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

L. Höglund-Isaksson

International Institute for Applied Systems Analysis, Laxenburg, Austria

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Correspondence to: L. Höglund-Isaksson (hoglund@iiasa.ac.at)

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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 anthropogenic methane emissions are estimated at 323 Mt methane in 2005, with an expected increase to 414 Mt methane in 2030. Major uncertainty sources in emission estimates are identified and discussed. Mitigation costs are estimated defining two different cost perspectives; the social planner cost perspective and the private investor cost perspective.

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 lifetime of 12 yr in the atmosphere, the GWP over 20 yr is considerably higher at 72 times that of CO_2. 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 a discussion of uncertainty issues in Sect. 4. Section 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 of this paper.

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.

$$E_{its} = \sum_m \left[A_{its} \cdot \mathrm{ef}_{ism} \cdot \mathrm{Appl}_{itsm}\right], \quad (1)$$

where

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

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, $\mathrm{ef}_{is}^{\mathrm{NOC}}$ is the no control emission factor for activity s, and remeff_{sm} is the removal efficiency of technology m when applied to activity s.

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 FAOSTAT (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, with −13 and −16 percent, respectively. 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 (2009) 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; 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 analysed period. This assumption together with including only 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.

2.2.2 Mitigation costs per activity unit

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 unit cost of technology m in country i and year t is defined as:

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

where $I_{im}\left[\frac{(1+r)^T\cdot r}{(1+r)^T-1}\right]$ is the annualized investment cost for technology m in country i and with interest rate r and technology lifetime of T 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.

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

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

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. When interpreting mitigation costs it is important to bear in mind that costs cannot be expressed in absolute terms but are always relative to a set of alternative costs and benefits available to an investor in a certain moment in time. The subjective perspective of the investor is therefore decisive for investment decisions. To reflect some of the effects of differences in investor perspectives, we define two different cost perspectives: a "social" and a "private". The social cost perspective refers to a social planner or public investor, who optimizes costs and benefits over a considerably longer time horizon and is able to accommodate risks better than a private investor, who is defined as having an interest in short-term profits at a minimum of uncertainty. To define the two cost perspectives, the unit cost of mitigation defined in Eq. (3) is calculated using different assumptions about interest rate, relevant equipment lifetime and willingness to anticipate expected increases in fuel prices in today's investment decisions. With a social cost perspective, the social interest rate is taken to be 4 percent, equipment is used over its entire lifetime of maximum 20 yr, and expected increases in the future gas price, here foreseen by the IEA-WEO (2009) Reference scenario, are fully anticipated in today's investment decisions. With a private cost perspective, the private interest rate is taken to be 10 percent, investors only consider equipment lifetime up to maximum ten years, and only observed fuel price levels are anticipated in the investment decisions, meaning that investment decisions for the future are based on the assumption that today's fuel price levels are sustained also in the future.

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 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 CH_4 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.

Figures 4 and 5 show the distribution of baseline 2030 emissions and technical mitigation potentials by world region. China and Latin and 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 and 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 Baseline comparison to other global inventories

Table 7 presents global CH_4 emissions as estimated in the current version of the GAINS model and in comparison with two previous estimates also using the GAINS model, UNEP (2011) and Cofala et al. (2007), as well as a comparison with two external inventories, the draft USEPA (2011) inventory from August 2011 and the EDGAR online database (2012). Comparing the three scenarios generated with different versions of the GAINS model, the 2005 global baseline estimates range from 287 to 323 Mt CH_4. Main differences between the UNEP and the current GAINS estimates are the higher estimates in the latter for emissions from oil production and from industrial waste and wastewater. In the UNEP study, emission factors were derived from country reports coupled with IPCC Tier 1 factors, while the most recent GAINS scenario produces separate estimates for emissions from venting of associated gas and unintended leakage from oil production. It also makes use of empirical measurements of venting emissions from extraction of different types of hydrocarbons published by Johnson and Coderre (2011), which when coupled with country-specific amounts of associated gas generated and flared allows for deriving consistent emission factors for venting and flaring, which can be verified against satellite images of flares (NOAA, 2010). The higher emissions from industrial waste and wastewater in the more recent scenario are due to a more complete coverage of these sources in developing countries. Total baseline emissions for 2005 are quite comparable in the most recent GAINS scenario and the two external scenarios from USEPA and EDGAR. A sector comparison, however, reveals some differences. Again, the GAINS estimate for emissions from oil production is higher than in the EDGAR or USEPA inventories for very much the same reasons as mentioned above for the comparison with the UNEP study. CH_4 emissions from livestock in 2005 are comparable in the GAINS and USEPA inventories, however, EDGAR estimates 12 percent higher emissions from this source. Rice cultivation emissions are estimated about 20 percent lower in GAINS than in the two other inventories. This may be an effect of GAINS emission factors only being scaled by differences in water regimes but not by differences in the use of organic amendments, which USEPA takes account of in its estimate. A major difference between GAINS and the two other inventories is that GAINS does not include emissions from pre-scribed burning of savannahs and grasslands nor from human-induced forest fires. These sources add about 20 Mt CH_4 to global CH_4 emissions in 2005 in the other two inventories. Finally, emissions from waste and wastewater sectors are comparable across the three inventories, however, emissions from solid waste are higher and from wastewater lower in GAINS than in the two other inventories. Some of the differences can be explained by GAINS including emissions from both domestic and industrial sources as well as from landfills and other types of waste treatment, e.g. composting or anaerobic digestion. USEPA only includes domestic sources and only emissions from landfills. EDGAR refers to the same sources as GAINS and uses a similar methodology, so it is unclear why emissions in particular from domestic wastewater are considerably higher in EDGAR. A comparison of the projected baseline emissions in 2030 between the most recent GAINS scenario and the USEPA shows again that the main difference is in estimates for the oil and gas production sectors. Also, emission estimates for coal mining are higher in GAINS than in the USEPA estimate, which is likely to be an effect of GAINS applying a higher average emission factor of 11 m^3 CH_4 t^{-1} coal produced in China (China University of Petroleum, 2008). Although the exact emission factor used for Chinese coal mines is not mentioned in USEPA (2011), previous studies, e.g. USEPA (2003) and GMI (2009), use considerably lower emission factors for China.

