with an expected increase by 16 percent until 2030. Solid waste and wastewater sectors contribute 57 Mt CH$_4$ to emissions in 2005 with an expected increase by 36 percent until 2030, much driven by an increase in emissions from food industry waste and wastewater. Combustion emissions account for about 11 Mt CH$_4$ per year and are expected to remain rather stable in the future.

The full technical mitigation potential for CH$_4$ in 2030 is estimated at 195 Mt CH$_4$, i.e. 47 percent below baseline or 33 percent below the 2005 emission level. Figure 3 shows how maximum implementation of available mitigation technology has immediate effect in all sectors except solid waste, where a slow decomposition of waste deposited to landfills postpones effects on emissions by an assumed ten years for fast degrading waste and twenty years for slow degrading waste (see Supplement for further details). More than 60 percent of the technical mitigation potential in 2030 can be realized in fossil fuel extraction, about 30 percent in waste and wastewater sectors and only eight percent in agriculture.

Table 6. Global CH_4 emissions and technical mitigation potentials in 2030.

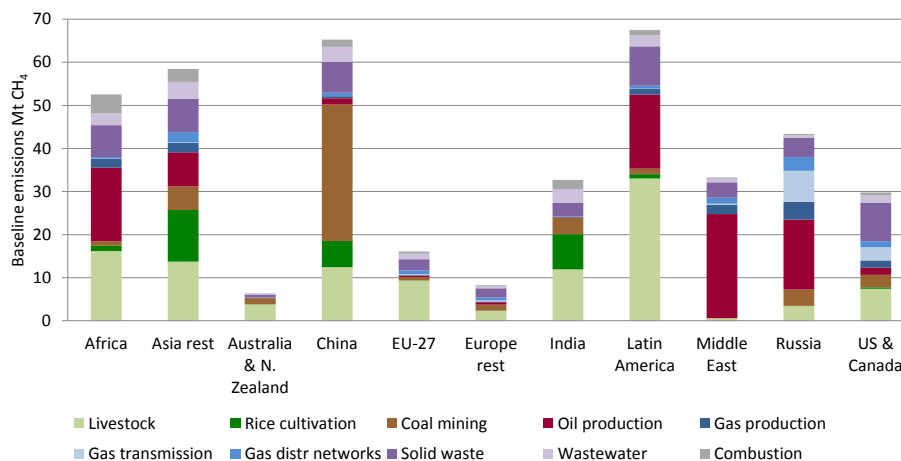| Emission source sector	Control measure	Baseline 2005	Baseline 2030	Max technical reduction 2030
		Mt CH_4	Mt CH_4	Mt CH_4 reduced
Non-dairy cattle	Liquid manure: max implementation of anaerobic digestion	0.2	0.2	0.1
	Ent. fermentation: diet changes indoor fed cattle	50.3	57.2	0.5
Dairy cows	Liquid manure: max implementation of anaerobic digestion	0.9	0.9	0.2
	Ent. fermentation: diet changes indoor fed cattle	17.3	20.3	1.0
Pigs	Max implementation of anaerobic digestion of liquid manure	5.6	6.8	1.9
Other livestock	No mitigation option identified	22.1	29.0	0.0
Rice cultivation: continuously flooded	Combined: aeration, alt. hybrids and sulphate amendments	19.7	21.5	7.2
Rice cultivation: intermittently aerated	Combined: alt. hybrids and sulphate amendments	7.1	7.5	1.9
Agricultural waste burning	Ban	3.1	3.6	1.9
MSW food&garden waste	Max separation and treatment, no landfill of biodegr. waste	10.3	11.8	9.2
MSW paper waste	Max separation and treatment, no landfill of biodegr. waste	16.7	18.2	15.2
MSW wood waste	Max separation and treatment, no landfill of biodegr. waste	5.0	5.5	5.5
Food industry solid waste	Anaerobic digestion with gas recovery and utilization	9.0	17.6	15.0
Pulp&paper ind solid waste	Max recovery and utilization of black liquor	0.2	0.4	0.3
Textile industry solid waste	Max recovery and utilization	1.1	1.2	1.2
Wood industry solid waste	Max recovery and utilization	2.0	2.2	1.8
Domestic wastewater	Upgrade to anaerobic treatm with gas recovery and utilization	7.9	9.2	1.9
Food industry wastewater	Upgrade to anaerobic treatm with gas recovery and utilization	2.0	4.7	3.9
Pulp&paper ind wastewater	Upgrade to anaerobic treatm with gas recovery and utilization	2.0	4.9	3.5
Org chemical ind wastewater	Upgrade to anaerobic treatm with gas recovery and utilization	1.2	2.4	2.0
Coal mining – brown coal: pre-mining	Pre-mining degasification	0.2	0.3	0.3
Coal mining – brown coal: mining (VAM)	No mitigation option identified	0.5	0.7	0.0
Coal mining – brown coal: post-mining	No mitigation option identified	0.1	0.1	0.0
Coal mining – hard coal: pre-mining	Pre-mining degasification	7.6	13.9	12.1
Coal mining – hard coal: mining (VAM)	Ventilation air oxidizer with improved ventilation systems	15.6	26.7	17.6
Coal mining – hard coal: post-mining	No mitigation option identified	6.6	11.9	0.0
Oil production – associated gas	Recovery and utilization of vented associated gas	55.9	68.9	60.3
Oil production – leakage	Good practice measures to reduce unintended leakage	13.4	15.0	5.3
Oil transportation and refining	Good practice measures to reduce leakage	0.2	0.2	0.1
Gas production – associated gas	Recovery and utilization of vented associated gas	1.8	2.9	2.5
Gas production – leakage	Good practice measures to reduce unintended leakage	8.1	11.7	4.1
Oil and gas production – associated gas flaring	Linked to mitigation of associated gas emissions	2.1	2.6	0.0
Long-distance gas transmission	Leakage reduced to 10 kg CH_4/(bcm*km)	7.7	11.2	6.7
Gas distr. networks (residential)	Replacement of grey cast iron pipes and doubling of control	4.9	6.3	6.1
Gas distr. networks (non-residential)	Replacement of grey cast iron pipes and doubling of control	4.3	5.6	5.2
Combustion – fossil fuels	No mitigation option identified	2.4	2.5	0.0
Combustion – biomass fuels	No mitigation option identified	8.3	8.2	0.0
Livestock & Rice cultivation		123.3	143.3	12.8
Waste & Wastewater		57.4	78.0	59.4
Fuel production, transportation & energy use		139.6	188.6	120.4
Burning of agr. waste		3.1	3.6	1.9
Total		323.4	413.6	194.6

