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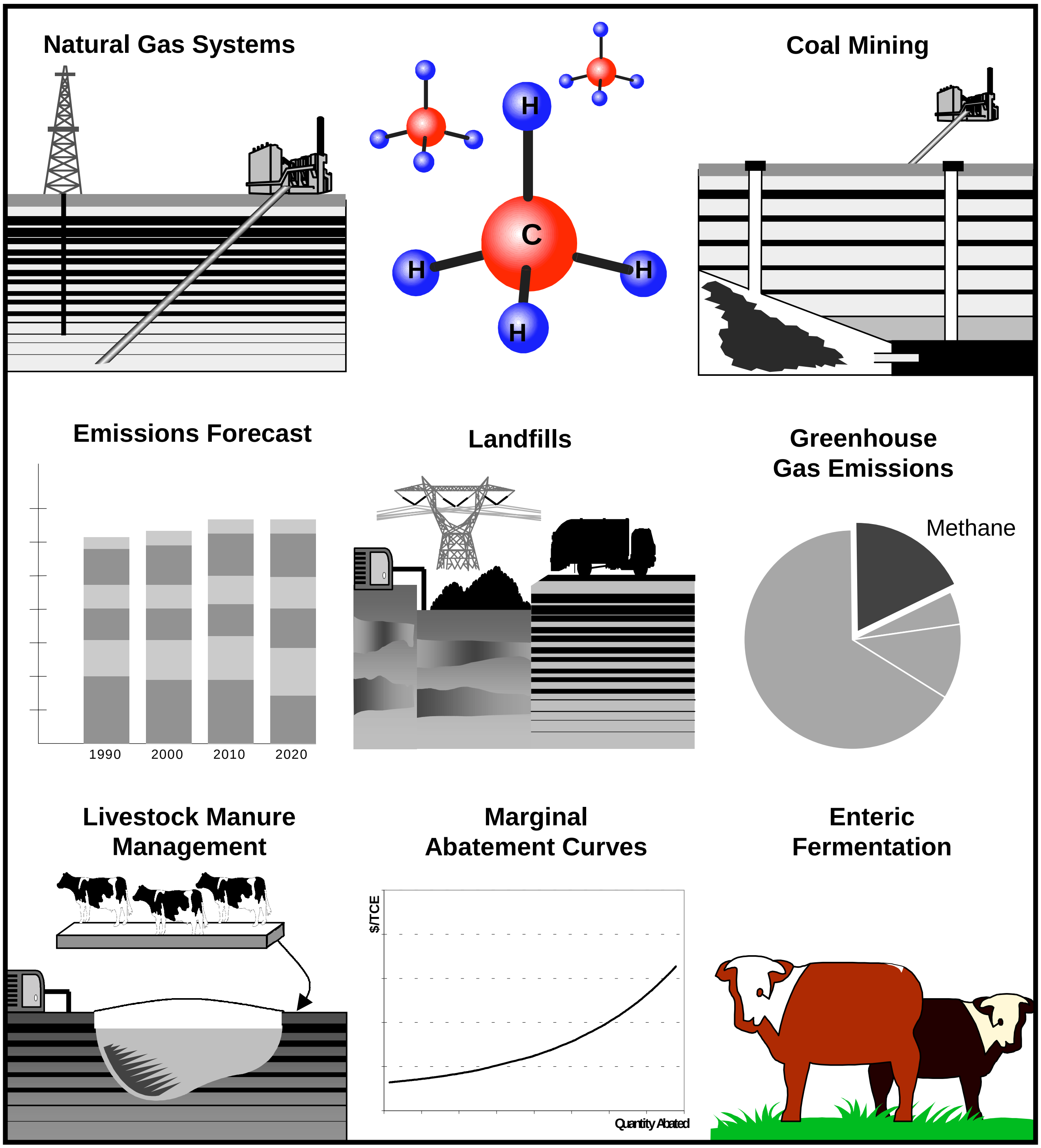
U.S. Methane Emissions 1990 – 2020: Inventories, Projections, and Opportunities for Reductions



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For Further Information

The results presented in this report are available to analysts in an electronic format. For additional information, contact Mr. Francisco de la Chesnaye, Office of Air and Radiation, Office of Atmospheric Programs, Climate Protection Division, Methane Energy Branch, Tel +1(202) 564 – 0172, Fax +1(202) 565 – 2077, or e-mail delachesnaye.francisco@epa.gov.

U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions

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U.S. Environmental Protection Agency
Office of Air and Radiation
401 M St., SW
Washington, DC 20460
U.S.A.

Abbreviations, Acronyms, and Units

AF	Activity factor
ASAE	American Society of Agricultural Engineers
Bcf	Billion cubic feet
BMP	Best management practice
CAA	Clean Air Act
CCAP	Climate Change Action Plan
C&D	Construction and demolition
CFC	Chlorofluorocarbon
CH_4	Methane
CMOP	Coalbed Methane Outreach Program
CO_2	Carbon dioxide
DI&M	Directed inspection and maintenance
DOE	Department of Energy
EF	Emission factor
EIA	Energy Information Administration
EPA	Environmental Protection Agency
E-PLUS	Energy Project Landfill Gas Utilization Software
GAA	Government Advisory Associates
GHG	Greenhouse gas
GSAM	Gas Systems Analysis Model
GWP	Global warming potential
IC	Internal combustion
IPCC	Intergovernmental Panel on Climate Change
kW	kilowatt
kWh	kilowatt-hour
LMOP	Landfill Methane Outreach Program
MAC	Marginal abatement curve
Mcf	Thousand cubic feet
MMBtu	Million British thermal units
MMcf/d	Million cubic feet per day
MMTCE	Million (metric) tons of carbon equivalent
MMT	Million (metric) tons
MSHA	Mine Safety and Health Administration
MSW	Municipal solid waste
MW	Megawatt
NMOC	Non-methane organic compound
NPV	Net present value
O&M	Operation and maintenance
PRO	Partner-reported opportunity
RLEP	Ruminant Livestock Efficiency Program
Tcf	Trillion cubic feet
Tg	Teragram
TCE	Metric ton of carbon equivalent
UNFCCC	United Nations Framework Convention on Climate Change
USDA	United States Department of Agriculture
VOC	Volatile organic compound
WIP	Waste-in-place