3.3 Mitigation costs

Global marginal mitigation cost curves for controlling anthropogenic methane emissions when using social and private cost perspectives are illustrated in Fig. 6. With a private cost perspective (blue line), expected baseline emissions in 2030 are reduced at a considerably higher cost than with a social cost perspective (red line). A detailed summary of the costs by implemented mitigation technology is presented in Table 8. With a social cost perspective the weighted 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, the corresponding picture changes to 987 Euro t^{-1} CH_4 or 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 on average be expected to pay for itself, while with a private cost perspective the cost can be regarded as considerable. It is particularly the full anticipation of the expected increase in the future gas price assumed in the social cost perspective, which makes it come out lower than in the private cost perspective.

From Table 8 can be read that 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 6600 M Euro per year in 2030 when implemented to its full global potential. With a private cost perspective, the cost is, however, considerable at about 77 000 M Euro per year. This is also illustrated in Figs. 7 and 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 it matters very much what cost perspective is applied and reliance on private investments only is unlikely to initiate investments today in CH_4 mitigation.

Another finding from Table 8 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 there is a considerable technical mitigation potential at negative cost 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).

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 from 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 both with a social and a private cost perspective.

Region-specific CH_4 mitigation costs in 2030 are presented in Table 9 and illustrated as marginal cost curves in Figs. 9 and 10. As expected, major fossil fuel producing regions like Russia, China, Latin and Central America, Africa and the Middle East have considerable technical mitigation potentials at low 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 that address emissions also in these regions.

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 11 presents the ranges for the identified sources of uncertainty in each sector. No merging up of sector uncertainty ranges to a global scale is undertaken, as it is difficult to estimate the relative uncertainty between sectors. An estimate of the uncertainty in the global emission estimates would require weighing the relative importance of the different sector uncertainty estimates. A comparison across sectors is still 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 world regions. 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 further disaggregation of the model structure to better take account of the variation in local conditions.

5 Conclusions

Methane (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. The analysis identifies and quantifies major global sources of anthropogenic 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 technical mitigation potential could almost halve baseline emissions in 2030 when implemented fully.

Fossil fuel extraction and use and agricultural activities each contribute about 40 percent to anthropogenic CH_4 emissions, while the remaining 20 percent comes primarily from waste and wastewater sectors. More than 60 percent of the entire technical mitigation potential in 2030 is found in fossil fuel production and use, while mitigation opportunities in agriculture are limited to less than 8 percent of the entire technical potential. Estimation results show that with a social cost perspective, mitigation costs in coal mining and oil production sectors are low or even profitable for some options and world regions. However, with a private cost perspective assuming a higher interest rate, shorter lifetime of equipment and no anticipation of future increases in the gas price, marginal mitigation costs for these sectors are a few times higher. With the exception of treating liquid pig manure from large farms in farm-scale anaerobic digesters and the use of small-scale household digesters to treat manure in developing countries, the technical mitigation options in the agriculture sector are relatively costly. For the waste and wastewater sectors, mitigation opportunities are extensive and cheap from a social cost perspective. In particular treatment of solid waste and wastewater with a high content of fast-degrading organic matter in anaerobic digesters with biogas recovery becomes a cheap option to reduce emissions substantially when anticipating a future expected increase in the gas price. However, again it is questionable if these mitigation investments are attractive enough in the near-term for private investors.

Being a strong but short-lived greenhouse gas it is desirable from a climate perspective with a fast and substantial reduction in global CH_4 emissions. This study has shown that there exists considerable technical potential to reduce global anthropogenic CH_4 emissions. Although costs are expected to fall substantially in the future as the price of gas increases, the costs facing private investors today are not 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. As much of the low cost mitigation potential is found in countries currently not regulated under the Kyoto protocol, it is important to find mitigation strategies that address mitigation incentives also in these countries.

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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 onshore pipelines (UNFCCC, 2010; IEA-WEO, 2009; IEA, 2010; Wuppertal Instutite, 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, 2009)	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 agr 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)

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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, pp. 4.43–4.35)	Types of hydrocarbons produced Fraction offshore production Associated gas as fraction of hydrocarbons produced (by energy content) Fraction of associated gas reinjected/recovered Fraction of associated gas flared or vented Satellite images of flares	Vented associated gas as fraction of gas vented or flared by type of hydrocarbon. Methane content of associated gas is assumed 86 percent.
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, pp. 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 Volume of gas transported	Emission factors in $kg\,CH_4\,bcm^{-1}\,km^{-1}$ derived for nine reference countries, which were applied to comparable world regions.
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, pp. 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. Fractions brown and hard coal produced. Fraction of hard coal produced underground for Annex-1 countries. Fractions of VAM and degasification emissions of total emissions recorded for USA, S Africa, Czech Rep., Germany, Poland, UK, Russia and China. Current recovery of degasification gas.	IPCC Tier 1 default emission factors for post-mining emissions. For derivation of emission factors, missing country specific information was replaced by default assumptions.
Combustion-fossil and bio fuels	IPCC Tier 1–2 (2006, Vol. 2, pp. 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.

Table 2. Continued.

Emission source	Emission calculation method	Country-specific factors used for deriving emission factors	Non-country specific factors used for deriving emission factors
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. 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	IPCC Tier 1 default emission factors by world region whenever country-specific information is missing.
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 Current MSW composition Current treatment of MSW in Annex-1 countries and for a few non-Annex-1 countries.	Missing country-specific info replaced by default assumptions 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.
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. Current treatment of industrial solid waste by industry for Annex-1 countries.	IPCC default factors for the content of degradable organic carbon (DOCm) in different types of waste. 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. Country-specific BOD per person. Current treatment of wastewater (primary/secondary and aero-bic/anaerobic).	Default MCF assumed for centralized collection is 0.5 and for decentralized collection 0.1.
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. Output by type of production process for pulp and paper industry.	For relevant food industries, IPCC default rates for COD content in wastewater per ton of product. 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.