Figures 4 and 5 show the distribution of baseline 2030 emissions and technical mitigation potentials by world region. China and Latin & Central America are expected to be the two dominating emitters in 2030. China because of extensive extraction and use of coal as fuel and Latin & Central America because of extensive cattle raising and heavy oil extraction. The technical mitigation potential in 2030 is primarily found in world regions with extensive fossil fuel extraction.

3.2 Mitigation costs

Marginal mitigation cost curves for controlling global anthropogenic methane emissions in 2020 and 2030 when using social and private cost perspectives are illustrated in Figs. 6 and 7. With a private cost perspective (blue line), expected baseline emissions are reduced at a considerably higher cost than with a social cost perspective (red line). With a social cost perspective the marginal cost for implementing the full technical mitigation potential in 2030 is on average −151 Euro t^{-1} CH_4, i.e. a net marginal profit corresponding to about 3.5 Euro t^{-1} CO_2eq. With a private cost perspective,

Table 7. Costs for global CH_4 technical mitigation potentials when estimated from social and private cost perspectives.

Emission source sector	Control measure	Max technical reduction 2030	Global costs max reduction 2030					
			Social cost perspective			Private cost perspective		
			Marginal cost (weighted average)	Regional range	Total cost	Marginal cost (weighted average)	Regional range	Total cost
		Mt CH_4 reduced	Euro t^{-1} CH_4	Euro t^{-1} CH_4	10^9 Euro	Euro t^{-1} CH_4	Euro t^{-1} CH_4	10^9 Euro
Non-dairy cattle	Liquid manure: max implementation of anaerobic digestion	0.1	6988	1712 to 51 877	0.5	15 262	8895 to 84 828	1.1
	Ent. fermentation: diet changes indoor fed cattle	0.5	1080	933 to 1255	0.6	1080	933 to 1255	0.6
Dairy cows	Liquid manure: max implementation of anaerobic digestion	0.2	−76	−912 to 950	0.0	3306	2756 to 4779	0.6
	Ent. fermentation: diet changes indoor fed cattle	1.0	884	353 to 1614	0.9	884	353 to 1614	0.9
Pigs	Liquid manure: max implementation of anaerobic digestion	1.9	−1864	−3059 to −1244	−3.5	−143	−1075 to 111	−0.3
Rice – continuously flooded	Combined: aeration, alt hybrids and sulphate amendments	7.2	361	103 to 1847	2.6	361	103 to 1847	2.6
Rice – intermittently aerated	Combined: alt hybrids and sulphate amendments	1.9	340	338 to 342	0.7	340	338 to 342	0.7
Agricultural waste burning	Ban	1.9	0	no range	0.0	0	no range	0.0
MSW food&garden waste	Source separation and treatment, no landfill of biodegr. waste	9.2	2081	640 to 6875	19.2	4014	1447 to 9779	37.0
MSW paper waste	Source separation and treatment, no landfill of biodegr. waste	15.2	−3279	−5139 to 1023	−49.9	−2484	−4235 to 401	−37.8
MSW wood waste	Source separation and treatment, no landfill of biodegr. waste	5.5	−2097	−3779 to −266	−11.6	1482	492 to 3396	8.2
Food industry solid waste	Anaerobic digestion w gas recovery and utilization	15.0	261	−146 to 318	3.9	1202	628 to 1570	18.0
Pulp&paper ind solid waste	Recovery and utilization of black liquor	0.3	−29 782	−38 602 to −15 441	−9.4	−21 392	−30 041 to −12 016	−6.8
Textile industry solid waste	Energy recovery	1.2	−3639	−4932 to −1481	−4.3	2219	1066 to 2665	2.6
Wood industry solid waste	Recycling and energy recovery	1.8	−2736	−3293 to −1325	−5.0	−1574	−1894 to −763	−2.9
Domestic wastewater	Upgrade to anaerobic treatm w gas recovery and utilization	1.9	2996	1716 to 4831	5.8	7628	4673 to 11 831	14.7
Food industry wastewater	Upgrade to anaerobic treatm w gas recovery and utilization	3.9	−227	−4103 to 390	−0.9	2039	1735 to 3411	7.9
Pulp&paper ind wastewater	Upgrade to anaerobic treatm w gas recovery and utilization	3.5	−652	−3055 to 1649	−2.3	1725	264 to 4327	6.0
Org chemical ind wastewater	Upgrade to anaerobic treatm w gas recovery and utilization	2.0	51	−2505 to 379	0.1	1665	1638 to 1669	3.3
Coal mining – brown coal: pre-mining	Pre-mining degasification	0.3	−52	−167 to −6	0.0	315	195 to 486	0.1
Coal mining – hard coal: pre-mining	Pre-mining degasification	12.1	957	−143 to 7523	11.6	1339	139 to 7942	16.3
Coal mining – hard coal: mining (VAM)	Ventilation air oxidizer w improved ventilation systems	17.6	163	97 to 1486	2.9	191	185 to 1816	3.4
Oil production – associated gas	Recovery and utilization of vented associated gas	60.3	−109	−778 to 358	−6.6	1278	569 to 1716	77.1
Oil production – leakage	Good practice measures to reduce leakage	5.3	1289	935 to 6417	6.9	1289	935 to 6417	6.9
Oil transportation and refining	Good practice measures to reduce leakage	0.1	240	236 to 243	0.0	373	369 to 376	0.0
Gas production – associated gas	Recovery and utilization of vented associated gas	2.5	−490	−515 to −451	−1.2	−132	−135 to −130	−0.3
Gas production – leakage	Good practice measures to reduce unintended leakage	4.1	1068	799 to 12 009	4.4	1382	1081 to 12 291	5.7
Long-distance gas transmission	Leakage reduced to 10 kg CH_4 bcm^{-1} km^{-1}	6.7	−191	−395 to 4086	−1.3	372	−29 to 8785	2.5
Gas distr. networks (residential)	Replacement of grey cast iron pipes	6.1	541	−58 to 1289	3.3	2141	898 to 3893	13.0
Gas distr. networks (non-residential)	Replacement of grey cast iron pipes	5.2	561	−73 to 1231	2.9	2189	902 to 3842	11.5
Livestock & Rice cultivation		12.8	129	−3059 to 51 877	1.7	480	−1075 to 84 828	6.1
Waste & Wastewater		59.4	−914	−39 602 to 6875	−54.3	843	−30 041 to 9779	50.1
Fossil fuel extraction and use		120.4	190	−778 to 12 009	22.9	1129	−135 to 12 291	136.0
Burning of agricultural waste		1.9	0	no range	0	0	no range	0
Total		195	−153	−683 to 829	−30	988	568 to 2344	192