Conversions

1 Mcf Methane = 1 MMBtu
1 Bcf = 1,000 MMcf
1 Tg = 1×10^{12} g
1 Tg CH_4 = 1 MMT CH_4
1 MMT CH_4 = 5.73 MMTCE
GWP of CO_2 = 1
GWP of CH_4 = 21

Acknowledgements

This report was produced by the U.S. EPA's Methane Energy Branch in the Office of Air and Radiation, Office of Atmospheric Programs, Climate Protection Division. The report would not have been complete without the efforts and contributions of many individuals and organizations. The following individuals reviewed a preliminary version of this report and provided useful comments, many of which were addressed for this final version. The reviewers included: Peter Carothers (Alternative Energy Development), Tom Conrad (SCS Engineers), Kimberly Denbow (American Gas Association), Lorna Greening (Hagler Bailly Services, Inc.), Matthew R. Harrison (Radian International), William Jewell (Cornell University), Barry L. Kintzer (USDA), Eugene Lee (USEPA), Bob Lott (Gas Research Institute), Richard Mattocks (Environomics), John Reilly (Massachusetts Institute of Technology), Glenda E. Smith (American Petroleum Institute), Pramod C. Thakur (Consol Inc.), Lori Traweek (American Gas Association), Greg Vogt (SCS Engineers), Ann C. Wilkie (University of Florida), and Peter Wright (Cornell University). Although these individuals participated in the review of this analysis, their efforts do not necessarily constitute an endorsement of the report's results or of any U.S. EPA policies and programs.

In particular, the Methane Energy Branch staff contributed significantly to the report. They are: Ed Coe, Shelley Cohen, and Brian Guzzone on Landfills; Paul Gunning and Carolyn Henderson on Natural Gas Systems; Karl Schultz and Roger Fernandez on Coal Mining; Kurt Roos on Livestock Manure; Mark Orlic and Tom Wirth on Enteric Fermentation; Bill Irving on Inventories; and Michele Dastin-van Rijn on the preliminary version of the report. Francisco de la Chesnaye directed the final analysis and completion of the report with support from Reid Harvey and oversight from Dina Kruger.

The staff of the Global Environmental Issues Group at ICF Consulting deserves special recognition for its expertise, efforts in preparing many of the individual analyses, and for synthesizing this report.

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Executive Summary

Methane gas is a valuable energy resource and the leading anthropogenic contributor to global warming after carbon dioxide. Atmospheric methane concentrations have doubled over the last 200 years and continue to rise, although the rate of increase is slowing (Dlugokencky, et al., 1998). By mass, methane has 21 times the global warming potential of carbon dioxide over a 100-year time frame. Methane accounts for 10 percent of U.S. greenhouse gas emissions (excluding sinks) and reducing these emissions is a key goal of the U.S. Climate Change Action Plan (EPA, 1999).

The major sources of anthropogenic methane emissions in the U.S. are landfills, agriculture (livestock enteric fermentation and manure management), natural gas and oil systems, and coal mines. Smaller sources in the U.S. include rice cultivation, wastewater treatment, and others. Unlike other greenhouse gases, methane can be used to produce energy since it is the major component (95 percent) of natural gas. Consequently, for many methane sources, opportunities exist to reduce emissions cost-effectively or at low cost by capturing the methane and using it as fuel.

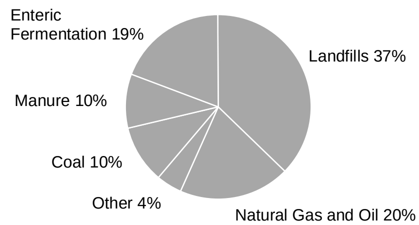
This report has two objectives. First, it presents the U.S. Environmental Protection Agency's (EPA's) baseline forecast of methane emissions from the major anthropogenic sources in the U.S., and EPA's cost estimates of reducing these emissions. Emission estimates are given for 1990 through 1997 with projections for 2000 to 2020. The cost analysis is for 2000, 2010, and 2020. Second, this report provides a transparent methodology for the calculation of emission estimates and reduction costs, thereby enabling analysts to replicate these results or use the approaches described herein to conduct similar analyses for other countries.

Baseline Methane Emission Estimates

EPA estimates annual emissions for 1990 to 1997 and forecasts emissions for 2000, 2010, and 2020. In 1990, the U.S. emitted 169.9 million metric tons of carbon equivalent (MMTCE) or 29.7 Teragrams (Tg) of methane. By 1997, estimated methane emissions were slightly higher at 179.6 MMTCE (31.4 Tg) (EPA, 1999). The baseline U.S. methane emission forecast for 2010 is 186.0 MMTCE (32.5 Tg) which is almost a ten percent increase over the 1990 levels. However, this forecast excludes the expected reductions associated with U.S. voluntary programs. When these programs are taken into account, methane emissions are expected to remain at or below 1990 levels through 2020. Exhibit ES-1 shows current methane emissions and projections by industry.

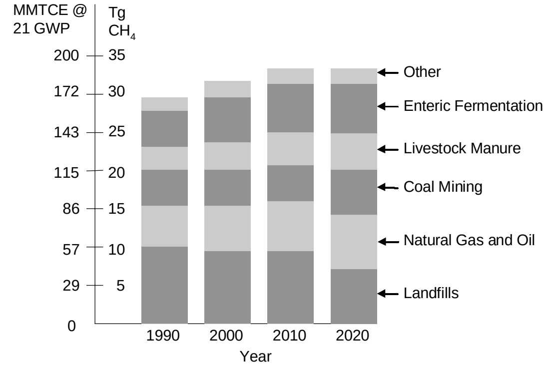
Exhibit ES-1: U.S. Methane Emissions (MMTCE)

Source Breakdown of 1997 U.S. Methane Emissions



Total = 179.6 MMTCE
Source: EPA, 1999.

Source Breakdown of Baseline Forecast Emissions



To estimate historic and future emissions, EPA characterizes the source industries in detail and identifies the specific processes within those industries that produce emissions. Forecasts are based on a consistent set of industry factors, e.g., consumption, prices, technological change, and infrastructure makeup. The major emission sources are outlined below.

