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Claudia Kemfert • Wolf-Peter Schill

Mitigation of Methane Emissions - A Rapid and Cost-effective Response to Climate Change

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DIW Berlin
German Institute for Economic Research
Mohrenstr. 58
10117 Berlin
Tel. +49 (30) 897 89-0
Fax +49 (30) 897 89-200
http://www.diw.de

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Mitigation of methane emissions - a rapid and cost-effective response to climate change

Claudia Kemfert[1 2]

Wolf-Peter Schill[3]

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[1] Director of Department "Energy, Transportation and Environment", DIW Berlin

[2] Professor of Environmental Economics and Sustainability at the Hertie School of Governance, Berlin

[3] Graduate Center of Economic and Social Research, DIW Berlin

Abstract

Methane is a major anthropogenic greenhouse gas, second only to carbon dioxide (CO_2) in its impact on climate change. Methane (CH_4) has a high global warming potential that is 25 times as large as the one of CO_2 on a 100 year time horizon according to the latest IPCC report. Thus, CH_4 contributes significantly to anthropogenic radiative forcing, although it has a relatively short atmospheric perturbation lifetime of 12 years. CH_4 has a variety of sources that can be small, geographically dispersed, and not related to energy sectors.

In this report, we analyze methane emission abatement options in five different sectors and identify economic mitigation potentials for different CO_2 prices. While mitigation potentials are generally large, there are substantial potentials at low marginal abatement costs. Drawing on different assumptions on the social costs of carbon, we calculate benefit/cost ratios for different sectors and mitigation levels.

We recommend an economically efficient global methane mitigation portfolio for the year 2020 that includes the sectors of livestock and manure, rice management, solid waste, coal mine methane and natural gas. Depending on assumptions of social costs of carbon, this portfolio leads to global CH_4 mitigation levels of 1.5 or 1.9 $GtCO_2$-eq at overall costs of around $14 billion or $30 billion and benefit/cost ratios of 1.4 and 3.0, respectively. We also develop an economically less efficient alternative portfolio that excludes cost-effective agricultural mitigation options. It leads to comparable abatement levels, but has higher costs and lower benefit/cost ratios.

If the global community wanted to spend an even larger amount of money – say, $250 billion – on methane mitigation, much larger mitigation potentials could be realized, even such with very high marginal abatement costs. Nonetheless, this approach would be economically inefficient. If the global community wanted to spend such an amount, we recommend spreading the effort cost-effectively over different greenhouse gases.

While methane mitigation alone will not suffice to solve the climate problem, it is a vital part of a cost-effective climate policy. Due to the short atmospheric lifetime, CH_4 emission reductions have a rapid effect. Methane mitigation is indispensable for realizing ambitious emission scenarios like IPCC's "B1", which leads to a global temperature increase of less than 2°C by the year 2100. Policy makers should put more emphasis on methane mitigation and aim for realizing low-cost methane mitigation potentials by providing information to all relevant actors and by developing appropriate regulatory and market frameworks. We also recommend including methane in emissions trading schemes.

JEL: Q52, Q53, Q54

Keywords: Methane, mitigation, climate change, cost-benefit analysis

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Abbreviations

CO_2-eq	CO_2 equivalent
MtCO_2-eq	Million metric tons of CO_2-equivalent
GtCO_2-eq	Billion metric tons of CO_2-equivalent
B/C	Benefit / Cost
EMF21	Energy Modeling Forum 21: Multi-gas mitigation and climate change
GHG	Greenhouse gas
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Change
MAC	Marginal abatement cost
SCC	Social costs of carbon
USEPA	U.S. Environmental Protection Agency

1 Definition and description of Climate Change

The latest Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) states that warming of the global climate system is unequivocal. It reports that most of the observed increases in global average temperatures are very likely due to a rise in anthropogenic greenhouse gas (GHG) concentrations. As shown in Figure 1, global GHG emissions due to human activities have grown since pre-industrial times, with an increase of around 70% between 1970 and 2004. Carbon dioxide (CO_2) is the most important anthropogenic GHG. Its annual emissions have grown by about 80% between 1970 and 2004 (IPCC 2007).

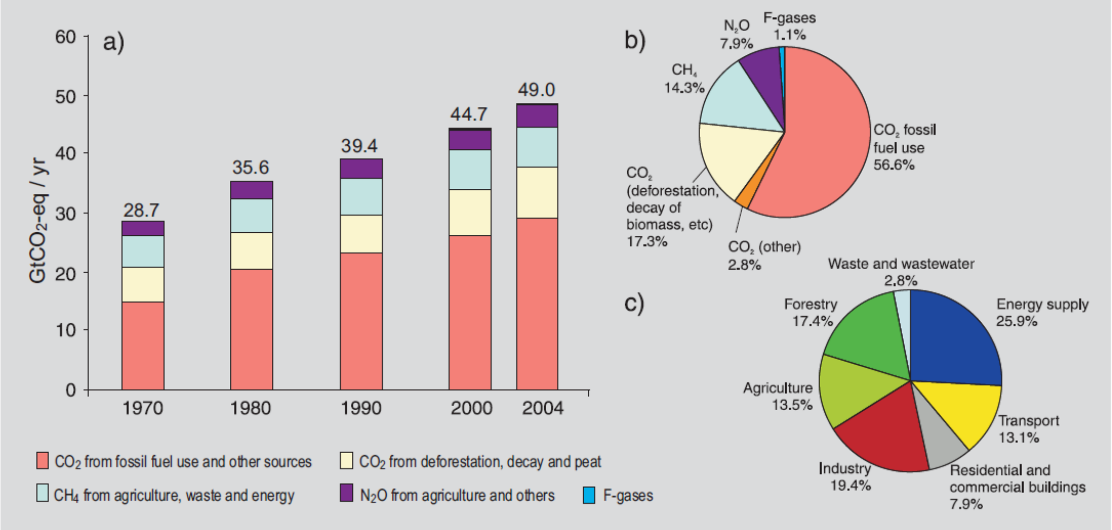

Figure 1: Global GHG emissions; (a) Global annual emissions of anthropogenic GHGs from 1970 to 2004. (b) Share of different anthropogenic GHGs in total emissions in 2004 in terms of carbon dioxide equivalents (CO_2-eq). (c) Share of different sectors in total anthropogenic GHG emissions in 2004 in terms of CO_2-eq. Forestry includes deforestation. Source: IPCC 2007

Methane is another major anthropogenic green house gas, second only to CO_2 in its impact on climate change. The radiative forcing of anthropogenic CH_4 contributes about 0.48 W/m^2 to total net anthropogenic radiative forcing of 1.6 W/m^2 (IPCC 2007a)[4]. Including indirect CH_4 effects like enhancements of tropospheric ozone or stratospheric water vapor further increases its total radiative impact.

If current emission trends persist, the global earth surface temperature will increase substantially in the future. The IPCC reports that stabilizing atmospheric concentrations of carbon dioxide equivalents (CO_2-eq) at around 445-490 ppm would lead to a global average temperature increase above pre-industrial levels of around 2.0-2.4 °C (Celsius). Stabilizing emissions at 855-1130 ppm CO_2-eq would lead to a temperature increase of around 4.9-6.1 °C (IPCC 2007).

According to IPCC, further warming would induce many changes in the global climate system until 2100, such as changes in wind patterns, precipitation, weather extremes and sea ice. A global temperature rise of more than 2 °C compared to pre-industrial levels might result in abrupt or irreversible changes. IPCC's "B1" emission scenario realizes this 2°C target (see

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[4] Total net anthropogenic forcing also contains some negative forcings, for example caused by anthropogenic aerosols.

section 3.5.3). IPCC has identified five “reasons for concern” including risks to unique and threatened systems, risks of both more frequent and more violent extreme weather events, the distribution of impacts and vulnerabilities, aggregate impacts, and the risks of large-scale singularities (IPCC 2007). In order to avoid such vulnerabilities and threats, it is necessary to reduce the global volume of GHG emissions significantly and stabilize global GHG concentrations at nearly today's level.

Extreme weather events are already causing enormous economic damages. However, estimates of future climate change damages and their economic consequences are highly uncertain (cp. Tol 2002a and Tol 2002b, Stern 2006, Weizman 2007, Nordhaus 2007, OECD 2008). One reason for this is that the effects are subject to temporal and spatial disparities. For example, the benefits of climate protection policies pursued in Europe today may not necessarily also be felt in Europe. They could equally materialize in Southeast Asia, where exposed island nations might be spared a flood produced by a rising sea level. Moreover, as a result of the long atmospheric lifetime of several greenhouse gases, many potential effects will emerge in the distant future.

While many publications on greenhouse gas mitigation have been dealing with CO_2, we focus solely on different methane emission mitigation solutions and assess their economic costs and benefits. We first give an overview of the characteristics of methane and its emission sources. Subsequently, we describe several options for reducing methane emissions. Economic mitigation potentials and marginal abatement costs for specific solutions are listed. Next, we estimate economic costs and benefit of different options, drawing on different assumptions on social costs of carbon emissions. Finally, we recommend a cost-effective portfolio of CH_4 mitigation options that could be implemented by 2020.

Most of the existing literature on methane mitigation cost assessments focuses on time frames until about 2020 or 2030[5]. Accordingly, most costs described in this study are in this time range, while the benefits of lower global temperatures due methane mitigation will be visible over longer periods (cp. Hope 2005).