Fig. 4. CH_4 baseline emissions in 2030 by sector and world region.

the corresponding picture changes to 988 Euro t^{-1} CH_4, i.e. a net marginal cost of about 40 Euro t^{-1} CO_2eq. Hence, with a social cost perspective the technically feasible cut by half in global CH_4 emissions can be expected to pay for itself, while with a private cost perspective the cost can be regarded as considerable.

In Fig. 7 the effects on the global CH_4 mitigation cost curve of each of the different assumptions made for defining the private cost perspective have been separated out. Starting from the social perspective cost curve and adding only the assumption about not anticipating future gas price increases in the investment decision, has a significant effect on marginal

mitigation costs for low cost options. This is the cost range where most options involving recovery of gas can be found. For more expensive options, the higher private interest rate and the shorter investment time horizon play more important roles in the marginal cost than the level of the gas price.

A detailed summary of the costs by implemented mitigation technology is presented in Table 7 with illustrations of global sector mitigation cost curves in Fig. 8. The single most effective mitigation option both in terms of removed emissions and social costs is recovery of associated gas from oil production. With a social cost perspective, this option is estimated to bring a net profit of about 6.6 billion Euro per year
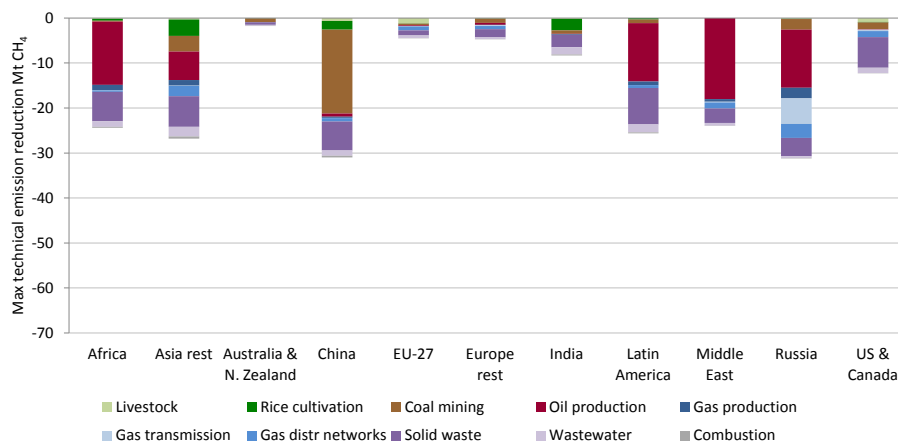
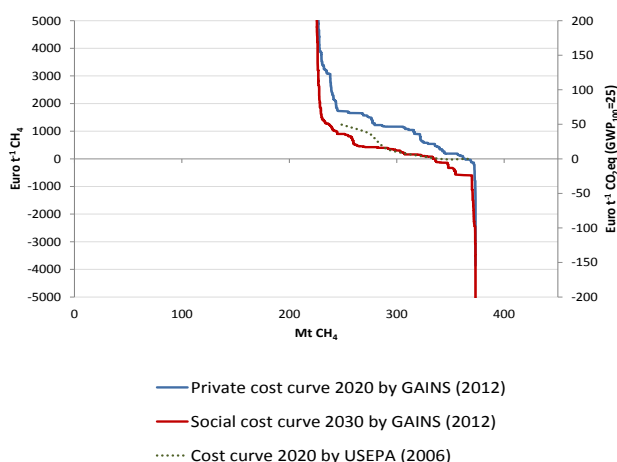**Fig. 5.** CH_4 maximum technical reduction in 2030 by sector and world region.

Fig. 6. Global CH_4 mitigation cost curve 2020 with private and social cost perspectives and in comparison to USEPA (2006).

in 2030 when implemented to its full global potential. With a private cost perspective, the cost is, however, considerable at about 77 billion Euro per year. This is illustrated for the oil and gas sector in Fig. 8, where the red line depicting the marginal cost curve for oil production jumps from having almost half of the potential below zero cost with a social cost perspective to being well above the zero line with a private cost perspective. Hence, in particular for this sector the cost perspective matters and sole reliance on private investments is unlikely to initiate investments today in CH_4 mitigation.