- **Landfills.** The largest source (accounting for 37 percent) of U.S. anthropogenic methane emissions, landfills generate methane during anaerobic decomposition of organic waste. In 1990, landfills generated 56.2 MMTCE (9.8 Tg) of methane, which increased to 66.7 MMTCE (11.6 Tg) by 1997 (EPA, 1999). Baseline emissions are expected to decrease to 52.0 MMTCE (9.1 Tg) in 2010, due to the Clean Air Act New Source Performance Standards and Emissions Guidelines (Landfill Rule). The Landfill Rule requires the nation's largest landfills to reduce emissions of non-methane organic compounds and results in a simultaneous reduction in methane emissions. The principal technologies for reducing emissions from landfills involve collecting methane and using it as fuel for electric power generation or for sale to nearby industrial users.

- **Natural Gas Systems.** Emissions of methane occur throughout the natural gas system from leaks and venting of gas during normal operations, maintenance, and system upsets. In 1990, methane emissions from the U.S. natural gas system totaled about 32.9 MMTCE (5.7 Tg), and by 1997 methane emissions were estimated at 33.5 MMTCE (5.8 Tg) (EPA, 1999). EPA expects emissions to increase as natural gas consumption increases, although at a lower rate than gas consumption growth. Baseline emissions reach 37.9 MMTCE (6.6 Tg) in 2010. Improved management practices and technologies can reduce leaks or avoid venting of methane from all parts of the natural gas system.

- **Coal Mining.** Methane and coal are formed together by geological forces during coalification. As coal is mined, the methane is released. Because methane is hazardous to miners, underground mines use ventilation systems to dilute it and additional techniques to recover it during or in advance of mining. In 1990, coal mine methane emissions were estimated at 24.0 MMTCE (4.2 Tg). By 1997, emissions fell to 18.8 MMTCE (3.3 Tg) mainly due to reduced coal production at "gassy" mines and increased methane recovery (EPA, 1999). Baseline methane emissions reach 28.0 MMTCE (4.9 Tg) by 2010 due to growth in coal mining from deep mines. The major technologies for reducing emissions include recovery and sale to pipelines, use for power generation, or on-site use. Catalytic oxidation of methane in ventilation air may also be undertaken to reduce emissions.

- **Livestock Manure Management.** Methane is produced during the anaerobic decomposition of livestock manure. The major sources of U.S. livestock manure methane include large dairy and cattle operations and hog farms that use liquid manure management systems. In 1990, livestock manure emitted about 14.9 MMTCE (2.6 Tg) of methane. Emissions from this source increased to 17.0 MMTCE (3.0 Tg) by 1997 (EPA, 1999). Baseline emissions reach 22.3 MMTCE (3.9 Tg) in 2010 due to animal population growth driven by increases in total meat and dairy product consumption and increasing use of liquid waste management systems that produce methane. Existing cost-effective technologies can be used to recover this methane to produce energy.

- **Enteric Fermentation.** Methane emissions from livestock enteric fermentation were 32.7 MMTCE (5.7 Tg) in 1990 and 34.1 MMTCE (6.0 Tg) in 1997 (EPA, 1999). Baseline methane emissions reach 37.7 MMTCE (6.6 Tg) by 2020 due to increased domestic and international demand for U.S. livestock products. Emissions can be reduced through the application of improved management practices. The cost-effectiveness of these practices has not been quantified as part of this analysis, however.

Costs of Reducing Emissions

This report presents the results of extensive benefit-cost analyses conducted on the opportunities (technologies and management practices) to reduce methane emissions from four of the five major U.S. sources: landfills, natural gas systems, coal mining, and livestock manure. To date, most economic analyses of U.S. greenhouse gas (GHG) emission reductions have focused on energy-related carbon emissions since carbon dioxide (CO_2) currently accounts for about 82 percent of the total U.S. GHG emissions (weighted by 100-year global warming potentials) (EPA, 1999). The cost estimates for reducing methane emissions presented in this report can be integrated into economic analyses to produce more comprehensive assessments of total GHG reductions. By including methane emission reductions, the overall cost of reducing GHG emissions in the U.S. is reduced. At increasing values for emission reductions, in terms of dollars per metric ton of carbon equivalent ($/TCE), more costly CO_2 reductions can be substituted by lower cost methane reductions, when available, thereby lowering the marginal cost and the total cost of a particular GHG emission reduction level.

The cost analysis is conducted for the years 2000, 2010, and 2020. All values are in 1996 constant dollars. Results for the source-specific analyses are summarized below.

- **Landfills.** The cost analysis focuses on technologies for recovering and using landfill methane for energy. Two options are evaluated: use of landfill methane for electricity generation and as a fuel for direct use by a nearby end-user. After accounting for emission reductions due to the Landfill Rule, at $0/TCE, about 21 percent of baseline emissions from landfills could be captured and used cost-effectively in 2000. Cost-effective reductions decrease slightly to 20 percent, at $0/TCE, in 2010, in part reflecting greater coverage of total emissions by the Landfill Rule. At $30/TCE, emissions could be reduced by 38 percent from the baseline in 2000, and by 41 percent in 2010. Emission reductions approach their maximum at $100/TCE in 2000, and $40/TCE in 2010. EPA projects the incremental benefits of higher values for carbon equivalent to be slightly smaller in 2020 due to the Landfill Rule.
- **Natural Gas Systems.** Cost curves for reducing methane emissions from natural gas systems are based on technologies and practices for reducing leaks and venting of natural gas in the natural gas system. EPA evaluates 118 technologies and practices that have been identified by the gas industry in conjunction with EPA's Natural Gas STAR Program. EPA's analysis assesses the cost-effectiveness of each technology and practice based on the value of methane as natural gas. In 2000, 2010, and 2020, about 30 percent of the projected emissions from natural gas systems can be avoided cost-effectively, based on the value of the saved methane. When a value of $30/TCE for avoided emissions is added to the market price for gas, about 35 percent of the emissions can be reduced. At $100/TCE, about 49 percent of emissions can be reduced. Additional technologies could likely emerge in this sector to reduce emissions at high values for carbon equivalent, however, EPA only examines current technologies in this analysis.
- **Coal Mining.** EPA's analysis for reducing coal mine methane emissions focuses on recovering methane from underground mining, which comprises 65 percent of the emissions from this source. Two emission reduction strategies are analyzed: recovering methane from mines for sale as natural gas and using new catalytic oxidation technologies. The results suggest that in 2010, 37 percent of emissions from coal mines can be cost-effectively reduced at energy market prices, or $0/TCE. Up to 71 percent of emissions can be reduced at $30/TCE, which represents essentially all of the technically recoverable methane from this source. In 2020, the same pattern exists with 41 percent recoverable at $0/TCE and 71 percent recoverable at $30/TCE.
- **Livestock Manure Management.** Cost curves for reducing methane emissions from livestock manure are based on recovering and utilizing