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 ass 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 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 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	Upgrade of current treatment systems to two-stage anaerobic treatment with biogas recovery followed by aerobic treatment industry.

Table 4. Development in 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

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

Table 6. Summary results: global CH_4 emissions and technical mitigation potentials in 2030.

Global CH_4 estimates				
		GAINS estimates		
Emission source sector	Control measure	Baseline 2005	Baseline 2030	Max technical reduction 2030
		kt CH_4	*kt* CH_4	*kt* CH_4 reduced
Non-dairy cattle	Liquid manure: max implementation of anaerobic digestion	243	232	70
	Ent. Fermentation: diet changes indoor fed cattle	50 328	57 165	548
Dairy cows	Liquid manure: max implementation of anaerobic digestion	886	914	191
	Ent. Fermentation: diet changes indoor fed cattle	17 257	20 269	988
Pigs	Max implementation of anaerobic digestion of liquid manure	5644	6774	1891
Other livestock	No mitigation option identified	22 100	28 955	0
Rice cultivation: continuously flooded	Combined: aeration, alt hybrids and sulphate amendments	19 658	21 517	7165
Rice cultivation: intermittently aerated	Combined: alt hybrids and sulphate amendments	7148	7489	1940
Agricultural waste burning	Ban	3088	3628	1910
MSW food & garden waste	Max separation and treatment, no landfill of biodegr. waste	10 303	11 813	9209
MSW paper waste	Max separation and treatment, no landfill of biodegr. waste	16 682	18 207	15 208
MSW wood waste	Max separation and treatment, no landfill of biodegr. waste	5048	5525	5521
Food industry solid waste	Anaerobic digestion w gas recovery and utilization	8957	17 590	14 961
Pulp & paper ind solid waste	Max recovery and utilization of black liquor	226	361	316
Textile industry solid waste	Max recovery and utilization	1093	1174	1172
Wood industry solid waste	Max recovery and utilization	2030	2157	1829
Domestic wastewater	Upgrade to anaerobic treatm w gas recovery and utilization	7866	9219	1926
Food industry wastewater	Upgrade to anaerobic treatm w gas recovery and utilization	2012	4720	3862
Pulp & paper ind wastewater	Upgrade to anaerobic treatm w gas recovery and utilization	2013	4877	3468
Org chemical ind wastewater	Upgrade to anaerobic treatm w gas recovery and utilization	1205	2369	1959
Coal mining-brown coal: pre-mining	Pre-mining degasification	234	315	278
Coal mining-brown coal: mining (VAM)	No mitigation option identified	510	696	0
Coal mining-brown coal: post-mining	No mitigation option identified	53	56	0
Coal mining-hard coal: pre-mining	Pre-mining degasification	7562	13 863	12 147
Coal mining-hard coal: mining (VAM)	Ventilation air oxidizer w improved ventilation systems	15 611	26 712	17 598
Coal mining-hard coal: post-mining	No mitigation option identified	6563	11 917	0
Oil production-ass gas	Recovery and utilization of vented associated gas	55 929	68 888	60 334
Oil production-leakage	Good practice measures to reduce unintended leakage	13 405	15 000	5348
Oil transportation and refining	Good practice measures to reduce leakage	169	184	112
Gas production-ass gas	Recovery and utilization of vented associated gas	1762	2909	2532
Gas production-leakage	Good practice measures to reduce unintended leakage	8065	11 684	4131
Oil and gas production-ass gas flaring	Linked to mitigation of ass gas emissions	2091	2644	0
Long-distance gas transmission	Leakage reduced to 10 kg CH_4/(bcm km)	7688	11 171	6666
Gas distr. networks (residential)	Replacement of grey cast iron pipes and doubling of control	4942	6315	6053
Gas distr. networks (non-residential)	Replacement of grey cast iron pipes and doubling of control	4284	5618	5238
Combustion-fossil fuels	No mitigation option identified	2444	2511	0
Combustion-biomass fuels	No mitigation option identified	8335	8155	0
Agriculture		126 352	146 942	14 703
Waste & wastewater		57 435	78 012	59 431
Fossil fuel extraction and use		131 312	180 483	120 438
Biomass combustion		8335	8155	0
Total		323 434	413 591	194 572

Table 7. Comparison of GAINS baseline to other global inventories.