Another finding from Table 7 is that on a global scale, mitigation in waste and wastewater sectors are the least costly on average with a social cost perspective, however, the marginal cost differs considerably for treatment of different types of waste and industry. E.g. treating food waste residuals in anaerobic digestion with biogas recovery is estimated at a cost of about 2000 Euro t^{-1} CH_4 for source separated household food waste, 261 Euro t^{-1} CH_4 for solid waste from food

industry and a net profit of 227 Euro t^{-1} CH_4 for wastewater from food industry. The differences in the cost take into account differences in collection and treatment costs as well as different potentials for converting the organic content into biogas (see Supplement for further details).

As shown in Fig. 8 a considerable technical mitigation potential at negative cost is found in the solid waste sector also with a private cost perspective. Apart from a limited potential to further extend recovery and utilization of black liquor from pulp and paper industry in developing countries, the profitable potential can be referred to recycling of household paper waste. The profitable potential estimated for this option should be interpreted with caution as the negative cost may be a result of distortions in the market for recycled pulp (see the Supplement for further discussion). The smaller mitigation potential in 2020 compared to 2030 reflects the delayed effect on emissions when decreasing landfill disposal of slow-degrading waste like paper and wood waste. The mitigation cost curve in 2020 only reflects mitigation of emissions from fast-degrading waste like food and garden waste.

Control of coal mining emissions is expected to account for 15 percent of the entire global technical mitigation potential in 2030 with more than a third in China. About 60 percent of the mitigation potential comes from controlling ventilation air methane (VAM) during mining of hard coal and 40 percent from pre-mining degasification. The weighted global marginal cost for degasification of hard coal mines is estimated at 957 Euro t^{-1} CH_4 with a social cost perspective and 1339 Euro t^{-1} CH_4 with a private cost perspective. For China, the cost is estimated at 1223 Euro t^{-1} CH_4 with a social cost perspective to be compared with 177 Euro t^{-1} CH_4 for US and Canada. The primary reason for this difference is the assumed higher costs for extending the infrastructure to utilize the recovered gas in China. The weighted global marginal cost for controlling ventilation air methane through oxidation is estimated at about 200 Euro t^{-1} CH_4 in both cost perspectives.

Table 8. Costs for CH_4 technical mitigation potentials in 2030 by world region.

Cost range	World region	Social cost perspective			Private cost perspective		
		Emission reduction Mt CH_4	Marginal cost (weighted average) Euro t^{-1} CH_4	Total cost 10^9 Euro	Emission reduction Mt CH_4	Marginal cost (weighted average) Euro t^{-1} CH_4	Total cost 10^9 Euro
Max technical reduction 2030	Africa	24.4	−252	−6.1	24.4	1067	26.1
	Asia – rest	26.8	−257	−6.9	26.8	847	22.7
	Australia & N Zealand	1.7	395	0.7	1.7	1923	3.3
	China	31.0	−149	−4.6	31.0	568	17.6
	EU-27	4.5	−35	−0.2	4.5	1925	8.7
	Europe – rest	4.7	−100	−0.5	4.7	946	4.4
	India	8.3	−221	−1.8	8.3	866	7.2
	Latin & Central America	25.7	−287	−7.4	25.7	696	17.9
	Middle east	24.0	−683	−16.4	24.0	1140	27.4
	Russia	31.2	104	3.3	31.2	907	28.3
	USA & Canada	12.3	829	10.2	12.3	2344	28.8
	World	195	−153	−30	195	988	192
whereof <1250 Euro t^{-1} CH_4 (i.e. <50 Euro t^{-1} CO_2eq.)	Africa	23.2	−408	−9.5	9.2	−217	−5.0
	Asia – rest	25.6	−398	−10.2	14.7	−149	−3.8
	Australia & N Zealand	1.5	−109	−0.2	1.0	253	0.4
	China	30.5	−183	−5.6	25.2	133	4.0
	EU-27	3.9	−602	−2.3	2.6	210	0.8
	Europe – rest	4.5	−263	−1.2	3.3	48	0.2
	India	7.4	−650	−4.8	4.3	−446	−3.3
	Latin & Central America	24.7	−414	−10.2	22.0	241	5.9
	Middle east	23.9	−701	−16.7	21.6	855	20.4
	Russia	29.7	36	1.1	17.4	164	4.9
	USA & Canada	9.0	−310	−2.8	6.4	187	1.7
	World	184	−339	−62	128	205	26
whereof <500 Euro t^{-1} CH_4 (i.e. <20 Euro t^{-1} CO_2eq.)	Africa	20.1	−612	−12.3	3.7	−563	−11.3
	Asia – rest	20.5	−696	−14.3	9.3	−453	−9.3
	Australia & N Zealand	1.3	−263	−0.4	0.9	173	0.2
	China	19.0	−817	−15.5	15.2	−374	−7.1
	EU-27	3.1	−1033	−3.2	1.4	−135	−0.4
	Europe – rest	3.5	−599	−2.1	1.8	−336	−1.2
	India	5.9	−1034	−6.1	3.9	−631	−3.7
	Latin & Central America	21.6	−593	−12.8	5.3	−280	−6.1
	Middle east	22.1	−830	−18.4	1.6	−116	−2.6
	Russia	26.4	−56	−1.5	9.9	−73	−1.9
	USA & Canada	8.0	−496	−4.0	5.2	37	0.3
	World	152	−597	−90	58	−740	−43
whereof <250 Euro t^{-1} CH_4 (i.e. <10 Euro t^{-1} CO_2eq.)	Africa	8.0	−2020	−16.2	3.6	−1410	−11.3
	Asia – rest	11.4	−1513	−17.3	7.3	−874	−10.0
	Australia & N Zealand	1.3	−300	−0.4	0.0	−29	0.0
	China	16.0	−1024	−16.4	13.9	−474	−7.6
	EU-27	2.7	−1204	−3.3	1.1	−192	−0.5
	Europe – rest	3.2	−690	−2.2	1.6	−387	−1.2
	India	2.0	−3799	−7.5	1.3	−2339	−4.6
	Latin & Central America	19.0	−733	−13.9	3.4	−363	−6.9
	Middle east	21.8	−850	−18.5	1.6	−118	−2.6
	Russia	14.8	−379	−5.6	9.1	−151	−2.2
	USA & Canada	7.0	−602	−4.2	3.7	−13	−0.1
	World	107	−984	−106	47	−1008	−47
whereof <0 Euro t^{-1} CH_4	Africa	3.7	−4494	−16.6	3.1	−3079	−11.4
	Asia – rest	6.4	−2773	−17.9	5.0	−1614	−10.4
	Australia & N Zealand	0.5	−1135	−0.5	0.0	−79	0.0
	China	5.0	−3629	−18.2	2.9	−1931	−9.7
	EU-27	1.6	−2200	−3.4	0.7	−389	−0.6
	Europe – rest	1.6	−1486	−2.4	0.6	−847	−1.4
	India	1.8	−4110	−7.5	1.3	−2523	−4.6
	Latin & Central America	14.3	−1026	−14.7	3.0	−488	−7.0
	Middle east	20.1	−938	−18.9	1.6	−128	−2.6
	Russia	8.5	−716	−6.1	7.7	−284	−2.4
	USA & Canada	5.6	−820	−4.6	0.5	−64	−0.4
	World	69	−1602	−111	26	−1911	−50