methane produced at dairies and swine farms. EPA's analysis focuses on anaerobic digestion technologies (including covered and complete mix digesters) that capture methane for use on-site to generate electricity. At current energy prices, emissions from livestock manure could be reduced by 14 percent in 2000 and 2010. Emission reductions increase slightly to 15 percent in 2020. With an additional $30/TCE, emission reductions reach 30 percent in 2000, 31 percent in 2010, and 32 percent in 2020. At $100/TCE, emissions can be reduced by about 63 percent in 2000, 65 percent in 2010, and 67 percent in 2020.

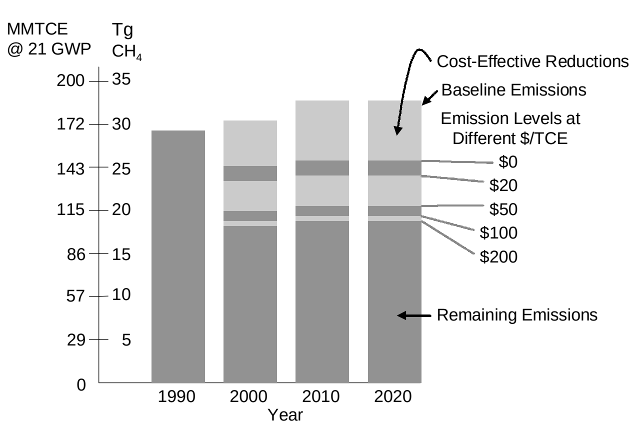
- **Enteric Fermentation**. Emissions from livestock enteric fermentation can be reduced through enhanced feeding and animal management techniques. The costs and cost-effectiveness of these reductions have not been quantified for this report.

The aggregate results of the analysis are presented in two ways. Exhibit ES-2 summarizes potential reductions across all sources at various carbon equivalent values. These reductions are the summation of source-specific results where different discount rates are applied to each source: 8 percent for landfills, 20 percent for natural gas systems, 15 percent for coal mining, and 10 percent for livestock manure management. For 2010, EPA estimates that up to 34.8 MMTCE (6.1 Tg) of reductions are possible at energy market prices or $0/TCE. Consequently, methane emissions could be reduced below 1990 emissions of 169.9 MMTCE (29.7 Tg) if many of the identified opportunities are thoroughly implemented. At higher emission reduction values, more methane reductions could be achieved. For example, EPA's analysis indicates that with a value of $20/TCE for abated methane added to the energy market price, U.S. reductions could reach 50.3 MMTCE (8.8 Tg) in 2010.

EPA also constructs marginal abatement curves (MACs) for each of the four sources along with an aggregate curve for 2010 which is shown in Exhibit ES-3. In order to properly construct the MAC for 2010, a discount rate of eight percent is equally applied to all sources.[1] MACs are derived by rank-ordering individual opportunities by cost per emission reduction amount. Methane values and marginal costs are denominated in both energy values (natural gas and electricity prices) and emission reduction values in terms of $/TCE. On the MACs, energy market prices are aligned to $0/TCE, where no additional price signals from emission reduction values exist to motivate reductions. At and below $0/TCE, all emission reductions are due to increased efficiencies, conservation of methane, or both. As a value is placed on methane emission reductions in terms of $/TCE, these values are added to the energy market prices and allow for additional reductions to clear the market. Any "below-the-line" reduction amounts, with respect to $0/TCE, illustrate this dual price-signal market, i.e., energy prices and emission reduction values.

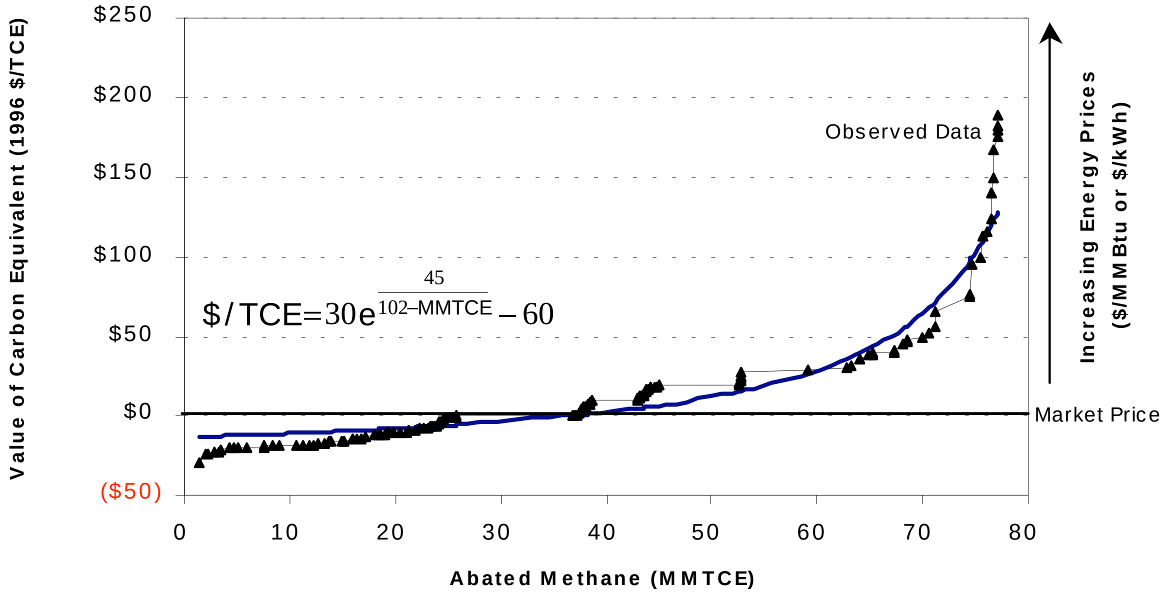
The aggregate U.S. MAC for 2010 in Exhibit ES-3 illustrates the following key findings. First, substantial emission reductions, 36.8 MMTCE (6.4 Tg), can be achieved at energy market prices with no additional emission reduction values ($0/TCE). Second, at