Global CH_4 estimates									
Source	Baseline 2005					Baseline 2030			
	GAINS (2012)	UNEP (2011)	Cofala et al. (2007)	Draft USEPA (Aug 2011)	EDGAR v4.2 (2012)	GAINS (2012)	UNEP (2011)	Cofala et al. (2007)	Draft USEPA (Aug 2011)
	kt CH_4	*kt* CH_4	*kt* CH_4	*kt* CH_4	*kt* CH_4	*kt* CH_4	*kt* CH_4	*kt* CH_4	*kt* CH_4
Non-dairy cattle	50 571	50 572	101 073	99 542	58 067	57 397	57 399	118 507	121 533
Dairy cows	18 143	17 875			19 114	21 183	20 777		
Pigs	5644	5749			10 466	6774	6886		
Other livestock	22 100	22 063			20 541	28 955	29 043		
Rice cultivation	26 806	26 806	28 807	33 829	34 450	29 005	29 005	30 606	35 195
Agricultural waste burning	3088	3085	10 526	20 019	1480	3628	3628	8382	20 019
Forest, grassland and savannah fires	0	0			22 262	0	0		
MSW food & garden	10 303	33 680	62 401	37 243	28 330	11 813	37 377	74 861	44 067
MSW paper	16 682					18 207			
MSW wood	5048					5525			
Food industry solid waste	8957	7006				17 590	9892		
Pulp & paper ind solid waste	226					361			
Textile industry solid waste	1093					1174			
Wood industry solid waste	2030					2157			
Domestic wastewater	7866	7788	6470	20 252	23 840	9219	9116	7735	25 305
Food industry wastewater	2012	1342			6197	4720	1777		
Pulp & paper ind wastewater	2013					4877			
Org chemical ind wastewater	1205					2369			
Coal mining-brown coal	797	39 552	25 617	24 538	39 801	1067	70 645	37 535	37 629
Coal mining-hard coal	29 737					52 491			
Oil production-ass gas	55929	50 406	70 239	69 648	16 855	68 888	62 541	152 390	93 886
Oil production-leakage	13 405					15 000			
Oil transportation and refining	169					184			
Gas production-ass gas	1762				19 172	2909			
Gas production-leakage	8065					11 684			
Long-distance gas transmission	7688	7689			17 385	11 171	11 171		
Gas distr. networks (residential)	4942	14 277			10 167	6315	15 685		
Gas distr. networks (non-residential)	4284					5618			
Combustion-fossil fuels	4535		0	10 743	18 139	5155		0	16 919
Combustion-biomass fuels	8335		0	9448		8155		0	10 938
Industrial processes	0	0	0	0	222	0	0	0	0
Agriculture	126 352	126 150	140 406	153 390	166 379	32 633	32 633	157 495	55 214
Waste & wastewater	57 435	49 816	68 871	57 495	58 367	78 011	58 162	82 596	69 372
Fossil fuel extraction and use	131 312	111 924	95 856	104 929	121 518	180 483	160 042	189 925	148 434
Biomass combustion	8335	0	0	9448		8155	0	0	10 938
Total	323 434	287 891	305 133	325 262	346 486	413 591	364 941	430 016	405 491

Table 8. Summary results: costs for CH_4 technical mitigation potentials when estimated from social and private cost perspectives.

Global CH_4 estimates								
Emission source sector	Control measure	Max technical reduction 2030	Global costs max reduction 2030					
			Social cost perspective			Private cost perspective		
		kt CH_4 reduced	Weighted MC Euro t^{-1} CH_4	Regional range Euro t^{-1} CH_4	Total cost M Euro	Weighted MC Euro t^{-1} CH_4	Regional range Euro t^{-1} CH_4	Total cost M Euro
Non-dairy cattle	Liquid manure: max implementation of anaerobic digestion	70	6988	1712 to 51 877	488	15 262	8895 to 84 828	1065
	Ent. Fermentation: diet changes indoor fed cattle	548	1080	933 to 1255	592	1080	933 to 1255	592
Dairy cows	Liquid manure: max implementation of anaerobic digestion	191	−76	−912 to 950	−14	3306	2756 to 4779	632
	Ent. Fermentation: diet changes indoor fed cattle	988	884	353 to 1614	873	884	353 to 1614	873
Pigs	Liquid manure: max implementation of anaerobic digestion	1891	−1864	−3059 to −1244	−3525	−143	−1075 to 111	−270
Rice cultivation: continuously flooded	Combined: aeration, alt hybrids and sulphate amendments	7165	361	103 to 1847	2584	361	103 to 1847	2584
Rice cultivation: intermittently aerated	Combined: alt hybrids and sulphate amendments	1940	340	338 to 342	659	340	338 to 342	659
Agricultural waste burning	Ban	1910	0	no range	0	0	no range	0
MSW food & garden waste	Source separation and treatment, no landfill of biodegr. waste	9209	2081	640 to 6875	19161	4014	1447 to 9779	36 966
MSW paper waste	Source separation and treatment, no landfill of biodegr. waste	15 208	−3279	−5139 to 1023	−49 870	−2484	−4235 to 401	−37 772
MSW wood waste	Source separation and treatment, no landfill of biodegr. waste	5521	−2097	−3779 to −266	−11 575	1482	492 to 3396	8180
Food industry solid waste	Anaerobic digestion w gas recovery and utilization	14 961	261	−146 to 318	3908	1202	628 to 1570	17 978
Pulp & paper ind solid waste	Recovery and utilization of black liquor	316	−29 782	−38 602 to −15 441	−9411	−21 392	−30 041 to −12 016	−6760
Textile industry solid waste	Energy recovery	1172	−3639	−4932 to −1481	−4267	2219	1066 to 2665	2602
Wood industry solid waste	Recycling and energy recovery	1829	−2736	−3293 to −1325	−5005	−1574	−1894 to −763	−2879
Domestic wastewater	Upgrade to anaerobic treatm w gas recovery and utilization	1926	2996	1716 to 4831	5769	7628	4673 to 11 831	14 689
Food industry wastewater	Upgrade to anaerobic treatm w gas recovery and utilization	3862	−227	−4103 to 390	−878	2039	1735 to 3411	7876
Pulp & paper ind wastewater	Upgrade to anaerobic treatm w gas recovery and utilization	3468	−652	−3055 to 1649	−2261	1725	264 to 4327	5982
Org chemical ind wastewater	Upgrade to anaerobic treatm w gas recovery and utilization	1959	51	−2505 to 379	100	1665	1638 to 1669	3261
Coal mining-brown coal: pre-mining	Pre-mining degasification	278	−52	−167 to −6	−15	315	195 to 486	88
Coal mining-hard coal: pre-mining	Pre-mining degasification	12 147	957	−143 to 7523	11 628	1339	139 to 7942	16 263
Coal mining-hard coal: mining (VAM)	Ventilation air oxidizer w improved ventilation systems	17 598	163	97 to 1486	2868	191	185 to 1816	3367
Oil production-ass gas	Recovery and utilization of vented associated gas	60 334	−109	−778 to 358	−6585	1278	569 to 1716	77 099
Oil production-leakage	Good practice measures to reduce unintended leakage	5348	1289	935 to 6417	6893	1289	935 to 6417	6893
Oil transportation and refining	Good practice measures to reduce leakage	112	240	236 to 243	27	373	369 to 376	42
Gas production-ass gas	Recovery and utilization of vented associated gas	2532	−490	−515 to −451	−1242	−132	−135 to −130	−335
Gas production-leakage	Good practice measures to reduce unintended leakage	4131	1068	799 to 12 009	4412	1382	1081 to 12 291	5708
Long-distance gas transmission	Leakage reduced to 10 kg CH_4/(bcm km)	6666	−191	−395 to 4086	−1273	372	−29 to 8785	2481
Gas distr. networks (residential)	Replacement of grey cast iron pipes	6053	541	−58 to 1289	3276	2141	898 to 3893	12 962
Gas distr. networks (non-residential)	Replacement of grey cast iron pipes	5238	561	−73 to 1231	2939	2189	902 to 3842	11 464
Agriculture		14 703	113	−3059 to 51 877	1656	417	−1075 to 84 828	6136
Waste & wastewater		59 431	−914	−39 602 to 6875	−54 327	843	−30 041 to 9779	50 125
Fossil fuel extraction and use		120 438	190	−778 to 12 009	22 930	1129	−135 to 12 291	136 031
Total		194 572	−153	−683 to 829	−29 740	988	568 to 2344	192 291