2 The solution category: methane mitigation

2.1 Background on methane emissions

Compared to CO2, methane it is relatively short-lived. Its atmospheric perturbation lifetime is 12 years (IPCC 2007a). CH4 is removed from the atmosphere mainly through a hydroxyl radical reaction process. As methane is a much more short-lived greenhouse gas than CO2, it has high reduction potentials and high impacts on radiative forcing within short time periods. On the other hand, CH4 has a higher global warming potential (GWP) than CO2, controlling for its shorter atmospheric lifetime. In the first IPCC assessment report of 2001, methane was estimated to trap heat 23 times more effectively than CO2. According to the second assessment report, its GWP is 21 relative to CO2 on a 100 year time horizon. This value is also used for reporting under the United Nations Framework Convention of Climate Change. The latest IPCC assessment report includes a GWP estimate of about 25 compared to CO2 over a 100 year time horizon (USEPA 2006, IPCC 2007a). The GWP for CH4 calculated by

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[5] One example for long-term cost assessment is provided by Lucas et al. (2007).

IPCC includes indirect effects from enhancements of tropospheric ozone and stratospheric water vapor[6].

Methane is generated when organic matter decays in anaerobic conditions. Natural methane sources include wetlands, termites, oceans, and gas hydrates (cp. Milich 1999). Recently, Keppler et al. 2006 have suggested large-scale methanogenesis by plants in aerobic conditions. Given this newly detected emission source, it has been calculated that plants could account for up to 45% of global methane emissions. However, Nisbet et al. 2009 refute Keppler et al. and conclude that there is no such biochemical pathway for aerobic methane synthesis in plants, thereby rejecting the notion that plants may be a major source of global methane production.

Major anthropogenic methane sources in 2005 included enteric fermentation of ruminants (ca. 30% of anthropogenic CH_4 emissions), natural gas and oil systems (18%), landfills (12%), wetland (paddy) rice cultivation (10%), wastewater (9%), coal mining (6%) and livestock manure (4% according to USEPA 2006 and 2006b). That is, agriculture production (ruminant livestock, manures and rice grown under flooded conditions) currently accounts for about half of global anthropogenic methane emissions. This is also confirmed by other sources (Povellato et al. 2007, Smith et al. 2008). However, the relative importance of anthropogenic methane sources varies significantly between countries. For example, municipal solid waste landfills are the largest methane source in the United States, while livestock dominates emissions in other countries (de la Chesnaye et al., 2001). The largest percentage of global coal mine methane emissions comes from China (Yang 2009).

Looking at emission trends, CH_4 emissions and atmospheric concentrations have increased markedly since pre-industrial times. Atmospheric concentrations of CH_4 increased from pre-industrial values of about 715 ppb to about 1774 ppb in 2005 and exceed by far the natural range over the last 650,000 years (IPCC 2007a). Bousquet et al. 2006 find that while anthropogenic methane emissions were decreasing in the 1990s, they have been rising again since 1999. The latest increase in anthropogenic emissions has been masked by a coincident decrease in natural CH_4 emissions, mostly from wetlands. In general, Bousquet et al. 2006 find very large fluctuations in the growth rate of atmospheric methane concentrations from one year to the next. The inter-annual variability seems to be dominated by wetland methane emissions. USEPA 2006b projects an increasing global anthropogenic emission trend until 2020.

2.2 Definition and description of the solution category

The solution category “methane mitigation” includes different measures for capturing methane or for avoiding its release. In most cases, captured methane will be oxidized to CO_2, which significantly reduces its climate impact. The oxidization energy may be utilized for energy purposes, which entails additional GHG mitigation if carbon-intensive fuels are substituted.

Anthropogenic methane is emitted by various sources across different sectors and regions. Accordingly, mitigation potentials and cost vary widely. In this report, we focus on sectors that are characterized by both significant methane emissions and substantial mitigation potentials. In order to identify these sectors, we survey the relevant literature. For example,

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[6] Regarding the assessment of benefits and costs of specific mitigation options, we do not draw on GWP, but directly use the values of CO2-eq provided by the respective studies.

Milich 1999 provides an early overview of methane mitigation strategies. De la Chesnaye et al. 2001 survey US non-carbon GHG emission reductions strategies, including methane mitigation. An IEA 2003 study builds global cost curves for industrial sources of several non-CO_2 greenhouse gases. Povellato et al. 2007 review cost-effective GHG mitigation potentials in the European agro-forestry sector. Johnson et al. 2007 focus their review on agricultural GHG mitigation options for the US. Smith et al. 2008 give another overview of GHG mitigation in the agricultural sector. They find that the largest methane mitigation potentials are related to rice management and livestock, while potentials for manure management are lower. Delhotal et al. 2006 evaluate international methane mitigation potentials and costs in the waste and energy sectors, including regional differentiations. Finally, USEPA 2006 provides a very comprehensive analysis of mitigation options across sectors and world regions and a calculation of marginal abatement cost curves.

The literature survey shows that the most important sectors for methane mitigation include 1) livestock and manure management, 2) rice management, 3) solid waste management, 4) coal mining and 5) processing, transmission and distribution of natural gas.

Aside from these sectors, wastewater is also a significant global methane source. We refrain from including wastewater in our analysis mainly due to a scarcity of mitigation costs data[7]. Moreover, while wastewater mitigation potentials might be significant, most technological options in this sector are related to significant changes of wastewater management and infrastructure, e.g. the installation of sewerage systems in developing countries (cp. USEPA 2006). Without such infrastructure measures, methane mitigation potentials are low. In general there are other driving forces for installing wastewater collecting and treatment facilities, above all sanitarian and hygienic ones (cp. Lucas et al. 2007). We have also excluded methane emissions from the oil sector due to its comparatively low methane mitigation potential (cp. USEPA 2006).

Our definition of "methane mitigation" focuses on capturing methane or avoiding its release. We exclude options for enhanced methane removal from the atmosphere since existing technologies have very limited potentials due to very low concentrations of CH_4 in the atmosphere. For example, Johnson et al. 2007 and Smith et al. 2008 mention some examples for removing CH_4 from the atmosphere by specific agricultural practices. However, their effect is small compared to overall methane fluxes. Another example is provided by Yoon et al. 2009 who analyze the feasibility of atmospheric methane removal using methanotrophic biotrickling filters. They find that such measures are infeasible for removing atmospheric methane since concentrations are far too low. Finally, we also refrain from exploring agriculture-climate interdependencies regarding GHG sources and sinks (cp. Povellato et al. 2007).

2.3 Description of specific solutions within the solution category

In the following section, we briefly describe five specific solutions for methane mitigation. First, we point out strategies, technical definitions, and technical mitigation potentials. We then quickly discuss the feasibility of their application and mention interdependencies and side effects, if applicable. Specific mitigation costs and according economic mitigation potentials are discussed in chapter 3.

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[7] IEA 2003 provide some short-term cost estimates for the wastewater methane mitigation option of electricity generation from recovered methane. Lucas et al. 2007 estimate long-term costs for this category.

2.3.1 Livestock and manure management

The most important livestock methane mitigation strategies include improved feeding practices (e.g. feeding concentrates), the use of specific agents or dietary additives (like antibiotics and antimethanogen that suppress methanogenesis), and long term management changes and animal breeding. All these measures aim for improving feed conversion efficiency, increasing animal productivity, and decreasing specific methane emissions (DeAngelo et al. 2006, USEPA 2006, IPCC 2007c, Smith et al. 2008).

Manure mitigation includes both low-tech strategies like covering and cooling manure lagoons during storage and alternative techniques for manure dispersion and application (Weiske et al. 2006, USEPA 2006, von Witzke et al. 2007, IPCC 2007c). More advanced technologies include frequent manure removal from animal housing into covered storage using scraping systems (Weiske et al. 2006) as well as farm scale or centralized digesters for biogas generation and utilization (DeAngelo et al. 2006, USEPA 2006). In small-scale farm digesters, biogas from local manure may be used for electricity and/or heat production. Larger, centralized digesters can also take in additional organic wastes. There are many different digester designs ranging from low-tech small-scale to high-tech large-scale models, for example polyethylene bag or covered lagoon digesters for cooking fuel, light flexible-bag digesters, and large-scale dome digesters (USEPA 2006).

Mitigation potentials for livestock and manure are relatively high in some countries, such as Germany (cp. von Witzke et al. 2007). In EU 15, the overall mitigation potential for milk production is around 3.5% of total EU 15 anthropogenic GHG emissions, of which a substantial share is related to CH_4 (Weiske et al. 2006). However, the applicability and technical efficiency of several measures varies by climate. For example, the technical mitigation potential of digesters is largest in warm climates (USEPA 2006). Nonetheless, the overall mitigation potential of digesters is limited (USEPA 2006). In general, technical potentials for livestock and manure management are limited in many areas of the world due to feeding practices, wide-area dispersion of livestock and local farming techniques.

In manure management, complex interdependencies between methane and N_2O exist, which might lead to trade-offs. For example, while aerobic conditions during manure storage suppress CH_4 formation, they can promote N_2O formation (cp. USEPA 2006, von Witzke et al., 2007). When applying mitigation measures in livestock and manure management, it is important not to generate counter-effective emission increases of other greenhouse gases. Some options related to livestock or manure management might potentially trigger increases in N_2O emissions in unfavorable circumstances. However, Smith et al. (2008) find that that the measures cited above have no adversary N_2O impacts and thus a net emission mitigation effect.

2.3.2 Rice management

This solution aims for reducing methane generation from flooded rice paddies. A major mitigation strategy is improving water management through ways such as draining wetlands during rice seasons, avoiding water logging in off-seasons, and shallow flooding. Additional measures include upland rice cultivation and future cultivars with lower exudation rates (DeAngelo et al. 2006, USEPA 2006, IPCC 2007c, Smith et al. 2008).