Exhibit ES-2: U.S. Baseline Emissions and Potential Reductions (source-specific discount rates) (MMTCE)



	2000	2010	2020
Baseline Emissions	173.9	186.0	183.7
Cumulative Reductions			
at $0/TCE	30.8	34.8	35.0
at $10/TCE	36.4	42.3	40.9
at $20/TCE	41.7	50.3	47.4
at $30/TCE	54.6	61.7	58.7
at $40/TCE	56.2	63.5	61.0
at $50/TCE	59.5	66.9	64.8
at $75/TCE	64.3	71.9	70.7
at $100/TCE	67.2	74.9	74.0
at $125/TCE	68.4	76.2	75.5
at $150/TCE	68.7	76.5	75.9
at $175/TCE	69.0	76.8	76.2
at $200/TCE	69.2	77.0	76.5
Remaining Emissions	104.7	108.9	107.2

Exhibit ES-3: Marginal Abatement Curve for U.S. Methane Emissions in 2010 (at an 8 percent discount rate)



$20/TCE and $50/TCE total estimated reductions are 52.6 MMTCE (9.2 Tg) and 70.0 MMTCE (12.2 Tg), respectively. Third, at $100/TCE, total achievable reductions are estimated at 75.5 MMTCE (13.2 Tg). Finally, above $100/TCE, the MAC becomes inelastic, that is, non-responsive to increasing methane values. This inelasticity indicates the limits of the options considered. The magnitude of the cost-effective and low-cost reductions reflects methane's value as an energy source and emphasizes that many proven technologies can be used to recover it. For several sources, the inelastic section of the curve at the higher end of the cost range indicates a limitation of the analysis, namely that only available technologies are assessed. Additional technologies may become available to reduce methane emissions at these prices; however, EPA has not yet assessed this possibility.

EPA has developed a number of voluntary programs as part of the Climate Change Action Plan (CCAP) to overcome market barriers and encourage cost-effective methane recovery projects. In this report, the emission reductions associated with these CCAP programs have not been subtracted from the baseline emission projections. However, EPA expects that approximately 50 percent of the reductions available in 2010 at $0/TCE will be captured by these programs. These programs have reduced emissions by 8 MMTCE in 1998 and are expected to reduce emissions by 12 MMTCE in 2000, and 20 MMTCE in 2010.

References

Dlugokencky, E.J., K.A. Masarie, P.M. Lang, and P.P. Tans. 1998. "Continuing Decline in the Growth Rate of the Atmospheric Methane Burden," *Nature*, v. 393, 4 June 1998.

EPA. 1999. *Inventory of Greenhouse Gas Emissions and Sinks 1990-1997*. Office of Policy, Planning, and Evaluation, U.S. Environmental Protection Agency, Washington, DC. (Available on the Internet at http://www.epa.gov/globalwarming/inventory/index.html.)

Endnotes

[1] In the construction of a national or aggregate marginal abatement curve, a single discount rate is applied to all sources in order to equally evaluate various options. Given a particular value for abated methane, all options up to and including that value can be cost-effectively implemented. An eight percent discount rate, the lowest in the range of the source-specific rates (8 to 20 percent), is used since it is closer to social discount rates employed in national level analyses. The results from the single, eight percent discount rate analysis are slightly higher than the results where source-specific discount rates are used because a lower discount rate reduces project costs enabling additional reductions.

1. Introduction and Aggregate Results

Introduction

This report has two objectives. First, it presents the U.S. Environmental Protection Agency's (EPA's) baseline forecast of methane emissions from the major anthropogenic sources in the U.S., and EPA's cost estimates of reducing these emissions. Emission estimates are given for 1990 through 1997 with projections for 2000 to 2020. The cost analysis is for 2000, 2010, and 2020. Second, this report provides a transparent methodology for the calculation of emission estimates and reduction costs, thereby enabling analysts to replicate these results or use the approaches described herein to conduct similar analyses for other countries.

The information presented in this report can be used in several ways. The emission estimates and forecasts represent the most up-to-date estimates of methane emissions in the U.S.; thus, this report replaces and expands upon EPA's *Anthropogenic Methane Emissions in the United States, Estimates for 1990, Report to Congress* (1993a). As such, this report can be used where estimates of future emissions are required. The report also summarizes the state of knowledge on methane emissions from the major anthropogenic sources.

While the emission estimations are refinements of earlier approaches, the cost analyses presented in this report represent a major contribution to the literature on mitigating emissions. To date, most economic analyses of greenhouse gas (GHG) emission reductions have focused on the energy-related carbon emissions since carbon dioxide (CO_2) currently accounts for about 82 percent of the total U.S. emissions (weighted by 100-year global warming potentials) (EPA, 1999). The cost-estimates for reducing methane emissions presented in this report can be integrated into economic analyses to produce more comprehensive assessments of total GHG reductions. By including methane emission reductions, the overall cost of reducing GHG emissions in the U.S. is reduced. At increasing values for emission reductions, more costly CO_2 reductions can be substituted by lower cost methane reductions, when available, thereby lowering the marginal cost and the total cost of a particular GHG emission reduction level.

The marginal abatement curves (MACs) developed in this report can be used to estimate possible emission reductions at various prices for carbon equivalent emissions or conversely, the costs of achieving certain amounts of reductions. EPA recognizes that the cost analyses will change with the introduction of new technologies and additional research into methane emission abatement technologies. Other countries, nevertheless, can use the cost analyses presented in this report as the basis for estimating emission reduction costs.