Table 9. Costs for CH_4 technical mitigation potential in 2030 by world region.

World region	Max technical reduction 2030	Costs for max reduction 2030			
		Social cost perspective		Private cost perspective	
		Weighted MC	Total cost	Weighted MC	Total cost
	kt CH_4 reduced	Euro t^{-1} CH_4	M Euro	Euro t^{-1} CH_4	M Euro
Australia & N Zealand	1737	395	686	1923	3341
EU-27	4496	−35	−157	1925	8654
Europe-rest	4699	−100	−468	946	4447
India	8339	−221	−1839	866	7225
China	30 996	−149	−4625	568	17 612
Asia-rest	26 788	−257	−6879	847	22 685
Africa	24 410	−252	−6142	1067	26 054
USA & Canada	12 278	829	10 174	2344	28 779
Latin & Central America	25 655	−287	−7351	696	17 865
Middle east	23 991	−683	−16 395	1140	27 356
Russia	31 183	104	3256	907	28 273
World	194 572	−151	−29 741	988	192 290

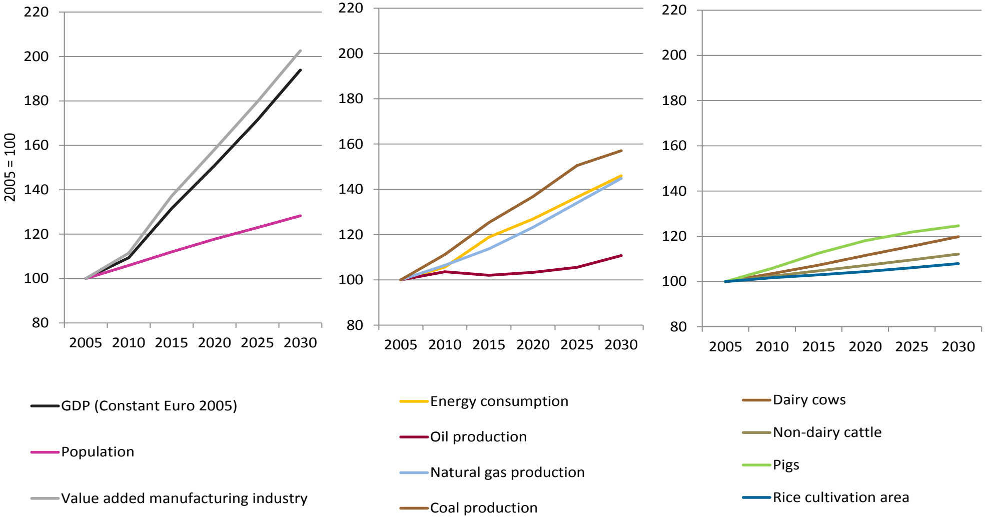

Fig. 1. Global development 2005–2030 in major drivers for CH_4 emissions entering model estimations from external sources (IEA-WEO, 2009; FAO, 2003; CAPRI model, 2009).

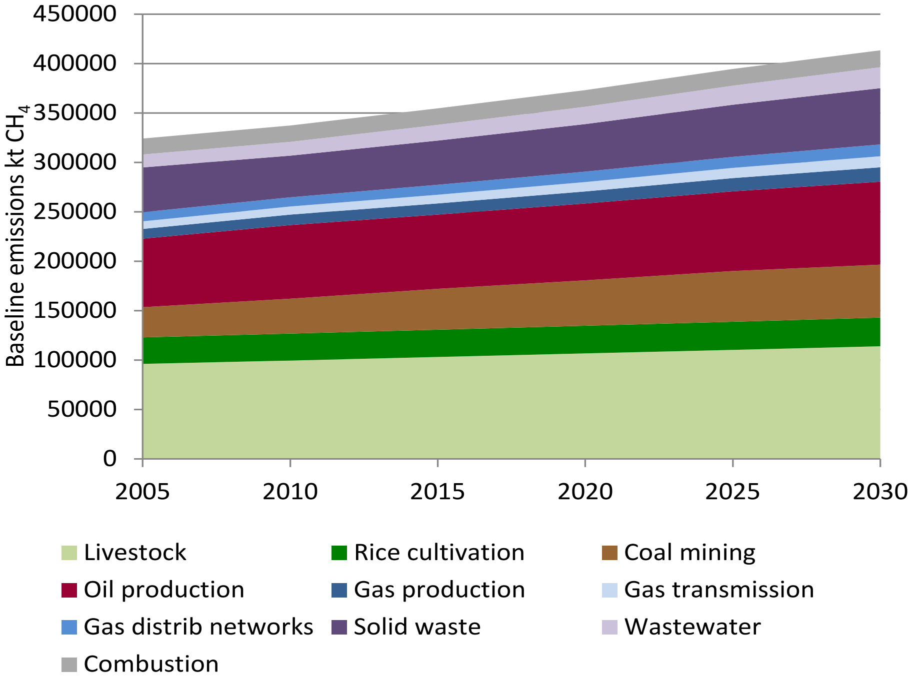

Fig. 2. Global anthropogenic CH_4 baseline emissions 2005 to 2030.