Aside from methane, rice cultivation leads to emissions of other green house gases like N_2O and soil CO_2 (USEPA 2006, Wassmann and Pathak 2007). Such emissions may be mitigated by applying additives like phosphygypsum and nitrification inhibitors. In addition, the utilization of rice husks as fuel for heat and electricity generation can substitute carbon-intensive fossil fuels (Wassmann and Pathak 2007). However, these strategies are not further explored in this report.

In the case of rice management, some mitigation practices might lead to increases of N_2O emissions. However, according to Smith et al. (2008), there is general agreement and evidence for net mitigation effects of these measures. In addition, rice-related mitigation strategies might face social and institutional barriers as well as challenges regarding monitoring and enforcement. These issues are briefly discussed in section 3.4.3.

2.3.3 Solid waste management

The single most important specific solution in the category of solid municipal waste is preventing the release of landfill methane into the atmosphere. Landfill methane can be captured by installing a landfill cap and an active gas extraction system that uses vertical wells and optionally also horizontal collectors (Monni et al. 2006, IPCC 2007c). Captured methane can be used directly as a gas or utilized for local heat and/or electricity generation. If carbon-intensive fuels are substituted, such measures have an additional GHG mitigation effect. If landfill methane concentrations are low or if there is a lack of local energy demand, methane can alternatively be oxidized to CO_2 by flaring (Gallaher et al. 2005, USEPA 2006). Landfill methane not captured may be oxidized by indigenous methanotrophic microorganisms in landfill cover soils. Moreover, “bioreactor landfill designs” allow enhanced methane generation and capturing (IPCC 2007c).

There are also strategies that aim for reducing methane generation in landfills by diverting organic matter from landfills. Such strategies include the application of anaerobic digestion or aerobic composting, mechanical biological treatment, waste incineration, as well as waste reduction, re-use and increased recycling activities (Monni et al. 2006, USEPA 2006, IPCC 2007c). These strategies imply a structural change of waste management practices and the related infrastructure.

Solid waste methane mitigation potentials vary substantially between countries. They are highest for China, followed by the U.S. and African nations (Delhotal et al. 2006). In general, methane mitigation options of this category are highly dependent on the country-specific organization and structure of the waste management sector. Furthermore, the primary waste management objective is typically not GHG mitigation, but rather controlling environmental pollutants or mitigating health risks (Monni et al. 2006, IPCC 2007c).

2.3.4 Coal mining

Depending on depth and geological conditions, coal seams can include significant amounts of methane. Since methane is flammable in a concentration range from 5% to 16% in air, coal mine methane is a safety hazard for mining operations. Thus, mine degasification by ventilation is a standard procedure in underground coal mining, resulting in substantial methane releases to the atmosphere (USEPA 2006).

While minor quantities of methane are released in post-mining operations like processing and transportation, major emissions occur during mining operations. Accordingly, the most relevant mitigation strategies focus on mining operations. There are three major mitigation strategies (Gallaher et al. 2005, USEPA 2006). First, degasification can be applied up to ten years before mining operations begin. This strategy aims for collecting and capturing methane through vertical drills (at later stages, horizontal drills can also be used). Captured methane may then be injected into pipelines or utilized for heat and/or electricity production. The second option is enhanced degasification, which follows the same principle, but includes advanced drilling and additional purification and enrichment of captured gas. The third major strategy is ventilation air methane abatement. In contrast to degasification, this option is carried out during mining operations. It aims for oxidizing methane in ventilation air which typically has much lower CH_4 concentrations than degasification air (mostly <1%). Thus, catalytic methane oxidation technologies are usually applied. The resulting oxidation heat may be used for space heating purposes (Gallaher et al. 2005, USEPA 2006).

In 2000, coal mining accounted for 3.3% of global anthropogenic methane emissions. China is the largest single emitter, followed by the U.S., India and Australia (USEPA 2006). In 2004, China emitted about 190 million tons CO_2-eq of coal mine methane, followed by the U.S. with less than 60 million tons CO_2-eq (Yang 2009). China also has by far the highest global coal mine mitigation potential (Delhotal et al. 2006). However, although several specific Chinese coal mine mitigation policies have been put into place, several country-specific barriers still remain, such as lack of suitable degasification technologies, shortage of micro-internal-combustion-engine generators, and low amounts of capital investment from the private sector (Yang 2009).

It is important to note that safety concerns and not GHG mitigation is the driving force behind coal mine ventilation. However, safety concerns only give an incentive for mine operators to reduce methane in the mines below flammable concentrations rather than fully mitigating its release into the atmosphere.

2.3.5 Processing, transmission and distribution of natural gas

In the natural gas sector, methane may be released during production, processing, transmission, storage and distribution (Gallaher et al. 2005). Typical sources are leaks in natural gas pipelines, compressor stations, or venting of pipelines for maintenance reasons.
Mitigation strategies focus on the replacement of pipeline or compressor equipment, or on alternative management practices, like increased maintenance and reduced venting (Delhotal 2006).

Selected measures include the use of gas turbines instead of reciprocating engines, the replacement of high-bleed pneumatic devices with low-bleed or compressed air systems, dry seals on centrifugal compressors, and catalytic converters (USEPA 2006). The replacement of wet centrifugal compressor seal oil systems with dry seals and the installation of low-bleed pneumatic devices might be the most promising of options. Favorable management and operation practices include optimizing compressor shutdown, minimizing venting before pipeline maintenance and periodic leak inspections (Lechtenböhmer et al. 2007).

Of all sectors mentioned in this paper, the natural gas sector might have the highest reduction potential in 2020. Most potential reductions are accumulated in a few world regions like Russia, the Middle East, Latin America, the U.S. and the Commonwealth of Independent States (Delhotal et al. 2006). Measurements along the world's largest gas-transmission system in Russia showed an overall methane leakage of around 1.4%, which is comparable to US leakage rates (Lelieveld et al. 2005). Additional analyses showed that methane emissions from the Russian natural-gas long-distance network might be even smaller (approximately 0.6% of the natural gas delivered) (Lechtenböhmer et al. 2007). It has been shown that with such low leakage rates, switching from coal or oil to natural gas as a fuel has positive overall GHG mitigation impacts even in the light of leakages. (Lelieveld et al. 2005)

Importantly, the projected higher utilization of liquefied natural gas (LNG) could increase methane emissions since liquefaction processes and LNG transportation provide new opportunities for methane release.

3 Economic evaluation of specific solutions

3.1 Methodology

3.1.1 Global economic mitigation potentials and marginal abatement costs

In chapter 3.2, we identify overall global economic potentials for the different mitigation solutions outlined above and for different values of carbon between 0-200 US$/tCO2-eq[8]. Most studies refer to mitigation potentials in the year 2020, while some reach up to the year 2030. Where data is available, we also provide information on economic potentials and/or marginal abatement costs (MAC) of specific technologies within one sector. The method of research is an extensive literature survey of relevant bottom-up studies. Since economic abatement potentials vary significantly between some sources, we provide a range of different estimates that represents different strands of the literature.

MAC curves illustrate the potentials for reducing emissions at different cost levels. They are constructed by ordering different mitigation options from least to most expensive. Typically, MAC curves are increasing with an ascending slope. While emission abatement of the first units of methane is often relatively cheap or even associated with negative costs, costs usually increase for additional abatement (cp. USEPA 2006). There are static and dynamic MAC curves. For example, Stanford University’s Energy Modeling Forum EMF21 used static MAC curves for a multi-gas mitigation modeling project. They were derived in cooperation with the US Environmental Protection Agency from a global cost analysis of non-CO_2 greenhouse gases, including methane. In contrast, Gallaher et al. (2005) have conducted a dynamic analysis of costs and potentials of methane mitigation strategies in the solid waste, coal mining, and natural gas sectors. Incorporating firm-level data, their approach assumes technical change and decreasing costs, resulting in different MAC curves for the years 2010, 2020, and 2030.

The USEPA (2006) report provides the most comprehensive calculation of global methane MAC curves for different world regions and sectors. Using these MAC curves, technical and economic potentials of different mitigation strategies at different CO_2 prices are calculated. At breakeven CO_2 prices, the net present value of a mitigation strategy is zero. For different CO_2 prices, according economic mitigation levels can be calculated. All numbers in the USEPA (2006) report are provided in constant year 2000US$. Typically, the report assumes a discount rate of 10% and a tax rate of 40%. This discount rate is also applied by IEA (2003). It represents an industry perspective. From a social perspective, lower rates might be more appropriate, leading to even higher economic mitigation potentials (cp. also section 3.4.1).

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[8] All numbers are in constant year-2000 US$, if nothing else is provided.

EPA provides more detailed technology-specific MAC curves with different discount and tax rates on their web site[9].

3.1.2 Different approaches for B/C assessments

The most coherent way of estimating costs and benefits of the methane mitigation solutions discussed in this report would be the application of Computable General Equilibrium (CGE) or Integrated Assessment (IA) models. In the literature, a large number of such models has been applied for analyzing various mitigation policies, focusing on different greenhouse gases and mitigation technologies.