Table 9. Comparison of GAINS model results for baseline global anthropogenic CH$_4$ emissions with the results of other models.

Year	Major sector	Model/Database									
		GAINS	GAINS	GAINS	USEPA	USEPA	EDGAR	MiniCAM	IMAGE	MESSAGE	AIM
		This study	UNEP (2011)	Cofala et al. (2007)	Draft Aug 2011	2006	v4.2	RCP 4.5	RCP3 PD (2.6)	RCP 8.5	RCP 6.0
		Mt CH$_4$									
Baseline 2005	Agriculture	123	123	130	133	170[a]	143	126	133	134	136
	Waste & wastewater	57	50	69	57	62	58	63	55	73	62
	Fuel produc., transport. & energy use	140	112	96	114	74	122	85	92	104	87
	Burning of agr. waste, grassland, forest	3	3	11	20	0	24	27	27	26	27
	Industrial processes	0	0	0	0	0	0	2	2	1	1
	Total	323	288	305	325	306	346	302	309	339	314
Baseline 2030	Agriculture	143	143	149	157	175[b]	n.a.	152	126	186	151
	Waste & wastewater	78	58	83	69	71[b]	n.a.	67	28	127	56
	Fuel produc., transport. & energy use	189	160	190	159	108[b]	n.a.	95	50	159	88
	Burning of agr. waste, grassland, forest	4	4	8	20	0	n.a.	16	26	25	28
	Industrial processes	0	0	0	0	0	n.a.	2	3	3	2
	Total	414	365	430	405	354[b]	n.a.	332	233	499	325

[a] 2005 value derived from linear interpolation between 2000 and 2020 values, [b] Baseline 2020 (estimates for 2030 not available).
Sources: UNEP (2011); Cofala et al. (2007); USEPA (2006;2011); EDGAR (2012); IIASA (2012).
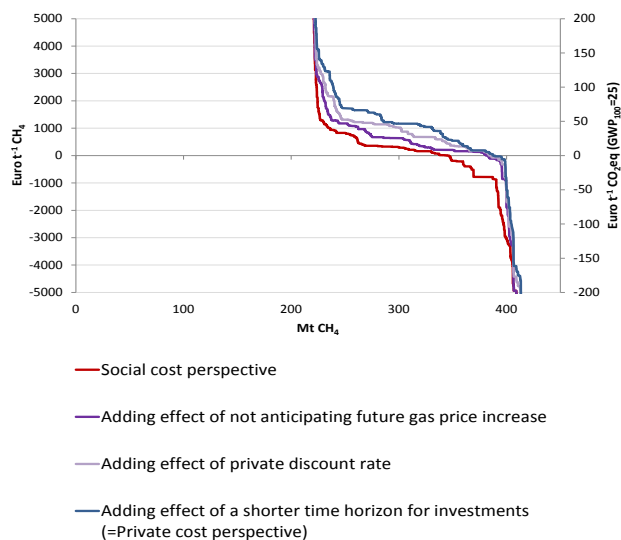
Fig. 7. Global CH$_4$ mitigation cost curve 2030 with private and social cost perspectives including a separation of the effects of the differences in assumptions between the social and private cost perspectives.

Rice cultivation mitigation options do not involve capital investments nor recovery of gas. The marginal cost curves for the social and private cost perspectives therefore coincide in Fig. 8.

Region-specific CH$_4$ mitigation costs in 2030 for different cost ranges are presented in Table 8. Estimation results show that with a social cost perspective almost 80 percent of the technical mitigation potential is available at a marginal cost less than 500 Euro t^{-1} CH$_4$ (i.e. 20 Euro t^{-1} CO$_2$eq.). With a private cost perspective, this fraction is only 30 percent. The fraction of the entire technical mitigation potential available

at a net profit is estimated at 35 percent with a social cost perspective and 13 percent with a private cost perspective. As expected, major fossil fuel producing regions like Russia, China, Latin & Central America, Africa and the Middle East have considerable technical mitigation potentials at low social costs but often at substantial private costs. There are only limited technical mitigation potentials available at low costs in India, Europe, Australia and New Zealand. The large mitigation potential at low cost foreseen in countries that are currently not among Annex 1 countries under the Kyoto protocol, shows the importance of finding future political solutions for methane which address emissions also in these regions.