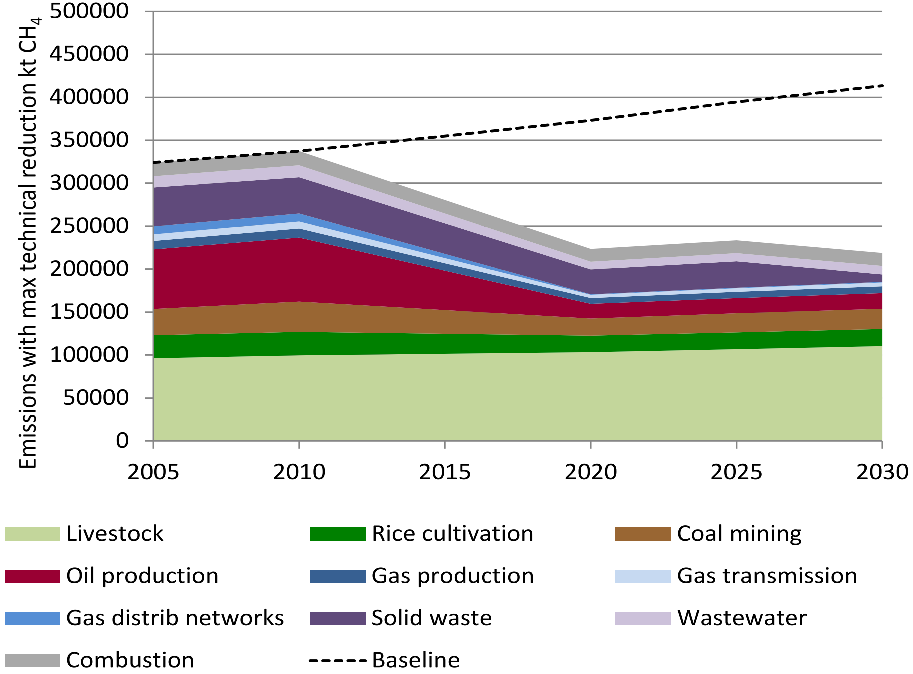

Fig. 3. Global anthropogenic CH_4 emissions with max implementation of available mitigation technology 2005 to 2030.

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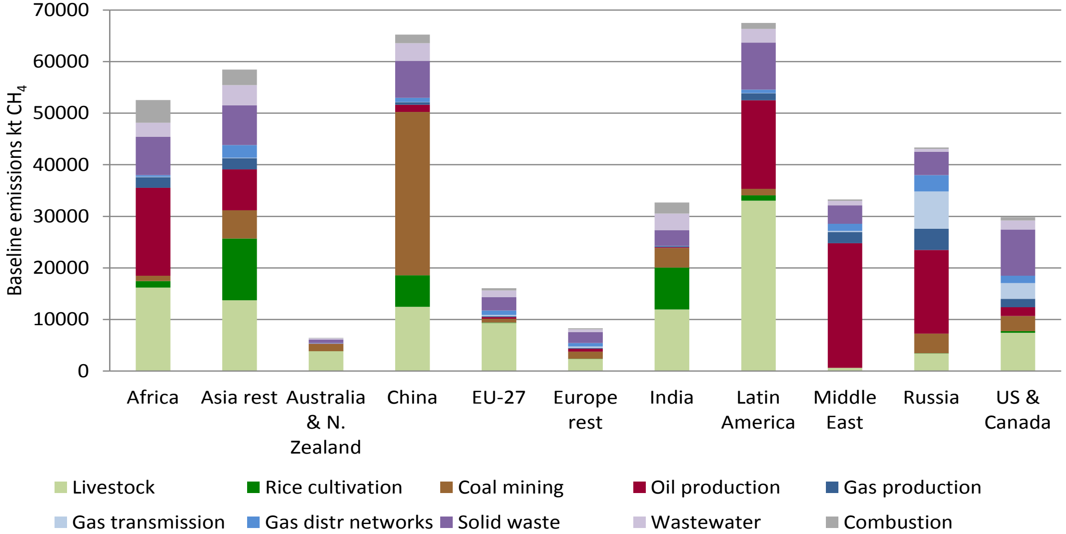

Fig. 4. CH_4 baseline emissions in 2030 by sector and world region.

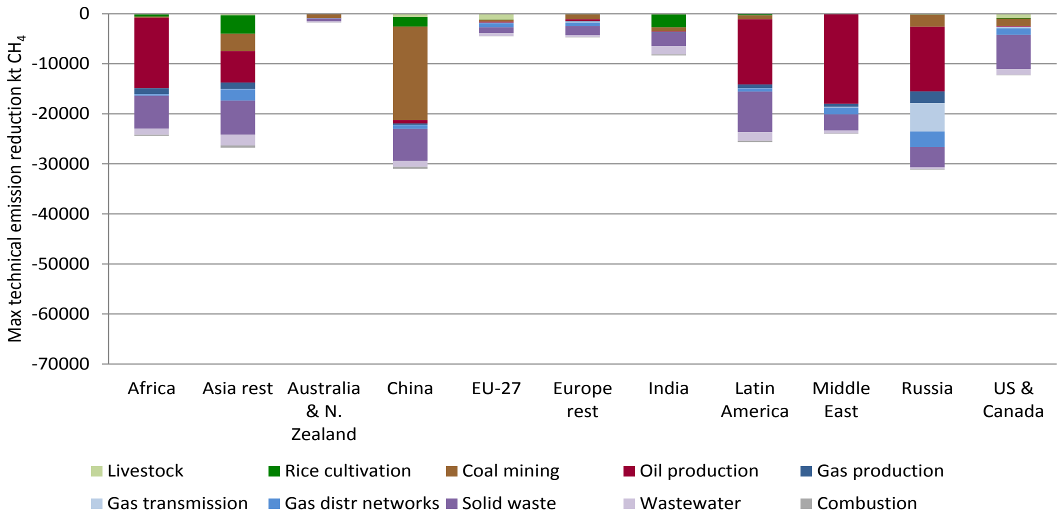

Fig. 5. CH_4 maximum technical reduction in 2030 by sector and world region.

