International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21[1]

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1 Study Objective

Information on the potential for and costs of abating greenhouse gases (GHGs) from anthropogenic sources is of primary importance to decision-makers seeking to optimize climate change policies and allocation of resources. Traditionally, economic analyses of GHG mitigation focused on carbon dioxide (CO_2) emissions from energy sources, while non-CO_2 GHGs were not incorporated into the studies. In recent years, however, increasing attention has focused on the benefits of reducing emissions of non-CO_2 GHGs such as methane. Economic models of climate change have demonstrated that multi-gas abatement strategies significantly reduce costs versus achieving the same level of GHG reductions through CO_2 strategies alone (Burniaux 2000, Hayhoe et al. 1999, Hyman et al 2003, Manne & Richels 2000, 2001, Reilly et al. 1999, 2000). At the same time, such strategies also may have significant environmental benefits, particularly in the near-term (Hansen et al 2000, Reilly et al. 2003).

While the incorporation of non-CO_2 GHGs emission estimates into these models is a substantial improvement, there is a need for better data on the costs of non-CO_2 GHGs abatement for countries and regions outside of the US and the European Union (EU). In the absence of such data, economic models could either: (a) apply US (or EU) aggregate percent reductions per marginal cost to a region's emissions, or (b) apply US (or EU) sector-specific percent reductions per marginal cost to another region's corresponding sectoral emissions. This second approach means, for example, applying the US percent reductions from the coal sector to China's coal sector emissions estimate.

This paper describes an analytical method that goes beyond these approaches to develop country- and region-specific abatement estimates that can be incorporated into economic models used for climate change analysis. This study is based on existing engineering-economic studies for the US (USEPA, 2001a, 1999) and the EU (EC, 2001) that apply available abatement options (technologies and management practices) to major methane-emitting sectors. These studies together with available country or region-specific emissions and economic data are the basis for this new international cost analysis of methane and nitrous oxide abatement. The results of the analysis are presented as marginal abatement curves (MACs) by region and by sector, and vary by discount/tax rate and energy price. Methane sources analyzed in this report include: coal mining; livestock manure management; natural gas production, processing, transmission, and distribution; oil production; and solid waste management. Nitrous Oxide sources analyzed in this report include adipic and nitric acid production only. Currently, methane emissions from enteric

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[1] This report was produced as part of a study organized by the Stanford Energy Modeling Forum on Multigas Mitigation and Climate Change. For more information go to www.stanford.edu/group/EMF/home/index.htm. This analysis benefited from the input of an international team of non-CO_2 experts including, Casey Delhotal, Francisco de la Chesnaye, Dina Kruger, Elizabeth Scheehle, Ann Gardiner, Judith Bates, Chris Hendriks, and ICF Consulting Inc. The lead author, C. Delhotal, is responsible for any omissions and remaining errors. Comments or questions should be addressed to: delhotal.casey@epa.gov.

fermentation and rice production, as well as nitrous oxide emission from agriculture are not included in this analysis due to insufficient data on costs and application of abatement options. Additional research is ongoing for these sources and will be provided as available.

2 Baseline Emissions for Methane and Nitrous Oxide

The methodology outlined in this study uses published methane and nitrous oxide data as inputs into the analysis. Current and projected methane and nitrous oxide emission estimates to 2020 in this report are obtained primarily from referenced documents. If historical or projected emission estimates are not available from the literature, they are estimated using IPCC default methodologies and emission drivers such as population or energy consumption.

Baseline (reference) projections for Annex I countries are largely based on publicly available reports produced by the countries themselves. The preferred sources are the 3rd National Communications (available from www.unfccc.org) containing current emissions and projections to 2020. Estimates from the various National Communications should be comparable in that they rely on the IPCC methodologies (or similar methods) and country-specific activity data. Baseline or "business as usual" scenarios do not include climate change mitigation efforts, though they do include non-climate based policies that indirectly reduce greenhouse gases. For the sake of consistency, if a country's reported projections included planned climate mitigation efforts, i.e., "with policies and measures", the reductions due to those efforts were added back into the emission projections where identified. If climate policy reductions could not be identified, a country's emissions projections were estimated by continuing trends from previous years as reported in historical inventories. Source-by-source and country-by-country explanations of how the projections were developed can be found in the Appendix to USEPA 2001b.