3.3 Comparison to other global inventories

Table 9 presents global CH$_4$ emissions as estimated in the current version of the GAINS model and in comparison with previous estimates using the GAINS model as well as estimates using other models and databases. These include estimates by USEPA with projections until 2030 (draft version from August 2011) and projections until 2020 (final version from 2006), an inventory of historical emissions by the EDGAR online database (2012) version 4.2, as well as comparisons to IPCC's Representative Concentration Pathways (RCPs) (Moss et al., 2008). The RCPs provide pathways until 2100 for emissions of all greenhouse gases including CH$_4$ and represent four different future pathways, where RCP 3-PD assumes a peak and decline in greenhouse gases, the RCP 4.5 and RCP 6.0 stabilizations at radiative forcing of 4.5 or 6.0 W m^{-2} and RCP 8.5 assumes rising radiative forcing to 8.5 W m^{-2} in 2100 (IIASA, 2012).

A comparison of baseline 2005 emission estimates suggests a close agreement across models at an aggregate level, but with differences at a sector level. The GAINS estimates presented in this study produce generally higher estimates for
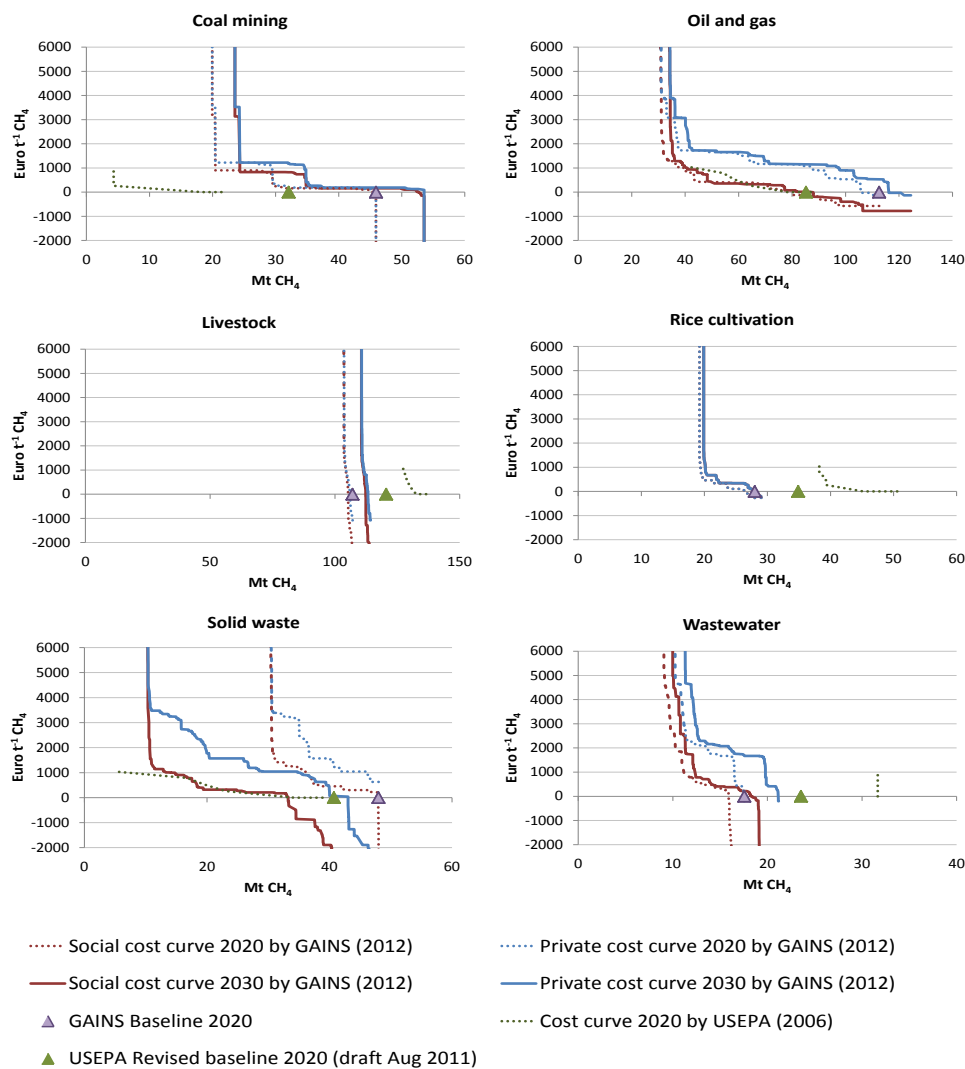
Fig. 8. Global CH$_4$ mitigation cost curve 2020 and 2030 by sector with private and social cost perspectives and in comparison to USEPA (2006).

emissions from fossil fuel production. The higher estimates are likely to derive from the extensive use of country-specific information in the estimations of emissions as well as the separation of emission estimates for venting of associated gas and unintended leakage from oil and gas production. The use of recent measurement results on the amounts of associated gas vented as opposed to flared during extraction of different types of hydrocarbons (Johnson and Coderre, 2011) and verification against country-specific satellite images of flares (NOAA, 2010) have also contributed to higher emissions in recent GAINS estimates. The coverage of CH$_4$ emissions from open burning of agricultural waste, pre-scribed burning of grasslands and human-induced forest fires appears less complete in GAINS than in other models. GAINS only includes emissions from open burning of agricultural waste using data from Niemi (2006), whereas emissions from grass-