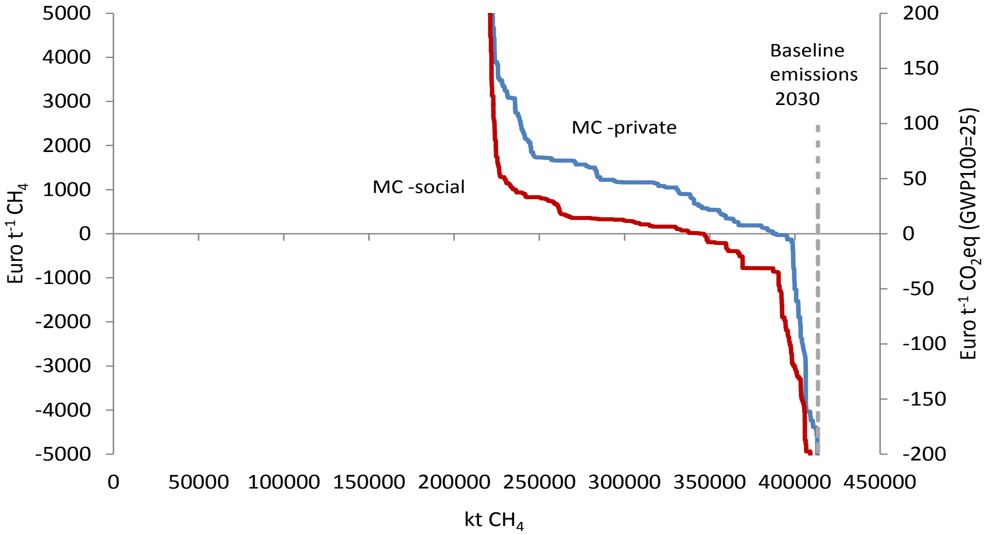

Fig. 6. Global CH_4 mitigation cost curve with private and social cost perspectives in 2030 (Euro 2005 price level).

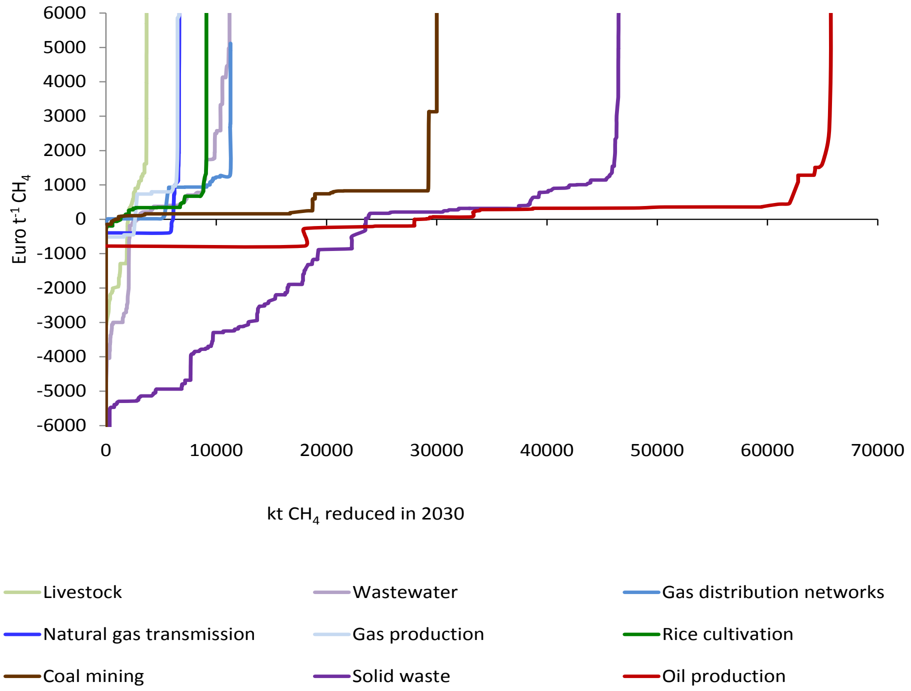

Fig. 7. Global CH_4 mitigation cost curves in 2030 by sector with a social cost perspective.

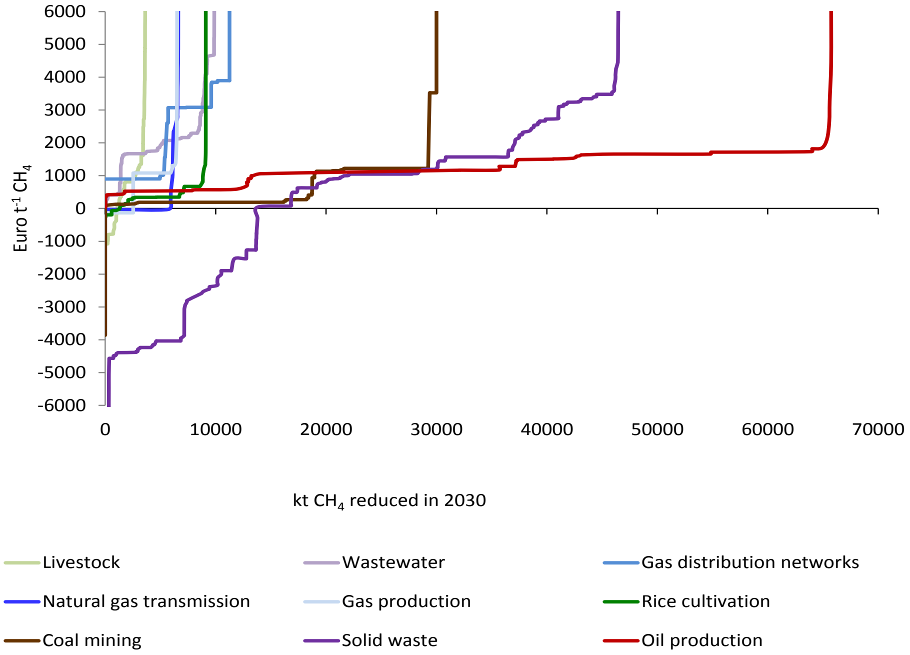

Fig. 8. Global CH_4 mitigation cost curves in 2030 by sector with a private cost perspective.