Estimates of historical and projected emissions for developing countries were based on national and international reports and also reflect the most recent results of the EPA draft study *Emissions and Projections of Non-*CO_2 *Greenhouse Gases for Developing Countries: 1990-2020* (USEPA, 2002). The preferred approach to estimate emissions from developing countries is to use the latest published information for each country. Some developing countries reported 1990 or later emissions estimates in their latest National Communications, *Asia Least-Cost Greenhouse Gas Abatement Strategy* (ALGAS, ADB, 1998), or as part of various country-specific reports. Preference is given to the latest published estimates from the National Communications and ALGAS reports, including both historical and projected estimates. When the emissions data from these references did not cover the entire historical or projected time series of 1990 to 2020, or in cases where no emissions data were reported, estimated emissions are obtained using the following approaches:

1) For countries reporting estimates from 1990 to 2010 in 10-year intervals, a linear interpolation was used to estimate values in 5-year increments.
2) For countries not reporting emissions to 2000, emission growth rates were estimated based on EPA estimates for the country for 1990 through 2000. EPA's estimates were developed using IPCC Tier 1 (or default) methods and internationally available data. The growth rates were applied to reported inventories since 1990 and used to estimate the remaining years up to 2000. Projections to 2020 are based on growth-rate projections

applied to source specific drivers for each country, using the estimate for 2000 as the base year.

3) When no emissions data were available or when the data were insufficient, EPA developed emissions estimates, projections or both, using the default methodology presented in the 1996 Revised IPCC Guidelines (IPCC, 1997) and the IPCC Good Practice Guidance (IPCC, 2001).

According to the IPCC Third Assessment Report–WG I, methane has a 100-year global warming potential (GWP) of 23 indicating that it is estimated to be 23 times more effective than carbon dioxide at trapping heat in the atmosphere over a 100-year period. Nitrous oxide's 100-year global warming potential is assumed to be 296 in the same report (IPCC, 2001). In this analysis, however, EPA uses GWP estimates from the Second Assessment Report – WG I, because it is the value currently used in reporting GHG emissions under the United Nations Framework Convention on Climate Change. Thus, in this analysis a GWP of 21 for methane and a GWP of 310 for nitrous oxide. Complete baseline data can be found in Appendix A.

3 Cost Analysis Methodology

The international estimates of methane and nitrous oxide abatement in this analysis are based on two previous methane abatement studies. The first, published by the US Environmental Protection Agency, contained cost estimates for methane abatement in the US from 1990 to 2020 (USEPA, 2001a, 1999). The second study was conducted by the European Commission and evaluated technologies and costs of methane abatement for the members of EU-15 from 1990 to 2010 (EC, 2001). Both the US and EU-15 studies provided estimates of potential methane emission reductions from major emitting sectors and quantified costs and benefits of these reductions.

The EU-15 study is based on evaluating the abatement potential and costs options at representative facilities or point sources of emissions, e.g., waste digesters, and then extrapolating the results to a country and to the EU-15 level. EPA's US analysis also uses representative facility estimates but applies them to a highly disaggregated and detailed set of emissions sources for all the major sectors and sub-sectors. EPA's analysis is more detailed because there is more abundant data in the US. For example, the US analysis of the natural gas sector is based on emission factors for over 100 sources for that industry, including gas well equipment, pipeline compressors and equipment, and system upsets.

As a result, the EC analysis provides more of a sector-average cost for individual abatement options at the country or EU-15 level, while the US analysis provides more detail at the sector and sub-sector level. This more detailed approach also results in a marginal abatement curve with more points for the US, i.e., additional abatement cost calculations per sector.

For this new, international analysis, average US abatement costs and benefits are estimated for each abatement option in order to build a set of options that are comparable to the EU options. Together, this new combined set of abatement options, including abatement options for nitrous oxide, is applied to the selected regions in the study. The advantage of using the "average" approach versus the more detailed analyses for the US and the EU is that it incorporates the latest emissions data from the respective National Communications and it provides for a consistent methodology throughout the whole analysis for all regions. It should be noted that mitigation estimates from this "average" approach are more conservative than those reported in the US and EC reports. MAC curves for all regions can be found in Appendix C.

3.1 Technical Characteristics of Abatement Options

The list of methane and abatement options evaluated in this study is compiled from the original analyses for the US (USEPA, 2001a, 1999) and the EU (EC, 2001). The list of nitrous oxide abatement options evaluated in this study are compiled from a US report on nitrous oxide abatement (USEPA, 2001c) and an IEAGHG report (IEAGHG, 2000). Either the entire set of sector-specific options or its subset is applied to each region. Some options are not applied to particular regions based on expert analysis of conditions in the region. The selective omission of options represents a 'static' view of the region's socio-economic conditions, which is a conservative approach. Ideally, more detailed information on country-specific conditions, technologies and experiences will be available in the future, which will enable more specific analyses of abatement potential in other regions.