A comprehensive modeling exercise that included methane has been carried out in an international collaboration under the previously mentioned Stanford University's Energy Modeling Forum EMF21. The results are presented in the 2006 special issue of The Energy Journal titled "Multi-gas mitigation and climate change". It includes various assessments of economic and energy sector impacts of multi-gas mitigation strategies. Drawing on a range of different IA models (for example, Aaheim et al, 2006, Jakeman and Fisher 2006, van Vuuren et al. 2006, Kemfert et al. 2006)[10], EMF 21 includes but is not restricted to methane mitigation measures. A general result is that including non-CO_2 GHG like CH_4 and N_2O results in substantially lower mitigation cost compared to restricting GHG mitigation to CO_2. A more recent example for a CGE analysis of mitigation options in the agricultural and forestry sectors is provided by Golub et al. 2009. Using a global model that includes opportunity costs of land use, the authors find that livestock and paddy rice methane mitigation strategies are preferable agriculture-related GHG mitigation options.

However, such models have not been consistently applied to the specific methane mitigation options discussed in this report. To our knowledge, there is no application of an IA model that explicitly analyses costs and benefits of sinlge methane mitigation measures in the fields of livestock / manure, rice, solid waste, coal mining methane and natural gas. Rather than assessing these mitigation measures separately, most models focus on integrated packages of different mitigation options. Moreover, in most cases a mixed mitigation strategy of CO_2 and a range of non-CO_2 GHG, including methane, are applied.

Given this gap in the literature, we refrain from using IA publications for estimating benefits and costs of specific methane mitigation options discussed in this report. Rather, we estimate costs and benefits separately and then provide B/C ratios, as described in the next sections.

3.1.3 Estimating costs

Cost calculations are relatively straightforward if marginal abatement cost data is available. Total mitigation costs up to a certain mitigation level equal the area under a MAC curve.

In the following, we calculate the total costs of applying specific mitigation solutions in two ways. One approach is multiplying technology-specific marginal abatement costs and according mitigation potentials, where such data is available. Another approach is looking at

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[9] Technology-specific MAC curves for different discount rates are provided at http://www.epa.gov/methane/appendices.html. However, USEPA provides aggregate global MAC curves only for a tax rate of 40% and a discount rate of 10%. Thus, we stick to these numbers in the report.

[10] The full list of models applied in EMF21 includes AIM, AMIGA, COMBAT, EDGE, EPPA, FUND, GEMINI-E3, GRAPE, GTEM, IMAGE, IPAC, MERGE, MESSAGE, MiniCAM, PACE, POLES, SGM, and WIAGEM.

the economic mitigation potentials at different CO_2 prices identified in chapter 3.2. Assuming carbon prices of 0 \$/tCO_2-eq, these price-quantity combinations can be interpreted as mitigation levels at different (marginal) mitigation costs. In steps of \$15/tCO_2-eq, we multiply these marginal costs with the according potentials and add the results up. This stepwise procedure is necessary due to a lack of information on the shape of the MAC curve between the intervals of 0, 15, 30, 45 and 60 \$/tCO_2-eq. Negative marginal costs are not considered, but regarded as costs of 0 \$/tCO_2-eq. This approach and the fact that MAC curves are usually convex leads to a systematic over-estimation of costs.

3.1.4 Estimating benefits

Calculating the benefits of different mitigation measures is less straightforward than calculating costs. Different approaches might be chosen. For example, one might draw on model results and calculate the benefits of emission reductions by using shadow price estimates on CH4[11]. For reasons of simplicity, traceability and data availability, we focus on a different approach for estimating benefits. We look at the CO_2-equivalents of avoided CH_4 emissions and assign a value to these emission reductions with an estimate of the social costs of carbon (SCC).

While this procedure is very transparent, it involves a range of challenges. For example, choosing an appropriate SCC value is demanding. Depending on climate change projections, damage functions and discount rates, SCC estimates in the literature vary significantly (Tol 2008). We use three different values in order to cover a range of different assumption which we obtain from a literature survey of Tol (2008). Drawing only at a sample of peer-reviewed studies, we use the median, the mean and the 90-percentile values calculated by Tol. The median SCC value is 48 \$/tC, the mean 71 \$/tC, and the 90-percentile is 170 \$/tC. With a conversion factor of 3.667 tCO_2/tC, this translates to about 13.1, 19.4 and 46.4 \$/tCO_2.

Another challenge of this approach is the conversion of CH_4 to CO_2-equivalents, which depends on the time horizon, given different atmospheric lifetime of CH_4 and CO_2 (cp. IPCC 2007a). We do not convert these values by ourselves, but rather take the CO_2-equivalents directly from the studies. However, the time horizons of CO_2-equivalents and the SCC values taken from Tol (2008) may differ. Finally, our approach might not consider important interdependencies, side effects and equilibrium issues that might be addressed in a more appropriate way with an IA model. Therefore, our B/C estimates should only be considered as first indications of the relative cost-effectiveness of different options.

3.2 Results: Global economic mitigation potentials and marginal abatement costs

3.2.1 Livestock and manure management

Estimations of costs and mitigation potentials in this category vary significantly between countries and world regions (cp. USEPA 2006 and Povellato et al. 2007). Table 1 provides an overview on different estimations of economic potentials at different CO_2 prices between 0 and 200 \$/CO_2-eq.

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[11] For example, Nordhaus' DICE Model could be used, see http://www.econ.yale.edu/~nordhaus/homepage/dicemodels.htm

Table 1: Livestock and manure – projected baseline emissions and economic mitigation potentials at different CO_2 prices

Source	Year	Baseline in $MtCO_2$-eq	Value of CO_2 in US$/$tCO_2$-eq						
			0	15	30	45	60	100	200
			Economic mitigation potentials in $MtCO_2$-eq						
DeAngelo et al. 2006	2010	567	29						31
USEPA 2006	2020	2,867	83	126	158	175	192		
Smith et al. 2008	2030	n/a						210	

Sources: USEPA 2006, Smith et al. 2008, own calculations
USEPA 2006: overall livestock and manure; Smith et al. 2008: only livestock

The table indicates that a large share of the mitigation potential is in the low cost range of less than 30 $/$tCO_2$-eq. Measures with very high costs do not substantially increase mitigation potentials. The absolute numbers provided by DeAngelo (2006) for the shorter time frame until 2010 are much lower than the ones provided by USEPA for 2020. However, since they also assume lower baseline emissions, the relative shares are comparable.

There seem to be substantial mitigation potential at zero or even negative costs. In fact, MAC curves of some mitigation strategies become negative if the mitigation measures lead to increased efficiency in meat and milk production (cp. DeAngelo et al. 2006, Weiske et al. 2006). Smith et al. (2008) provide additional information on marginal abatement costs of specific solutions that do not include negative values as shown in Table 2. Nonetheless, it can be seen that additives and improved soil application of manure are measures with particularly low costs.

Table 2: Livestock and manure – marginal abatement costs of selected technologies

	Solution	US$/$tCO_2$eq
Livestock management	Feeding	60
	Additives	5
	Breeding	50
Manure management	Soil application	10
	Storage, biogas	200

Source: Smith et al. 2008

3.2.2 Rice management

As in the case of livestock and manure management, the feasibility and the costs of rice mitigation strategies depend on regional characteristics (Povellato et al. 2007). Table 3 provides an overview of mitigation potentials related to rice management.

Table 3: Rice – projected baseline emissions and economic mitigation potentials at different CO_2 prices

Source	Year	Baseline in $MtCO_2$-eq	Value of CO_2 in US$/$tCO_2$-eq						
			0	15	30	45	60	100	200
			Economic mitigation potentials in $MtCO_2$-eq						
DeAngelo et al. 2006	2010	185	19						56
USEPA 2006	2020	1,026	114	235	238	259	259		
Smith et al. 2008	2030	n/a						230	

Sources: USEPA 2006, Smith et al. 2008, own calculations

In the case of rice management, the largest share of mitigation potentials seems to be in the low cost range of less than 15 \$/tCO_2-eq. Potentials hardly increase with higher costs. Again, DeAngelo et al. (2006) assume much lower potentials than the other mentioned sources. Yet, since they also assume lower baseline emissions, the relative shares are comparable.

3.2.3 Solid waste management

Table 4 provides an overview of economic mitigation potentials in this category at different CO2 prices. Since data availability in this category is high, it not only includes overall values, but also economic mitigation potentials for specific technologies.

Table 4: Solid waste – projected baseline emissions and economic mitigation potentials at different CO_2 prices

Source	Overall sector or specific measure	Year	Baseline in MtCO_2-eq	Value of CO_2 in US\$/tCO_2-eq							
				0	15	30	45	50	60	100	200
				Economic mitigation potentials in MtCO_2-eq							
IEA 2003	Overall	2020	1217	300	794	842	940	977	1,000	1,033	1,043
Delhotal et al. 2006	Overall	2020	271								138
USEPA 2006	Overall	2020	817	97	332	405	464		717		
IPCC 2007d	Overall	2020	910	109	373	455	519		801		
IPCC 2007d	Overall	2030	1,500	300-500				375-1,000		400-1,000	
Monni et al. 2006	Overall	2030	1,500	535				1,256		1,369	
	Anaerobic digestion	2030	n/a	0				94		124	
	Composting	2030	n/a	0				64		102	
	Mechanical biological treatment	2030	n/a	0				0		19	
	LFG recovery – energy	2030	n/a	411				162		65	
	LFG recovery – flaring	2030	n/a	0				0		0	
	Waste incineration with energy recovery	2030	n/a	124				936		1,059	

Sources: USEPA 2006, IPCC 2007d (drawing on Delhotal et al. 2006 and Monni et al. 2006), Monni et al. 2006, own calculations and interpolations. The studies take into account remaining CO_2 that results from methane oxidation or waste incineration

The numbers vary between sources. Delhotal et al. (2006) seem to represent an outlier with much lower baseline emissions and lower economic potentials than other sources. However, there are some general findings. Baseline emissions will increase considerably until 2030. Monni et al. (2006) show that emission growth will be particularly strong in non-OECD countries. Overall, most of the potentials could be realized at costs of less than \$50/tCO_2-eq. Several authors find substantial mitigation potentials at negative costs. This is mainly due to an assumed energy use of recovered landfill gas (LFG) or energy recovery from waste incineration. Gallaher et al. (2005) find very high relative mitigation potentials at zero cost until 2020 for U.S. and Chinese emissions of 62% and 64% respectively. As for specific technologies, LFG recovery and energy use has the largest potentials at low carbon prices, while waste incineration with energy recovery has very large potentials at higher carbon prices.