land burning and forest fires have not been included due to lack of systematic data. In models where these sources are included they account for about 20 Mt CH$_4$ per year or about seven percent of global CH$_4$ emissions.
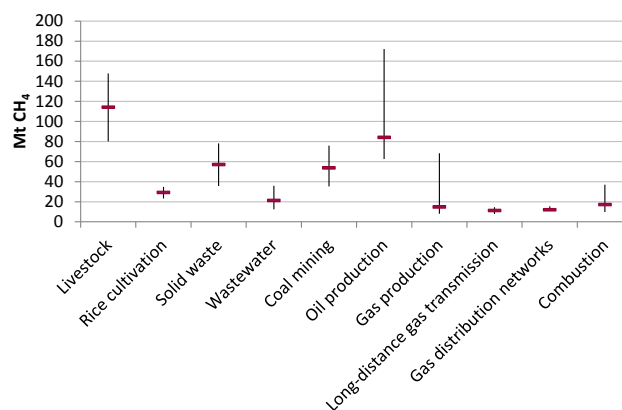
Figure 9 shows projections of global CH$_4$ emissions in the different models and scenarios. The current GAINS projection for global baseline CH$_4$ emissions until 2030 is almost identical to the draft USEPA (2011) projection. This is likely a result of both projections using the IEA World Energy Outlook (2009) reference scenario as driver for macroeconomic and energy activity data. As seen in Fig. 9, without further measures to reduce CH$_4$ emissions, the GAINS and USEPA baseline estimates suggest a future emission path which clearly exceeds the two IPCC stabilization pathways RCP 4.5 and RCP 6.0. On the other hand, with full implementation of currently available mitigation technology, the
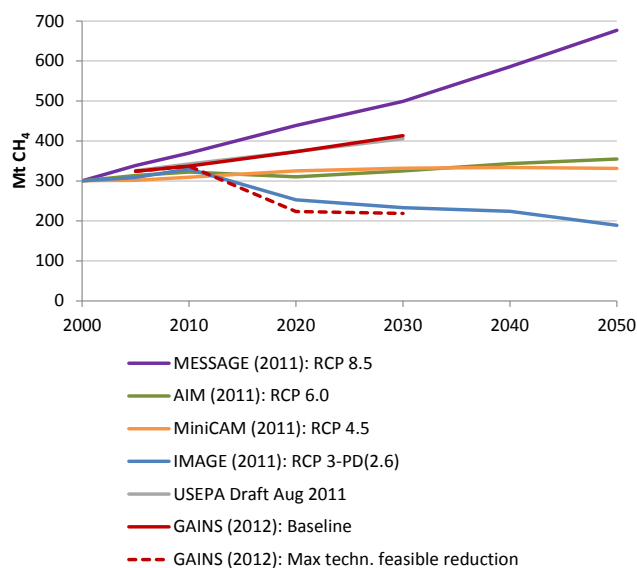
Fig. 9. Projection of baseline global anthropogenic CH_4 emissions in GAINS and in comparison to other models.

Fig. 10. Uncertainty ranges by sector for global CH_4 emission estimates in Baseline 2030.

GAINS model results show that it is technically possible until 2030 to enter a future emission path that is consistent with the IPCC peak and decline scenario RCP 3-PD.

USEPA (2006) estimated global anthropogenic CH_4 mitigation cost curves for year 2020. The marginal mitigation cost curves included mitigation measures in the range up to 60 \$ t CO_2eq. The financial assumptions were a discount rate of 10 percent and a tax rate of 40 percent. In Fig. 6, the USEPA global CH_4 mitigation cost curve for 2020 has been entered for comparison. As shown, it follows quite closely the social perspective cost curve in GAINS despite the differences in financial assumptions. A sector break down of the cost curves presented in Fig. 8 reveals some differences. Baseline emissions from coal mining and oil and gas production are higher in GAINS than in the USEPA estimates and therefore the mitigation potentials are larger, however, USEPA marginal cost levels are still close to those in GAINS. The mitigation potential for livestock is larger in the USEPA estimate, because additional measures to control enteric fermentation emissions are included, e.g. use of antibiotics or bovine somatotropin, propionate precursors and antimethanogen vaccine. Wide-spread adoption of propionate precursors and vaccines are in GAINS only considered available after 2030 (Höglund-Isaksson et al., 2012). The use of antibiotics or bovine somatotropin as CH_4 control options, are in GAINS considered infeasible due to the adverse effects on human and animal health. The USEPA mitigation cost curve for the solid waste sector in 2020 corresponds well to the social perspective cost curve for 2030 in GAINS. In GAINS, the 2020 mitigation potential is smaller and more costly as it only refers to the mitigation potential of fast-degrading waste like food and garden waste. For slow-degrading waste like paper and wood, the long time lag between disposal and emissions makes the effects on emissions only become visible in the 2030 cost curve. For the wastewater sector, USEPA does not consider any mitigation potential, while it is quite substantial, although relatively costly, in GAINS.

4 Uncertainty

There are several different types of uncertainty that enter into model estimations of emissions. EC4MACS (2010) distinguishes five different types: uncertainty in data, in model structure and methodology, in expert judgements, in the chosen system boundaries and in the choice of output indicators. This section focuses on uncertainty in the chosen methodology and information input used in the derivation of emission factors as well as uncertainty due to system boundaries. It does not address uncertainty in the projections of activity drivers as these have been taken from external sources.

Identifying reasons for and assessing approximate magnitudes of uncertainty in emission estimations is useful to find out the relative importance of estimation errors in individual assumptions on a global scale. By identifying particularly critical assumptions, the analysis can provide insights into what areas need further research to best reduce uncertainty in global CH_4 emission estimates. Uncertainty ranges have been quantified using default ranges suggested in the IPCC (2006) guidelines or when emission factors were derived from country-specific information, e.g. for the oil and gas production sectors, default uncertainty ranges were adjusted to take account of the better precision provided by the country-specific information. A detailed description of the uncertainty sources identified for each sector is presented in the Supplement.