Exhibit 1 provides a summary of the technical characteristics of the abatement options. The abatement options employed in this analysis are described in Appendix B. Detailed data for each option as applied to a specific region can also be found in Appendix B.

Exhibit 1: Technical Characteristics of Abatement Options

Characteristic	Unit	Definition
Availability (A)	Yes/No	Projected availability of a specific option in a given region and year.
Technical Applicability (TA)	Percent (%)	Percent of the total emissions from a particular emission source to which a given option can be potentially applied (e.g., percent of emissions from underground mining relative to total emissions from coal mining).
Economic Applicability (EA)	Percent (%)	Percent of emissions (Baseline Emissions * TA) to which a given option is applicable based on economic/infrastructure factors.[1]
Reduction Efficiency (RE)	Percent (%)	Percent of technically achievable emission abatement for an option after it is applied to a given emission stream.
Lifetime (L)	Years	The average technical lifetime of an option.
Abatement Potential (AP)	Percent (%)	The percent of baseline emissions that can be reduced at the national or regional level by a given option. This is the product of Technical Applicability, Economic Applicability, and Reduction Efficiency of the option.

[1] Economic Applicability for non-overlapping options, i.e., applicable to different emission streams, is assumed to be 100 percent.

Characteristic	Unit	Definition
Emission Reduction (ER)	MMTCE or Gg of CH_4	The absolute amount of baseline emissions reduced by an option per year in million metric tons of carbon equivalent (MMTCE) or Gigagram of methane (Gg CH_4)[2]. This value is estimated for each region and source by multiplying the total baseline emissions in a selected year by the Abatement Potential.

The total abatement potential of an option in each region is equal to an option's technical applicability times its economic applicability times reduction efficiency. In the current analysis the economic applicability of each of the **n** overlapping options is equal to **1/n**, which assumes a uniform distribution of emissions among the options, notwithstanding their net costs or other factors. In other words, the baseline is segmented and each option is applied to one segment of the baseline. Residual emissions from applying a particular option are not captured by another option. An example of two non-overlapping options in the natural gas system are (1) inspection and maintenance of compressors and (2) replacement of distribution pipes. These options are applied independently to different parts of the sector and do not "compete" for the same emission stream. This assumption reflects the lack of region-specific data for determining the relative level of diffusion of overlapping options or the market potential of each option that can be used as alternatives to abate the same emission stream.

Furthermore, this analysis does not account for indirect methane emission reductions, which can result from either the substitution of electricity from the grid with electricity produced on-site from recovered methane or the substitution of natural gas in pipelines with recovered methane. Calculation of such indirect reductions requires additional assumptions about the carbon intensity of electricity in different regions. In the US landfill sector, indirect reductions generally augment emission reductions by about 15 percent. For nitrous oxide, reductions do not include potential benefits in NOx from the abatement technologies.

3.2 Economic Characteristics of Abatement Options

Each abatement option is characterized in terms of its costs and benefits per an abated metric ton of carbon equivalent, ton of nitrous oxide or ton of methane. All values are reported in 2000 USD. Costs include capital or one-time costs (CC) and operation and maintenance or recurring costs (RC). Furthermore, some one-time costs (where data are available) are subdivided into labor and equipment components. The cost of abatement options for methane includes benefits or revenues from capturing the methane. Specifically, benefits or revenues from employing an abatement option include: (1) the value of methane either as natural gas or electricity/heat; (2) non-methane benefits of abatement options (e.g., compost or digestate for waste diversion options); and (3) the value of abating methane as a GHG in terms of \$/TCE or \$/TCH_4. In most cases, there are two price signals for the abatement of methane: based on its value as energy (since natural gas is 95 percent methane) and as a GHG. The cost of abatement options for

[2] 1 Gg of methane equals 1 Kiloton (10^3 metric tons) of methane.

nitrous oxide includes only the value of abating nitrous oxide as a GHG in terms of $/TCE or $/TN$_2$0.