USEPA (2006) provides additional information on marginal abatement costs in the form of breakeven costs and according mitigation potentials for some specific landfill methane abatement measures for 2020. Table 5 provides an overview. Heat production and direct gas use have large mitigation potentials at low costs. In case of heat production, there are even negative costs.

Table 5: Solid waste – breakeven costs and mitigation potentials for selected technologies

Technology	Breakeven Cost in US$/tCO$_2$-eq	Emission Reduction in 2020 in MtCO$_2$-eq
LFG capture and heat production	-17	0.36
LFG capture and direct gas use (profitable at base price)	1	0.39
LFG capture and direct gas use (profitable above base price)	8	0.39
LFG capture and flaring	25	0.39
Anaerobic digestion (low-tech type)	36	0.16
LFG capture and electricity generation	73	0.39
Composting (average)	254	0.51
Increased oxidation	265	0.24
Mechanical biological treatment	363	0.16

Source: USEPA 2006

3.2.4 Coal mining

Table 6 shows economic mitigations at different carbon prices.

Table 6: Coal mining – projected baseline emissions and economic mitigation potentials at different CO$_2$ prices

Source	Year	Baseline in MtCO$_2$-eq	Value of CO$_2$ in US$/tCO$_2$-eq					
			0	15	30	45	60	200
			Economic mitigation potentials in MtCO$_2$-eq					
IEA 2003	2020	648	140	418	418	418	418	418
Delhotal et al. 2006	2020	161						129
USEPA 2006	2020	450	65	359	359	359	359	

Sources: USEPA 2006, own calculations and interpolations

According to USEPA (2006), the MAC curve is very steep to the right of a carbon price of $15/tCO$_2$-eq. That is, most mitigation measures are in the low-cost area. Spending additional money does not result in increased mitigation. Gallaher et al. (2005) have similar findings when calculating regional MAC curves of coal mining. They find that in the U.S. and China, large shares of overall reduction potentials can be achieved at zero costs. This is due to the energy value of captured coal mine methane. Delhotal et al. (2006) assume lower absolute mitigation potentials than USEPA. However, since they also assume lower baseline emissions, they find the same relative mitigation potential (80%) at costs of $200/tCO$_2$-eq as USEPA for costs of $15-60/tCO$_2$-eq.

Additional information on breakeven prices and according potentials of some selected coal mining-related measures is provided by USEPA 2006. Table 7 includes some selected technologies. While all listed options are relatively low-cost, they potentially lead to large emission reductions by 2020. Pipeline injection of captured coal mine methane has negative abatement costs due to the revenues from selling the methane.

Table 7: Coal mining – breakeven costs and emission reductions for selected technologies

Technology	Breakeven Cost in US\$/tCO$_2$-eq	Emission reduction in 2020 in MtCO$_2$-eq
Degasification and pipeline injection	–12	0.55
Catalytic oxidation (U.S. technology)	14	0.94
Degasification and power production (“type C”)	20	0.83

Source: USEPA 2006

3.2.5 Processing, transmission and distribution of natural gas

Table 8 provides some estimates on economic potentials at different carbon prices.

Table 8: Natural gas – projected baseline emissions and economic mitigation potentials at different CO$_2$ prices

Source	Year	Baseline in MtCO$_2$-eq	Value of CO$_2$ in US\$/tCO$_2$-eq					
			0	15	30	45	60	200
			Economic mitigation potentials in MtCO$_2$-eq					
IEA 2003	2020	1,540	182	470	585	623	630	637
Delhotal et al. 2006	2020	379						144
USEPA 2006	2020	1,696	173	428	564	651	913	

Sources: IEA 2003, Delhotal et al. 2006, USEPA 2006, own calculations and interpolations

Delhotal et al. (2006) state that the natural gas sector offers many low-cost or no-regret options. However, compared to USEPA, they assume a much lower baseline and accordingly lower potential mitigation potentials, even at high costs. On the other end of the spectrum, USEPA estimates much larger mitigation potentials, with continuously increasing mitigation potentials at increasing costs. These numbers contrast with the analyses of Gallaher et al. (2005), which are slightly less optimistic than USEPA in relative terms. For China, Russia and the U.S. Gallaher et al. (2005) do not provide absolute numbers, but state that MAC curves are relatively steep. They assume that for the three countries mentioned, most of the mitigation potential that is economic at \$50/tCO$_2$-eq is also economic at zero cost.

USEPA (2006) provide more detailed cost data for specific technologies in this category, as shown Table 9. There is a range of options with relatively low costs that leading to sizeable comparable emission reductions.

Table 9: Natural gas – breakeven costs and emission reductions for selected natural gas mitigation technologies

Technology	Breakeven cost in US$/tCO$_2$-eq	Emission reduction in 2020 in MtCO$_2$-eq
Electronic monitoring at large surface facilities	1	0.33
Replace high-bleed pneumatic devices with lowbleed pneumatic devices	12	0.23
Enhanced inspection and maintenance in distribution	21	0.27
Dry seals on centrifugal compressors	37	0.20
Catalytic converter	77	0.20
Replace high-bleed pneumatic devices with compressed air systems	85	0.27
Gas turbines instead of reciprocating engines	113	0.27

Source: USEPA 2006

Lechtenböhmer et al. (2007) have analyzed the Russian gas transportation system and provide some additional calculations. They find that in the Russian case more than 30% of methane emissions (ca. 15 MtCO$_2$-eq) could be mitigated at investment costs below US$ 10/tCO$_2$-eq. Typical low-cost measures include operational practices like optimized compressor shutdown practices, minimized venting before maintenance or cost-effective leak inspections.

3.2.6 Summary of economic mitigation potentials

In the last section, we have provided economic methane mitigation potentials in specific sectors at different carbon values. In the following, we provide a summary of these potentials over all sectors. For the summary, we focus on USEPA data, since USEPA (2006) represents both the most detailed and the most consistent analysis of methane mitigation costs and potentials. The data for absolute and relative emission reductions at different carbon prices (i.e. different cost levels) for the year 2020 is summarized in Table 10 and Table 11. As before, the tables provide the mitigation levels (in MtCO2-eq or in %) that economically break even at a given carbon price ("economic mitigation potentials"). The CO2 prices can also be interpreted as marginal abatement costs.

Table 10: Summary of absolute economic mitigation potentials at or below different CO$_2$ prices

Sector	Baseline 2020 in MtCO$_2$-eq	Value of CO$_2$ in US$/tCO$_2$-eq				
		0	15	30	45	60
		Absolute economic mitigation potentials in MtCO$_2$-eq				
Livestock management	2,867	83	126	158	175	192
Rice management	1,062	114	235	238	259	259
Solid waste management	817	97	332	405	464	717
Coal mine methane	450	65	359	359	359	359
Natural gas	1,696	173	428	564	651	913
Sum	**6,891**	**531**	**1,480**	**1,723**	**1,908**	**2,439**

Source: USEPA 2006, own calculations

Table 11: Summary of relative economic mitigation potentials at or below different CO_2 prices

Sector	Baseline 2020 in $MtCO_2$-eq	Value of CO_2 in US$/t$CO_2$-eq				
		0	**15**	**30**	**45**	**60**
		Relative economic mitigation potentials in $MtCO_2$-eq				
Livestock management	2,867	3%	4%	6%	6%	7%
Rice management	1,062	11%	22%	22%	24%	24%
Solid waste management	817	12%	41%	50%	57%	88%
Coal mine methane	450	15%	80%	80%	80%	80%
Natural gas	1,696	10%	25%	33%	38%	54%
Sum	**6,891**	**100%**	**100%**	**100%**	**100%**	**100%**

Source: USEPA 2006, own calculations

We find the largest absolute mitigation potentials for the categories solid waste management and natural gas, in particular at high carbon prices. Interestingly, MAC curves for coal mine methane, rice management, and – to a lesser extent – livestock management are very steep at CO_2-prices of 15$/t. That is, spending additional money does hardly increase mitigation levels. The largest relative reduction potentials can be found in the categories of solid waste and coal mine methane, particularly in the case of high carbon prices. While natural gas also has substantial relative mitigation potentials, the values for livestock and rice management are much lower. Although these categories have high baseline emissions, the applicability of mitigation measures seems to be very restricted.

3.3 Results: B/C ratios

The following table provides an overview of benefit/cost ratios for the year 2020 estimated according to the procedure outlined above. B/C ratios are shown for various levels of application of selected mitigation options, i.e. up to marginal abatement costs of 15, 30, 45 and 60 $/tCO2-eq. The table distinguishes between three assumptions on the social cost of carbon, as described in section 3.1.4. We use SCC values of 13, 19 and 46 $/t$CO_2$-eq, which represent the median (13), mean (19) and 90-percentile (46) of Tol’s (2008) literature survey of peer-reviewed studies.