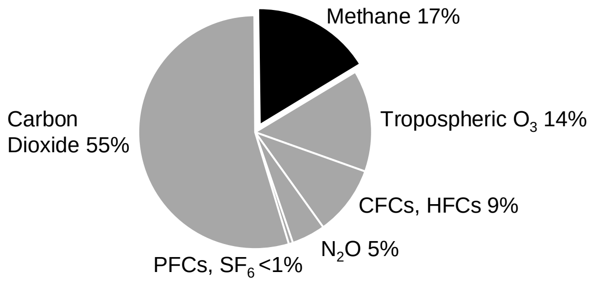
1.0 Overview of Methane Emissions

Next to carbon dioxide, methane is the second largest contributor to global warming among anthropogenic greenhouse gases. Methane's overall contribution to global warming is significant because, over a 100-year time frame, it is estimated to be 21 times more effective at trapping heat in the atmosphere than carbon dioxide. As illustrated in Exhibit 1-1, methane accounts for 17 percent of the enhanced greenhouse effect (IPCC, 1996a).[1]

Over the last two centuries, methane's concentration in the atmosphere has more than doubled from about 700 parts per billion by volume (ppbv) in pre-industrial times to 1,730 ppbv in 1997 (IPCC, 1996a). Exhibit 1-1 illustrates this trend. Scientists believe these atmospheric increases are largely due to increasing

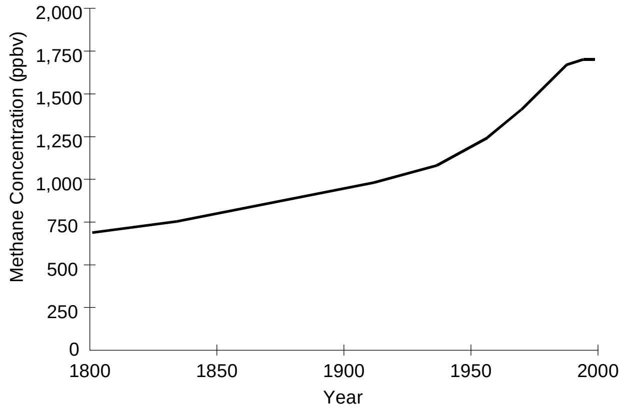
Exhibit 1-1: Global Enhanced Greenhouse Effect and Methane Concentrations

Contribution of Anthropogenic Gases to Enhanced Greenhouse Effect Since Pre-Industrial Times (measured in Watts/m^2)



Total = 2.85 Watts/m^2
Source: IPCC, 1996a.

Historical Global Atmospheric Methane Concentrations



Source: Boden, et al., 1994; Dlugokencky, et al., 1998.

emissions from anthropogenic sources. Although atmospheric methane concentrations continue to rise, the rate of increase appears to have slowed since the 1980s. If present trends continue, however, atmospheric methane concentrations will reach 1,800 ppbv by 2020 (Dlugokencky, et al., 1998).

Atmospheric methane is reduced naturally by sinks. Natural sinks are removal mechanisms and the greatest sink for atmospheric methane (CH_4) is through a reaction with naturally-occurring tropospheric hydroxyl (OH).[2] Methane combines with OH to form water vapor (H_2O) and carbon monoxide (CO), which in turn is converted into carbon dioxide (CO_2). Atmospheric methane, nevertheless, has a clearly defined chemical feedback that decreases the effectiveness of the hydroxyl sink. As methane concentrations rise, less hydroxyl is available to break down methane, producing longer atmospheric methane lifetimes and higher methane concentrations (IPCC, 1996a).

On average, the atmospheric lifetime for a methane molecule is 12.2 years (± 3 years) before a natural sink consumes it (IPCC, 1996a). This relatively short lifetime makes methane an excellent candidate for mitigating the impacts of global warming because emission reductions could lead to stabilization or reduction in methane concentrations within 10 to 20 years.

2.0 Sources of Methane Emissions

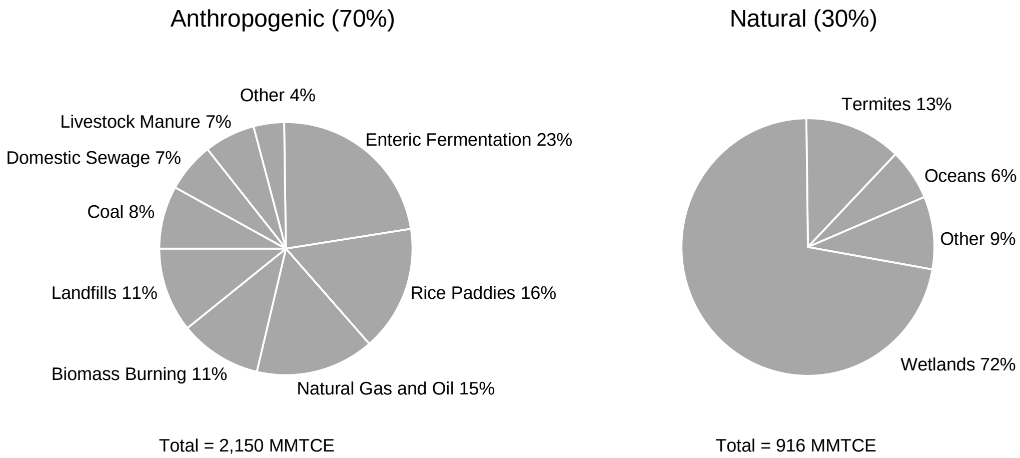
Methane is emitted into the atmosphere from both natural and anthropogenic sources. Natural sources include wetlands, tundra, bogs, swamps, termites, wildfires, methane hydrates, and oceans and freshwaters. Anthropogenic sources include landfills, natural gas and oil production and processing, coal mining, agriculture (livestock enteric fermentation and livestock manure management, and rice cultivation), and various other sources. By 1990, anthropogenic sources accounted for 70 percent of total global methane emissions (EPA, 1993a; IPCC, 1996a). This section summarizes the natural and anthropogenic sources of methane.

2.1 Natural Methane Emissions

In 1990, worldwide natural sources emitted 916 million metric tons of carbon equivalent (MMTCE) or 160 Teragrams (Tg) of methane into the atmosphere, or about 30 percent of the total methane emissions (IPCC, 1996a). The leading natural methane sources are described below in descending order of their contribution to emissions (see Exhibit 1-2).