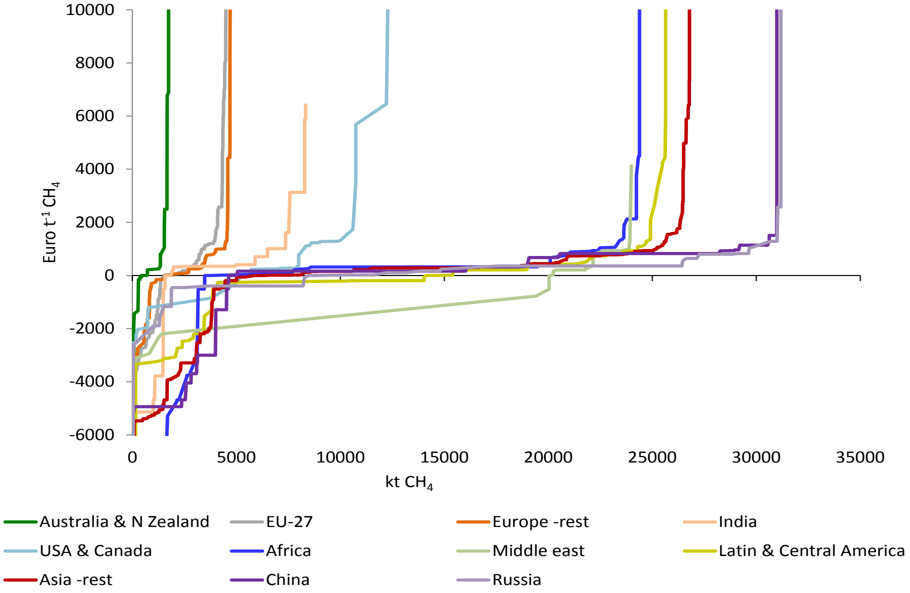

Fig. 9. CH_4 mitigation cost curves in 2030 by world region with a social cost perspective.

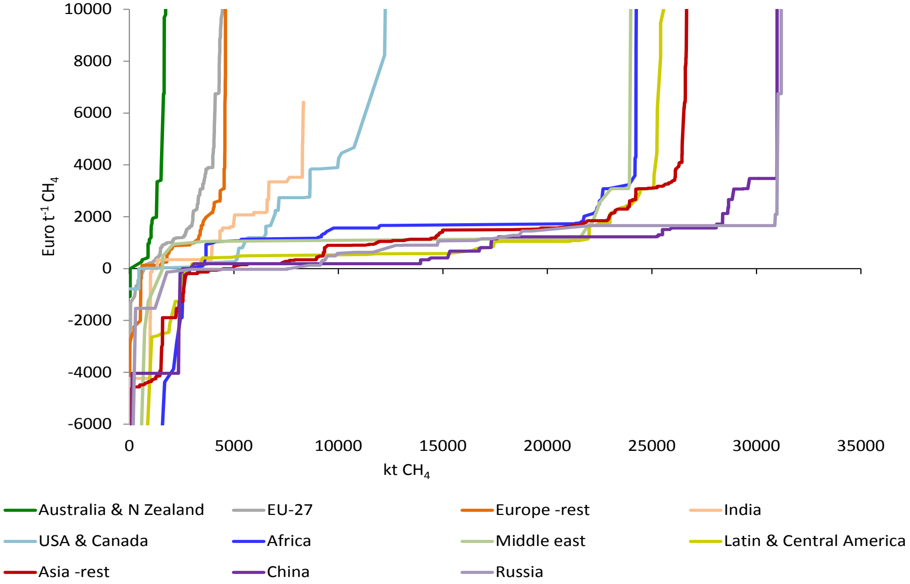

Fig. 10. CH_4 mitigation cost curves in 2030 by world region with a private cost perspective.

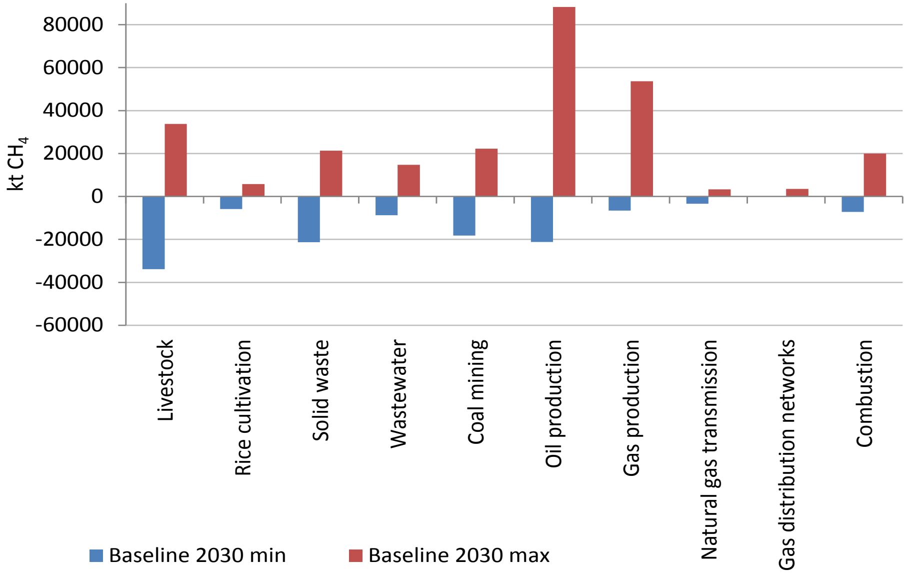

Fig. 11. Uncertainty ranges by sector for global CH_4 emission estimates.