Table 12: B/C ratios for different solution categories, mitigation levels and assumptions on SCC values

Sector	**Mitigation up to marginal abatement costs in US$/tCO$_2$-eq**											
	15			**30**			**45**			**60**		
	SCC in US$/tCO$_2$-eq											
	13	**19**	**46**	**13**	**19**	**46**	**13**	**19**	**46**	**13**	**19**	**46**
	B/C ratios											
Livestock management	2.6	3.8	9.1	1.3	1.9	4.6	1.0	1.4	3.4	0.7	1.1	2.6
Rice management	1.7	2.5	6.0	1.6	2.4	5.8	1.2	1.7	4.2	1.2	1.7	4.2
Solid waste management	1.2	1.8	4.4	0.9	1.4	3.3	0.7	1.1	2.6	0.4	0.6	1.4
Coal mining	1.1	1.6	3.8	1.1	1.6	3.8	1.1	1.6	3.8	1.1	1.6	3.8
Natural gas	1.5	2.2	5.2	0.9	1.4	3.3	0.7	1.1	2.6	0.4	0.6	1.5

Sources: USEPA 2006, own calculations
SCC values of 13, 19 and 46 US$/tCO$_2$-eq represent the median (13), mean (19) and 90-percentile (46) of Tol's (2008) literature survey of peer-reviewed studies on SCC estimations.

As expected, Table 12 shows that B/C ratios decrease with increasing mitigation levels (i.e. increasing marginal abatement costs). That is, B/C ratios are higher for the "first" mitigated CH$_4$ units in a sector that have low marginal abatement costs. In contrast, B/C ratios for a given mitigation level increase with assumed SCC values, since higher SCC values represent larger benefits of avoided emissions. Accordingly, B/C ratios are particularly high under the assumption of high social carbon costs.

The table shows that B/C ratios are always greater than 1.0 if marginal abatement costs are smaller or roughly equal to the social costs of carbon. That is, the benefits of CH$_4$ mitigation outweigh the costs in these cases, which is an expected result. Nonetheless, B/C ratios can be significantly larger than 1.0 even in cases where MACs exceed SCC values. This is due to the fact that substantial mitigation potentials can be realized at zero cost in several sectors, which improves average B/C ratios.

In general, the livestock category has the highest B/C ratios for low mitigation levels, followed by rice management and natural gas. These categories also have large baseline emissions and substantial absolute economic mitigation potentials. For higher mitigation levels, i.e. up to marginal abatement costs of 60 $/tCO$_2$-eq, rice management and coal mining have the highest B/C ratios. This is due to the fact that most of the reduction potentials in these sectors are in the low-cost range, i.e. moving towards higher marginal abatement costs does not lead to additional mitigation and thus does not change B/C ratios. Accordingly, B/C ratios should be used carefully. We recommend considering Table 12 only in combination with Table 10 and/or Table 11.

The B/C values in Table 12 refer to overall mitigation in the different sectors. It is complemented by Table 13, which provides more detailed B/C ratios for selected mitigation technologies in the sectors solid waste, coal mining and natural gas, where such data is available.

Table 13: B/C ratios for selected technologies and different assumptions on SCC values

Sector	Technology	SCC in US$/$tCO_2$-eq		
		13	19	46
		B/C ratios		
Solid waste management	LFG capture and heat production	*n/a – negative marginal costs*		
	LFG capture and direct gas use (profitable at base price)	14.5	21.5	51.5
	LFG capture and direct gas use (profitable above base price)	1.6	2.4	5.7
	LFG capture and flaring	0.5	0.8	1.9
	Anaerobic digestion (low-tech type)	0.4	0.5	1.3
	LFG capture and electricity generation	0.2	0.3	0.6
	Composting (average)	0.1	0.1	0.2
	Increased oxidation	0.0	0.1	0.2
	Mechanical biological treatment	0.0	0.1	0.1
Coal mining	Degasification and pipeline injection	*n/a – negative marginal costs*		
	Catalytic oxidation (U.S.)	0.9	1.3	3.2
	Degasification and power production (“type C”)	0.7	1.0	2.3
Natural gas	Electronic monitoring at large surface facilities	17.2	25.5	61.0
	Replace high-bleed pneumatic devices with lowbleed pneumatic devices	1.1	1.6	3.8
	Enhanced inspection and maintenance in distribution	0.6	0.9	2.2
	Dry seals on centrifugal compressors	0.4	0.5	1.3
	Catalytic converter	0.2	0.3	0.6
	Replace high-bleed pneumatic devices with compressed air systems	0.2	0.2	0.5
	Gas turbines instead of reciprocating engines	0.1	0.2	0.4

Sources: USEPA 2006, own calculations

The technologies are listed in the order of increasing marginal abatement costs. It is clear that the technologies with low marginal costs have high B/C ratios, and that B/C ratios increase with higher social costs of carbon. In general, only a few technologies within a category have B/C ratios greater than 1.0 for low social costs of carbon. However, for the most cost-effective technologies “LFG capture and heat production” and “Degasification and pipeline injection”, calculating B/C ratios is inappropriate since these technologies have negative marginal costs according to USEPA. These technologies should be the first ones to be implemented from a bottom-up point of view, since they involve only benefits and no costs.

3.4 Discussion

3.4.1 Economic potentials and MAC curves

In some cases, absolute mitigation potentials were calculated by multiplying relative potentials with projected baselines. This approach might be controversial. While most studies assume comparable relative mitigation potentials, the baselines vary considerably between the studies. The resulting absolute mitigation potentials (and the B/C ratios calculated from these potentials) are therefore sensitive to assumptions on future baseline emission scenarios.

Compared to other studies, data on abatement costs and economic mitigation potentials provided by USEPA (2006) appears to be somewhat optimistic. However, to our knowledge USEPA provides the most coherent and thorough analysis on global marginal abatement costs of different methane mitigation strategies. This data is calculated from an industry perspective with a 10% discount rate and a 40% tax rate. Lower discount rates would result in even higher mitigation potentials. In addition, our approach of calculating costs stepwise and treating negative abatement costs as zero costs systematically over-estimates costs. Lastly, if we assume positive global carbon prices under future international climate agreements, mitigation costs for a given amount of methane would be lower than calculated above. Considering these facts, our cost calculations (and the resulting B/C ratios in Table 12) can be considered as conservative.

A weakness with MAC curves provided by USEPA (2006) is that they mainly represent technical or engineering costs and not economic costs. For example, opportunity costs of some solutions might not be included, which may result in an under-estimation of costs. However, combined with the cost-increasing factors discussed in the last section, we assume that our overall cost estimates are reasonable.

3.4.2 Agricultural solutions

Livestock and rice management seem to be the most controversial sectors. The data provided in this report focuses on technical feasibility and technical costs. Implementing mitigation strategies in these sectors might be infeasible due to geographic or social barriers (see also next section). In contrast to landfills, waste management and natural gas systems, methane sources in agricultural sectors can be very small and geographically widely dispersed. Accordingly, it will be challenging to regulate, monitor and enforce methane mitigation measures in these sectors.

While most of the livestock-related measures discussed in this report increase production efficiency, it has to be assured that productivity-related emission reductions are not counter-balanced by increasing overall production of meat and milk. Interactions with other GHGs also should not be neglected. While several possible interactions have been assessed (cp. Smith et al. 2008), more research is necessary on agriculture-related GHG interdependencies. For example, when applying large-scale methane mitigation measures, it has to be made sure that there are no increases in emissions of other GHGs like N_2O. Another problem might be the costs of agriculture-related CH_4 mitigation measures, which might be prohibitive for farmers in developing countries. Solving this problem is a question of finding appropriate financing mechanisms like carbon trading. Policy maker should not put too much emphasis on agricultural methane mitigation options for the reasons mentioned above, but they should consider them as a promising part of a broader methane mitigation strategy.

3.4.3 Negative MACs and implementation barriers

By providing a summary of economic mitigation potentials in different sectors, shown in Table 10, we do not suggest that all of these potentials will automatically be realized under the according carbon prices. There are several implementation barriers. This is most obvious in the case of negative marginal abatement costs. The existence of such negative MACs is a well-known fact. For example, negative MACs are a frequent phenomenon in energy-related mitigation categories (compare McKinsey 2007, IPCC 2007). Some mitigation potentials are not realized although it would be profitable – but why should there be “dollar bills left lying on the sidewalk”?

One possible answer to this question is that the mentioned bottom-up studies do not include all economic costs, for example opportunity costs. Another answer is that there are several social and institutional implementation barriers, for example a lack of knowledge and awareness. Moreover, the availability of crucial technologies might be limited, for example in the case of geographically dispersed, extensive livestock, but also in the case of coal mine methane abatement in China (cp. Yang 2009). Financing might also be a problem if solutions are capital-intensive, e.g. in the waste management, coal mine methane or natural gas categories. Finally, there might be institutional barriers in countries with weak institutional frameworks.

These barriers also have economic costs. Such costs are not included into B/C calculations because of high uncertainties and a lack of data. However, there is some evidence that negative MACs are not persistent in the long run. In the case of the Russian gas transportation system, repeated leakage measurements have indicated that methane leakage rates tend to decrease over time, since according investments are profitable (cp. Lechtenböhmer et al. 2007).

Overall, the implementation of methane mitigation measures might be easier in such sectors where emission sources are geographically concentrated and a smaller number of owners and operators are involved. Solid waste management and coal mining methane might be particularly promising in this respect.