Wetlands. Methane is generated by anaerobic (oxygen poor) bacterial decomposition of plant material in wetlands. Natural wetlands emit about 659 MMTCE

Exhibit 1-2: Worldwide Natural and Anthropogenic Methane Emissions in 1990



World Total = 3,066 MMTCE

Source: IPCC, 1995 and 1996a.

(115 Tg) of methane per year, which is 72 percent of natural emissions and 20 percent of total global methane emissions (IPCC, 1995). Methane emissions from wetlands will probably increase with global warming as a result of accelerated anaerobic microbial activity. In addition, climate change models predict increased precipitation as global temperatures rise, which could create more wetlands (EPA, 1993b). Tropical wetlands (between 20° N and 30° S) represent 17 percent of total wetland area and 60 percent of emissions from wetlands. These relatively high emissions are due to higher temperatures, more precipitation and more intense solar radiation, which encourage higher plant growth and decomposition rates (EPA, 1993b).

Northern Wetlands (those above 45° N) are usually underlain with near-surface permafrost that prevents soil drainage and creates wetland conditions. Northern wetlands represent nearly 80 percent of the wetland area and 35 percent of methane emissions from wetlands (EPA, 1993b).

Termites. Microbes within the digestive systems of termites break down cellulose, and this process produces methane. Emissions from this source depend on termite population, amounts of organic material consumed, species, and the activity of methane-oxidizing bacteria. While more research is needed, some experts believe that future trends in termite emissions are more influenced by anthropogenic changes in land use, i.e., deforestation for agriculture, than by climate change. Termites emit an estimated 115 MMTCE (20 Tg) of methane each year (IPCC, 1995).

Oceans and Freshwaters. The surface waters of the world's oceans and freshwaters are slightly supersaturated with methane relative to the atmosphere and therefore emit an estimated 57 MMTCE (10 Tg) of methane each year (IPCC, 1995). The origin of the dissolved methane is not known. In coastal regions it may come from sediments and drainage. It also has been suggested that methane is generated in the anaerobic gastrointestinal tracts of marine zooplankton and fish (EPA, 1993b). Methane in freshwaters can result from the decomposition of wetland plants. (In this report, methane emissions from freshwaters are included in the estimates for wetlands.) As atmospheric methane concentrations increase, the proportion of methane supersaturated in oceans and freshwaters will decline relative to the atmospheric concentrations of methane, assuming that the methane concentration in oceans and freshwaters remains constant.

Gas Hydrates. Methane is trapped in gas hydrates, which are dense combinations of methane and ice located deep underground and beneath the ocean floor. Recent estimates of hydrates suggest that around 44 billion MMTCE (7.7 billion Tg) of methane is trapped in both oceanic and continental gas hydrates (DOE, 1998). Scientists agree that increasing temperatures will eventually destabilize many gas hydrates, but are unsure about the timing and the amount of methane emissions that would be released from the deeply buried hydrates (EPA, 1993b).

Permafrost. Small amounts of methane are trapped in permafrost, which consists of permanently frozen soil and ice. (To be classified as permafrost, the ice and soil mixture must remain at or below 0° Celsius year-round for at least two consecutive years.) Due to the large amount of existing permafrost, the total amount of methane stored in this form could be quite high, possibly several thousand Tg (EPA, 1993b). This methane is released when permafrost melts. However, no estimates have been made for current emissions from this source.

Wildfires. Wildfires are primarily caused by lightning and release a number of greenhouse gases, including methane which is a product of incomplete combustion. However, no estimates are available for methane emissions from this source.

2.2 Anthropogenic Methane Emissions

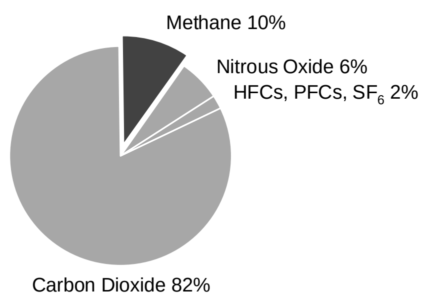
Methane emissions from anthropogenic sources account for 70 percent of all methane emissions and totaled 2,150 MMTCE (375 Tg) worldwide in 1990 (IPCC, 1996a). The leading global anthropogenic methane sources are described below in descending order of magnitude. The two leading sources of anthropogenic methane emissions worldwide are livestock enteric fermentation and rice production. By contrast, in the U.S., the two leading sources of methane emissions are landfills and natural gas and oil systems (see Exhibit 1-3). In 1997, the U.S. emitted 179.6 MMTCE (31.4 Tg) of methane, about 10 percent of global methane emissions for that year (EPA, 1999). The U.S. is the fourth-largest methane emitter after China, Russia, and India (EPA, 1994).

Enteric Fermentation. Ruminant livestock emit methane as part of their normal digestive process, during which microbes break down plant material consumed by the animal into material the animal can use. Methane is produced as a by-product of this digestive process, and is expelled by the animal. In the U.S., cattle emit about 96 percent of the methane from livestock enteric fermentation. In 1994, livestock enteric fermentation produced 490 MMTCE (85 Tg) of methane worldwide (IPCC, 1995), with the emissions coming from the former Soviet Union, Brazil, and India (EPA, 1994). EPA estimates that U.S. emissions from this source were 34.1 MMTCE (6.0 Tg) in 1997 (EPA, 1999). Under EPA's baseline forecast, livestock enteric fermentation emissions in the U.S. will increase to about 37.7 MMTCE (6.6 Tg) by 2020 (Exhibit 1-4). The projected increase is due to greater consumption of meat and dairy products.

Rice Paddies. Most of the world's rice, including rice in the United States, is grown on flooded fields where organic matter in the soil decomposes under anaerobic conditions and produces methane. The U.S. is not a

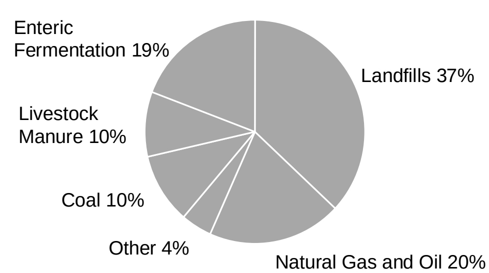
Exhibit 1-3: U.S. Methane Emissions

U.S. Greenhouse Gas Emissions in 1997
Weighted by Global Warming Potential



Total = 1,814 MMTCE
Source: EPA, 1999.