Figure 10 presents the ranges for the identified sources of uncertainty in each sector. Merging up the sector uncertainty ranges to a global scale is not considered possible as it would
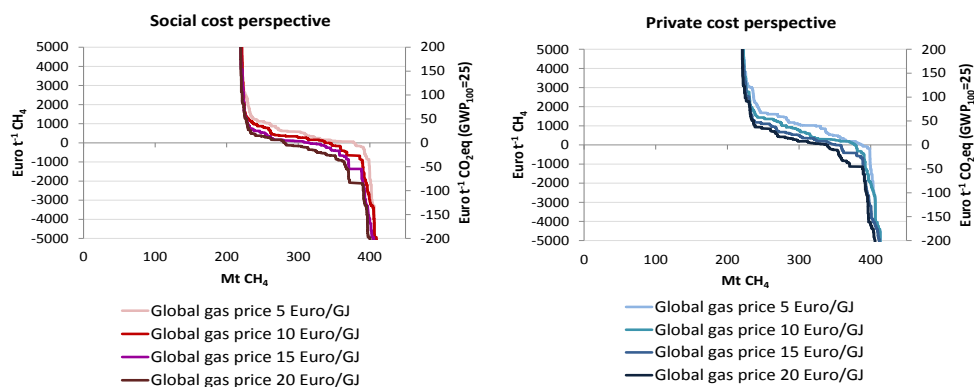
Fig. 11. Sensitivity of the global marginal mitigation cost curve in 2030 to different assumptions about the future gas price level.

require knowledge about the probability distributions of the sector ranges. With such knowledge, a global uncertainty range could have been obtained using Monte-Carlo simulation (Winiwarter and Rypdal, 2001). Despite this shortcoming, a comparison across sectors can still be useful as it allows for identifying which emission sources contribute the most to uncertainty in emission estimates. Based on the uncertainty sources identified here, global baseline emission estimates suffer the most from uncertainty in estimates of oil and gas production emissions. To reduce uncertainty it would be particularly desirable to obtain more measurement data on the fraction of associated gas vented as opposed to flared from extraction of different types of hydrocarbons in various parts of the world. It would also be an advantage to improve access to measurement data which could verify reported data, e.g. amounts of associated gas generated for major oil and gas producing countries (see example with Saudi Arabia in the Supplement). Livestock, solid waste and wastewater are sources with generally high uncertainty in emission estimates due to many small point sources and large site-specific variation in emission factors due to e.g. climatic factors and management practices. Reducing uncertainty in emission estimates for these sectors would include improved access to country- or provincial information, which would allow for further disaggregating the model structure to better take account of the variation in local conditions.

Just like for the estimation of baseline emissions, uncertainty is also present in the estimations of mitigation potentials. The cause for the uncertainty is similar in that lack of detailed country-specific information makes it necessary to use default assumptions. In contrast to baseline emissions, the IPCC guidelines do not provide uncertainty ranges for the estimation of mitigation potentials for different types of mitigation technology. This makes it difficult to quantify such uncertainty ranges here.

This paper has made an effort to improve the general understanding of the complexity by which different factors influence mitigation costs for CH_4, which is intended to reduce

uncertainty in mitigation cost estimates. Still, it is inevitable that lack of information is sometimes bridged by the use of default assumptions. Again, lack of default assumptions for uncertainty ranges makes it difficult to quantify such ranges here. Uncertainty in drivers for future mitigation costs can still be analyzed, e.g. how different future gas price levels influence costs. Figure 11 illustrates the global CH_4 marginal mitigation cost curve in 2030 for a range of future global gas price levels from 5 to 20 Euro GJ^{-1}. At lower gas price levels, the cost of controlling leakage of natural gas or recovering biogas increases, which shifts the marginal mitigation cost curve up. It is noteworthy that even if private investors anticipated a future gas price of 20 Euro GJ^{-1} in their investment decisions, only 38 percent of the entire mitigation potential in 2030 is found available at a net profit.

5 Conclusions

This analysis identifies and quantifies major global sources of anthropogenic methane (CH_4) emissions as well as technical opportunities and costs for mitigation. It also pinpoints important sources of uncertainty in emission estimations, which could serve to improve future estimates.

Without further mitigation efforts than currently in place or prescribed by adopted legislation, global anthropogenic CH_4 emissions are expected to grow from 323 Mt CH_4 in 2005 to 414 Mt in 2030, i.e. a growth by 28 percent. The full technical mitigation potential could almost halve baseline emissions in 2030. The fraction of the global technical mitigation potential available at a net profit is estimated at 35 percent with a social cost perspective and 13 percent with a private cost perspective. With a social cost perspective, almost 80 percent of the technical mitigation potential is found available at a marginal cost below 500 Euro t^{-1} CH_4 (i.e. 20 Euro t^{-1} CO_2eq.), while the corresponding fraction with a private cost perspective is 30 percent. More than 60 percent of the entire technical mitigation potential is found in sectors involving fossil fuel production and use. From a

social cost perspective most of these options come at a net profit, while for a private investor costs are usually considerable. Mitigation opportunities in agriculture are found limited and often costly both from social and private cost perspectives. About 30 percent of the global technical mitigation potential is found in waste and wastewater sectors. Options in these sectors are often sensitive to uncertainty in the future gas price level because they often involve recovery of biogas from treatment of biodegradable waste or wastewater.

CH_4 is a forceful but relatively short-lived greenhouse gas, which means that mitigation of CH_4 emissions can achieve considerable alleviations in global warming already in the short run. This study has shown there exists considerable technical potential to reduce global anthropogenic CH_4 emissions. Although costs are expected to fall in the future following an expected increase in the gas price, the costs facing private investors today are not likely attractive enough to initiate mitigation. Hence, for fast action to reduce global CH_4 emissions, public intervention through regulations or incentive-based schemes are needed. Such efforts should also address countries currently not regulated under the Kyoto protocol, as most of the low-cost mitigation potential is found in these regions.

Supplementary material related to this article is available online at: http://www.atmos-chem-phys.net/12/9079/2012/acp-12-9079-2012-supplement.pdf.

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