3.4.4 B/C ratios

Our B/C estimations are sensitive to the calculation of costs and benefits as well as to the projection of emission baselines. Some controversial issues regarding costs calculations have been discussed previously, such as under-estimations of costs that result in exaggerated B/C ratios and vice versa. As mentioned in chapter 3.1.3, our approach of stepwise mitigation cost calculation and the fact that MAC curves are usually convex leads to a systematic over-estimation of costs. It should also be noted that due to the procedure described above, the results implicitly assume carbon prices of 0 $/tCO_2$-eq. If future international agreements would lead to positive global carbon prices, the costs calculated in this report would decrease. For that reason, resulting B/C values might be conservative.

As for our calculation of benefits, the challenges of drawing on social cost of carbon estimates have been discussed in section 3.1.4. Other concerns are the sensitivity to different discount rates and the timing of costs and benefits. Our approach is not very detailed regarding both of these issues. While our mitigation cost estimates implicitly assume relatively high discount rates – 10% in data provided by USEPA (2006) – our discount rate in the benefit estimation is somewhat vague, since we use the median, mean and 90-percentile values of SCC from a literature survey that includes many different studies with different assumptions on discount rates. According to Hope (2005), benefits are highly sensitive to the discount rate. For immediate methane cutbacks, he estimates benefits of about 5$/tCO_2$-eq using a pure time preference rate of 3%, but 18$/tCO_2$-eq with a rate of only 1% (in 1990 US$ and using the IPCC conversion factor between CH_4 and CO_2 of 21). Hope (2005) also finds a regional disparity of methane mitigation benefits. In his model, most benefits materialize outside the USA and the EU.

In general, mitigation options with B/C ratios below 1.0 should not be implemented. Due to the problems discussed above, we recommend dealing very cautiously with B/C ratios, particularly if they are calculated over long time horizons. Alternatively, mitigation policy decisions may directly be based on marginal abatement costs. Options with low MACs should be preferred to such with high MACs in order to achieve cost-effectiveness. From an economic perspective each abatement option should be implemented up to such a level that marginal mitigation costs are equal over all mitigation solutions. It is important to note that the B/C ratios in Table 12 include relatively large mitigation potentials that can be realized at zero costs in most categories. Large low-cost mitigation potentials can lead to B/C ratios larger than 1.0 even in such cases where marginal abatement costs significantly exceed marginal benefits of mitigation, i.e. the avoided social costs of carbon.

Our estimations on B/C ratios certainly do not represent a comprehensive social benefit-cost analysis, but they may provide valuable indications of the relative cost-effectiveness of specific measures. More thorough research is necessary if the global community wanted to spend very large amounts of money on methane mitigation. We recommend a more detailed and dedicated analysis of benefits and costs of the solutions outlined in this report with appropriate IA models in the near future.

3.5 Recommendations

If the international community wanted to spend a large amount of money – say, $250 billion – on methane mitigation, how should it be done?

First, we recommend tackling “low-hanging fruits”. Mitigation potentials at zero or even negative costs should be realized by removing institutional and social barriers. This includes educational efforts, making information and technology available in the right places, and developing appropriate legal frameworks. Methane mitigation needs to be taken seriously in the national and international climate policy debate.

Assuming restricted resources for mitigation monitoring and enforcement, it might be beneficial to focus on methane emissions that come from relatively large and well-identified sources, for example landfills, coal mines and natural gas systems. It might not be advisable relying only on agricultural solutions given the challenges of monitoring and enforcing. Although the potentials for methane mitigation in livestock, manure and rice management are large, there are high uncertainties regarding implementation barriers and the short-term feasibility of some options. In addition, the effectiveness of several mitigation options in livestock has not yet been demonstrated on a large scale. More research is required on unintended side effects, for example releases of other GHGs like N_2O. Nonetheless, it is clear that policy makers should not “put all their eggs in one basket” in order to diversify risks. We recommend spreading methane mitigation efforts over several sectors instead of focusing on a single sector.

We recommend a global solution portfolio that covers all five sectors discussed in this report (Portfolio 1). We also develop an alternative portfolio that leaves out the agricultural sectors for the reasons described earlier (Portfolio 2). In both portfolios, marginal abatement costs are equalized over all included sectors in order to ensure economic efficiency. We differentiate between two previously used extreme social cost of carbon values of 13 and 46 $/tCO_2$-eq, which represent the median and the 90-percentile SCC value in the literature survey of Tol (2008). In order to achieve economic efficiency, marginal abatement costs should equal the social costs of carbon. Thus, we choose efficient mitigation levels of 15 and 45 $/tCO_2$-eq for Portfolio 1[12]. As for Portfolio 2, we give up this efficiency condition and mitigate up to such levels that the marginal abatement costs exceed the assumed SCC values by about 15 $/tCO_2$-eq. In doing so, the absence of agricultural mitigation options is roughly counter-balanced in

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[12] These marginal abatement costs do not exactly match the SCC values, but are the closest data points available.

terms of total abatement. This procedure also represents a security margin and thus a more precautionary approach towards SCC estimations and climate damages.

We recommend implementing the cost-effective Portfolio 1. However, policy makers may come to the conclusion that implementation barriers in the agricultural sectors are too high, or additional research may show that agricultural methane mitigation is less feasible or more expensive than assumed today. In these cases, the more precautionary and less cost-effective Portfolio 2 could be implemented in order to achieve mitigation levels comparable to Portfolio 1.

3.5.1 Portfolio 1

Portfolio 1 includes all five sectors mentioned in this report. We choose mitigation levels such that MACs are equal over all categories and also roughly equal to the social costs of carbon emissions. We differentiate between two cases: a SCC assumption of 13 \$/tCO2-eq (and corresponding mitigation levels up to MACs of 15 \$/tCO2-eq) and a SCC assumption of 46 \$/tCO2-eq (and corresponding efficient MACs of 45 \$/tCO2-eq). Total abatement levels, total costs and B/C ratios for the year 2020 for both cases are summarized in Table 14 and Table 15.

Table 14: Portfolio 1: Total abatement level, costs and B/C ratios for SCC of 13 \$/tCO$_2$-eq.

Sector	Total emission abatement		Total abatement costs		B/C ratios
	in MtCO$_2$-eq	sector share	in million \$	sector share	
Livestock management	126	9%	645	5%	2.6
Rice management	235	16%	1,816	13%	1.7
Solid waste management	332	22%	3,536	25%	1.2
Coal mine methane	359	24%	4,403	31%	1.1
Natural gas	428	29%	3,831	27%	1.5
Total	**1,480**	**100%**	**14,231**	**100%**	**1.4**

This table shows global solution Portfolio 1 for the year 2020 with a SCC assumption of 13\$/tCO$_2$-eq and according efficient abatement levels at marginal abatement costs of 15 \$/tCO$_2$-eq over all sectors.
Sources: USEPA (2006), own calculations.

Table 15: Portfolio 1: Total abatement level, costs and B/C ratios for SCC of 46 $/tCO$_2$-eq.

Sector	Total emission abatement		Total abatement costs		B/C ratios
	in MtCO$_2$-eq	sector share	in million $	sector share	
Livestock management	175	9%	2,365	8%	3.4
Rice management	259	14%	2,867	10%	4.2
Solid waste management	464	24%	8,381	28%	2.6
Coal mine methane	359	19%	4,403	15%	3.8
Natural gas	651	34%	11,833	40%	2.6
Total	**1,908**	**100%**	**29,850**	**100%**	**3.0**

This table shows global solution Portfolio 1 for the year 2020 with a SCC assumption of 46$/tCO$_2$-eq and according efficient abatement levels at marginal abatement costs of 45 $/tCO$_2$-eq over all sectors.
Sources: USEPA (2006), own calculations.

Drawing on our fairly conservative cost estimates described in chapter 3.1.3 (stepwise calculation, no negative costs), it would be efficient to mitigate nearly 1.5 GtCO$_2$-eq at overall costs of around $14.2 billion at a SCC value of 13 $/tCO$_2$-eq. Assuming a SCC value of 46 $/tCO$_2$-eq, around 1.9 GtCO$_2$-eq could be efficiently mitigated at costs of about $29.9 billion. Most money should be spent in the sectors of solid waste management, coal mining and natural gas in both cases. Overall B/C ratios are larger than 1.0 for all included sectors and both SCC assumptions. For the high SCC value, B/C ratios are much larger than in the case of the low SCC value, since benefits related to low-cost mitigation potentials increase with SCC.

3.5.2 Portfolio 2

Portfolio 2 disregards mitigation solutions in the livestock / manure and rice management sectors. It only includes waste management, coal mine methane and natural gas. We once again distinguish between SCC values of 13 and 46 $/tCO2-eq, but increase mitigation levels up to marginal abatement costs of 30 and 60 $/tCO2-eq, respectively. In doing so, we roughly compensate for the missing agricultural mitigation. As mentioned earlier, this procedure represents a more precautionary approach. The results for the year 2020 are summarized in Table 16 and Table 17.

Table 16: Portfolio 2: Total abatement level, costs and B/C ratios for SCC of 13 $/tCO$_2$-eq.

Sector	Total emission abatement		Total abatement costs		B/C ratios
	in MtCO$_2$-eq	sector share	in million $	sector share	
Solid waste management	405	31%	5,727	32%	0.9
Coal mine methane	359	27%	4,403	24%	1.1
Natural gas	564	42%	7,896	44%	0.9
Total	**1,328**	**100%**	**18,026**	**100%**	**1.0**

This table shows global solution Portfolio 2 for the year 2020 with a SCC assumption of 13$/tCO$_2$-eq and abatement levels at marginal abatement costs of 30 $/tCO$_2$-eq over all sectors, representing a more precautionary approach than Portfolio 1.
Sources: USEPA (2006), own calculations.