Costs and benefits of abatement options are adjusted based on labor costs, and for methane, energy costs, in the corresponding regions. The equipment component of fixed costs is not adjusted and is the same for all the regions. Since labor costs comprise the majority of O&M costs, they are used as a proxy to adjust O&M costs across regions as well as the labor component of the one-time cost. Specifically, O&M costs for each region are estimated based on a ratio between the average regional labor cost in manufacturing in that region and in the United States for US-based options or the European Union for EU-based options, respectively. Regional labor costs in manufacturing are taken from World Bank data (2000). Adjustment calculations can be found in Appendix B.

For methane, revenues are scaled based on the ratio between average prices of natural gas (when methane is abated and sold as natural gas) or of electricity (when methane is used to generate electricity or heat) in a given region and either the US or the EU.

A present value analysis of each option is used to determine break-even abatement costs in a given region. Specifically, the analysis solves for **P** in the following equation:

PV (Benefits) = PV (Costs) or more specifically,

$$\sum_{t=1}^{T}\left[\frac{(PxER)+R+TB}{(1+DR)^{t}}\right]=CC+\sum_{t=1}^{T}\left[\frac{(RC)}{(1+DR)^{t}}\right]$$

where: P is the break even price of the option in \$/TCE, \$/TCH$_4$ or \$/TN$_2$0

ER is the emissions reduction achieved by the technology

R is the revenue generated from energy production (scaled based on regional energy prices) or sales of by-products of abatement (e.g., compost). This is only used in the case of methane.

T is the option lifetime

DR is the selected discount rate, and

CC is the capital cost of the option

RC is the recurring (O&M) cost the option (scaled based on regional labor costs)

TB is the tax break equal to CC/T * TR

TR is the tax rate.

The analysis is conducted for the following combinations of discount and tax rates, respectively: from a social perspective – 4 and 0 percent; 5 and 0 percent; 10 and 0 percent; and from various industry perspectives – 10 and 40 percent, 15 and 40 percent, and 20 and 40 percent. In addition, because of the high sensitivity to energy prices, the methane analysis tested the MAC sensitivity to changes in base energy price (from –50% to +200%), both for electricity and natural gas. A detailed list of country-specific energy prices is included in Appendix B. All costs and benefits are expressed in constant 2000 USD. The conversion of EU costs, which were initially expressed in 1990 Euros (in the EC report), is conducted using appropriate inflation and exchange rates.

4 Limitations and Uncertainties

The major objective of this analysis is to evaluate the international potential and costs of methane and nitrous oxide abatement. While its results cover major emitting regions and most of emission sources and abatement options, there are a few limitations that are briefly discussed below.

4.1.1 Omission of Abatement Options for Enteric Fermentation and Rice Production for Methane and Soils for Nitrous Oxide.

Combined, rice production and enteric fermentation are responsible for about 115,900 Gg of anthropogenic methane in 2000 compared to approximately 122,000 Gg of methane due to coal, natural gas, oil, manure management and solid waste management combined (USEPA, 2002). In such regions as China, India, and Brazil, enteric fermentation and rice generate up to 70 percent of all methane emissions (USEPA, 2002). In 2000, nitrous oxide emissions from agricultural soils account for approximately 75% of total anthropogenic nitrous oxide emissions worldwide. (USEPA, 2002). This analysis does not include these sources due to limited amount of quantitative data on corresponding abatement options and their applicability in different environments. Research is currently underway to address these sources.

4.1.2 Static Approach to Abatement Assessment

The analysis does not account for the technological change in such option characteristics as availability, reduction efficiency, applicability, and costs. For example, the same sets of options are applied in 2010 and 2020 and an option's parameters are not changed over its lifetime. This current limitation likely underestimates abatement potential – especially in later years - because technologies generally improve over time and costs fall. The introduction of a dynamic approach to assessing regional abatement potentials requires additional assumptions about rates of technological progress and better baseline projections, that, once incorporated into this analysis, will yield better a representation of how MACs change over space and time.

4.1.3 Limited Use of Regional Data

The analytical framework used in this study is flexible enough to incorporate regional differences in all the characteristics of abatement options. However, limited country-specific data led to a reliance on expert judgement, which was obtained from source-level technical experts in government and industry with knowledge of project-level technologies, costs, and specific regional conditions. Applicability of abatement options, for example, is reliant on expert judgement, as the make-up of the current infrastructure in a given country in a given sector is uncertain. A much greater use of data originating from local experts and organizations is recommended for the follow-up research of methane and nitrous oxide abatement in countries outside the US and EU.

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