Table 17: Portfolio 2: Total abatement level, costs and B/C ratios for SCC of 46 $/tCO$_2$-eq.

Sector	Total emission abatement		Total abatement costs		B/C ratios
	in MtCO$_2$-eq	sector share	in million $	sector share	
Solid waste management	717	36%	23,537	42%	1.4
Coal mine methane	359	18%	4,403	8%	3.8
Natural gas	913	46%	27,513	50%	1.5
Total	**1,988**	**100%**	**55,452**	**100%**	**1.7**

This table shows global solution Portfolio 2 for the year 2020 with a SCC assumption of 46$/tCO$_2$-eq and abatement levels at marginal abatement costs of 60 $/tCO$_2$-eq over all sectors, representing a more precautionary approach than Portfolio 1.
Sources: USEPA (2006), own calculations.

We find comparable total abatement levels for Portfolios 1 and 2, but widely differing costs. Portfolio 2 is less cost-effective due to the exclusion of low-cost agricultural solutions and due to the precautionary approach of abating up to marginal costs that exceed SCC by about 15 $/tCO$_2$-eq. This is also evident in the lower B/C ratios of Portfolio 2 compared to Portfolio 1.

3.5.3 Context

We want to put the total emission abatement levels that can be achieved with our portfolios into context. Exactly quantifying their effect on global temperatures is challenging due to timing and the importance of other factors like the development of the global population, the economy and other GHG emission trends. Yet, we can put the numbers into the context of current emissions and future IPCC emission scenarios.

Global anthropogenic GHG emissions amounted to 44.7 GtCO$_2$-eq in 2000 and 49 GtCO$_2$-eq in 2004, with increasing trends (IPCC 2007). Our portfolios lead to mitigation levels of around 1.3-2 GtCO$_2$-eq by the year 2020, which corresponds to about 3-4% of total global anthropogenic GHG emissions in the year 2000. These numbers indicate that methane offers substantial cost-effective emission reduction opportunities.

IPCC has developed several emission scenarios. The most optimistic scenario B1 assumes a convergent world with rapid economic change towards a service and information economy, large-scale adoption of efficient and clean technologies and a global solution approach. In this scenario, global temperature increases less than 2°C by 2090-99 relative to 1980-99. In order to make B1 reality, global emissions have to grow less than 10 $GtCO_2$-eq by 2030 compared to 2000 levels and must peak around the year 2040. A portfolio of short-term methane emission abatement measures as outlined above could play an important role in achieving such ambitious targets. While our portfolio alone will certainly not suffice to realize B1, it should be a cost-effective part of a larger mitigation strategy.

If the global community wanted to spend an even larger amount of money – say, $250 billion – on methane mitigation, much larger methane reductions than in Portfolio 1 or 2 could be realized. With such an amount of money it should be possible to realize virtually all methane reduction potentials in the five sectors identified in this study, including the ones with very high marginal abatement costs. However, it is clear that this approach would be inefficient. If the global community really wanted to spend such a large amount of money, we would recommend including other methane mitigation options that have not been analyzed in this report, for example in the wastewater sector. In order to ensure economic efficiency, we also recommend spreading such large amounts of money over a portfolio of different greenhouse gases.

4 Summary and conclusions

Several analyses have shown that including non-carbon greenhouse gas mitigation measures can decrease mitigation costs substantially compared to focusing exclusively on CO2 (e.g. Kemfert et al. 2006 and other contributions of EMF21[13]). Methane emission abatement is a particularly promising supplement to CO_2 mitigation due to large global low-cost abatement potentials. Methane has the largest overall mitigation potentials among all non-CO_2 GHG (USEPA 2006). In addition, due to the short atmospheric lifetime of CH_4, the beneficial effects of methane mitigation will be more instantaneous than for example in the case of CO_2 mitigation.

In contrast to CO_2, some methane emission sources are small, geographically dispersed, and not related to the energy sector. For example, there are several such methane sources in the agricultural sector. CH_4 mitigation may therefore require different approaches regarding regulation, monitoring and enforcement than CO_2. Another difference between CO_2 and CH_4 is that methane is an energy carrier that has an energetic value, while CO_2 is mainly a waste product without a market value.

Several specific methane mitigation solutions in different sectors have been identified in this report. The most important mitigation strategies regarding mitigation potentials and cost-effectiveness can be found in the sectors of livestock and manure management, rice management, solid waste management, coal mining, and natural gas.

Absolute economic methane mitigation potentials in livestock management are limited relative to the large emissions of this sector, but most of the overall livestock-related potential reductions can be found in the low cost range of up to ca. 15 US$/$tCO_2$-eq. That is, spending more money does not provide much additional benefit. The same is true for rice management.

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[13] See de la Chesnaye and Weyant (2006): Multi-Greenhouse Gas Mitigation and Climate Policy. A Special Issue of *The Energy Journal*, 2006

However, geographical, social and institutional barriers may impede the implementation of agriculture-related mitigation potentials. Solid waste management has higher absolute mitigation potentials than the agricultural sectors. MAC curves are flatter in this case, which means that more expensive measures (up to about 60 $/tCO_2$-eq) still lead to substantial emission reductions. For coal mining methane mitigation, absolute economic potentials are generally lower than for landfills. By far the largest part of mitigation measures related to coal mining is cheaper than 15 $/tCO_2$-eq. Natural gas processing, transmission and distribution are characterized by relatively high methane emissions and large economic mitigation potentials over a broad cost range.

Total economic mitigation potentials identified in this report are subject to discussion. While USEPA (2006) provides the most comprehensive and coherent data on economic potentials, the values are rather optimistic relative to other studies. The conversion of relative to absolute mitigation potentials is also highly sensitive to the baseline projection. In addition, there may be institutional barriers that prevent economic mitigation potentials from being realized.

Our rough estimation of costs and benefits of methane mitigation in the categories livestock, rice, solid waste, coal mining and natural gas shows that B/C ratios decrease with increasing mitigation levels since they involve higher marginal abatement costs. In contrast, B/C ratios increase with assumed social costs of carbon since higher SCC values correspond to larger benefits of avoided emissions. B/C ratios can be significantly larger than 1.0 even in cases where marginal abatement costs exceed social costs of carbon. This is due to the fact that substantial mitigation potentials can be realized at low or even zero cost in several sectors. Such low-cost potentials improve average B/C ratios.

We want to stress that our B/C values represent only rough estimates on the relative cost-effectiveness of different measures. We recommend that mitigation policies rather focus on marginal abatement costs. From an economic point of view, the marginal cost of mitigating one ton of CO_2-eq should be equal over all different strategies and green house gases. Moreover, marginal abatement costs should be equal to the social costs of carbon emissions. However, since estimations on SCC values per ton of CO_2-equivalent are challenging and highly uncertain, a more precautionary approach might be advisable where marginal abatement costs exceed SCC assumptions.

In this study, we have developed two solution portfolios for methane mitigation. Portfolio 1 includes all sectors discussed in this report. With two different assumptions on social costs of carbon, Portfolio 1 leads to economically efficient global methane mitigation levels of 1.5 or 1.9 $GtCO_2$-eq by 2020 at costs of around $14 billion or $30 billion, and with overall B/C ratios of 1.4 and 3.0, respectively. Portfolio 2 not only disregards agricultural mitigation strategies, but also represents a more precautionary – and economically less efficient – approach by mitigating up to marginal abatement costs that exceed assumed social costs of carbon by around 15 $/tCO_2$-eq. Portfolio 2 leads to mitigation levels of 1.3 and 2.0 $GtCO_2$-eq by 2020, which are comparable to Portfolio 1. Yet, costs are much higher at around $18 billion or $55 billion respectively, due to the inclusion of less cost-effective measures. B/C ratios are also lower at 1.0 and 1.7, respectively. Comparing Portfolio 1 to Portfolio 2 provides a good illustration of economic inefficiencies resulting from the exclusion of low-cost abatement options.

If the global community wanted to spend a large amount of money on mitigating GHG emissions, it should definitely include cost-effective methane mitigation options, as described in this report. From a social perspective, there should be priority for such methane mitigation solutions that involve large co-benefits, for example increasing agricultural production, or health and security benefits in coal mining and waste management. We recommend that policy makers focus on information and education of all involved actors. In addition, methane should urgently be included in emissions trading schemes. There may be also a role for administrative rules and regulatory policies.

We want to conclude with some additional remarks. First, it should be noted that the comparison of CH_4 and to CO_2-equivalents remains challenging due to different time horizons. Many calculations in the literature are sensitive to this issue. Second, in order to fully assess the costs, benefits and co-benefits of methane mitigation strategies, more integrated modeling approaches should be applied. Next, while many methane mitigation options are relatively low-cost, most of them do require positive carbon prices in order to break even economically. Accordingly, global carbon regulation, preferably in the form of carbon markets, is necessary for promoting these mitigation options. Institutional barriers impeding the implementation of some methane mitigation options and the full realization of their technical potentials should be addressed by policy makers. In addition, new potential methane emission sources should be avoided, as probably in the case of future undersea methane clathrate mining. To conclude with, several options mentioned above have long lead times, for example coal mine degasification or waste management strategies. Thus, early action and clear policy signals are urgently required.

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