Source Breakdown of 1997 U.S. Methane Emissions



Total = 179.6 MMTCE
Source: EPA, 1999.

Exhibit 1-4: Baseline Methane Emissions in the United States (MMTCE)

Source	1990[a]	1997[a]	2000	2010	2020
Landfills	56.2	66.7	51.4	52.0	41.1
Natural Gas Systems	32.9	33.5	35.6	37.9	38.8
Oil Systems	1.6	1.6	1.6	1.6	1.7
Coal Mining	24.0	18.8	23.9	28.0	30.4
Livestock Manure Management	14.9	17.0	18.4	22.3	26.4
Enteric Fermentation	32.7	34.1	35.2	36.6	37.7
Other[b]	7.3	7.4	7.8	7.6	7.6
Total	**169.9**	**179.6**	**173.9**	**186.0**	**183.7**

[a] Source: EPA, 1999.

[b] These estimates developed by EPA for the 1997 *Climate Action Report* (DOS, 1997).

Totals may not sum due to independent rounding.

major producer of rice and therefore emits little methane from this source. Worldwide emissions of methane from rice paddies were 345 MMTCE (60 Tg) in 1994 (IPCC, 1995), with the highest emissions coming from China, India, and Indonesia (EPA, 1994). EPA estimates U.S. emissions from this source at 2.7 MMTCE (0.5 Tg) in 1997 and expects emissions to remain stable in the future (EPA, 1999).

Natural Gas and Oil Systems. Methane is the major component (95 percent) of natural gas. During production, processing, transmission, and distribution of natural gas, methane is emitted from system leaks, deliberate venting, and system upsets (accidents). Since natural gas is often found in conjunction with petroleum, crude petroleum gathering and storage systems are also a source of methane emissions. In 1994, natural gas systems worldwide emitted 230 MMTCE (40 Tg) of methane and oil systems emitted 85 MMTCE (15 Tg) of methane (IPCC, 1995). EPA estimates that 1997 U.S. emissions were 33.5 MMTCE (5.8 Tg) from natural gas systems and 1.6 MMTCE (0.27 Tg) from oil systems (EPA, 1999). EPA expects emissions from oil systems to remain near 1997 levels through 2020. The baseline emission forecast is 38.8 MMTCE (6.8 Tg) from natural gas systems in 2020 (Exhibit 1-4). The increase results from higher consumption of natural gas and expansions of the natural gas system.

Biomass Burning. Biomass burning releases greenhouse gases, including methane, but is not a major source of U.S. methane emissions. In 1994, biomass burning produced 230 MMTCE (40 Tg) of methane worldwide (IPCC, 1995). EPA estimates that U.S. emissions from this source were 0.2 MMTCE (0.03 Tg) in 1997 and that emissions will remain stable through 2020 (EPA, 1999).

Landfills. Landfill methane is produced when organic materials are decomposed by bacteria under anaerobic conditions. In 1994, landfills produced 230 MMTCE (40 Tg) of methane worldwide (IPCC, 1995). EPA estimates that U.S. emissions from this source were 66.7 MMTCE (11.6 Tg) in 1997 (EPA, 1999). The baseline forecast is 41.1 MMTCE (7.2 Tg) from U.S. landfills in 2020 (Exhibit 1-4). Landfill methane is the only U.S. source that is expected to decline in the baseline over the forecast period. This decline is due to the implementation of the New Source Performance Standards and Emissions Guidelines (the Landfill Rule) under the Clean Air Act (March 1996). While the Landfill Rule controls greenhouse gas emissions that form tropospheric ozone (smog), it also will lead to lower methane emissions. The Landfill Rule requires large landfills to collect and combust or use landfill gas emissions.

Coal Mining. Methane is trapped within coal seams and the surrounding rock strata and is released during coal mining. Because methane is explosive in low concentrations, underground mines install ventilation systems to vent methane directly to the atmosphere. In 1994, coal mining produced 170 MMTCE (30 Tg) of methane worldwide (IPCC, 1995). EPA estimates that U.S. emissions from this source were 18.8 MMTCE

(3.3 Tg) in 1997 (EPA, 1999). EPA's baseline estimate indicates that emissions from coal mines could reach 30.4 MMTCE (5.3 Tg) by 2020 (Exhibit 1-4). The increase results from greater coal production from deep mines.

Domestic Sewage. The decomposition of domestic sewage in anaerobic conditions produces methane. Domestic sewage is not a major source of methane emissions in the U.S., where it is collected and processed mainly in aerobic (oxygen rich) treatment plants. In 1994, domestic sewage produced 145 MMTCE (25 Tg) of methane worldwide (IPCC, 1995). EPA estimates that emissions from sewage in the U.S. were 0.9 MMTCE (0.2 Tg) in 1997 and expects emissions to increase only slightly by 2020 (EPA, 1999). This increase will be due primarily to population increases.

Livestock Manure Management. The decomposition of animal waste in anaerobic conditions produces methane. Over the last eight years, methane emissions from manure have generally followed an upward trend. This trend is driven by: (1) increased swine and poultry production; and (2) increased use of liquid manure management systems, which create the anaerobic conditions conducive to methane production. In 1994, manure management produced 145 MMTCE (25 Tg) of methane worldwide (IPCC, 1995). EPA estimates that U.S. emissions from this source were 17.0 MMTCE (3.0 Tg) in 1997 (EPA, 1999). Emissions from livestock manure in the baseline are projected to increase to 26.4 MMTCE (4.6 Tg) by 2020 (Exhibit 1-4) mainly due to increases in livestock population and milk production.

3.0 Options for Reducing Methane Emissions

One of the key elements of the U.S. Climate Change Action Plan (CCAP) is the implementation of cost-effective reductions of methane emissions through voluntary industry actions.[3] Because methane is a valuable energy resource, recovering methane that normally would be emitted into the atmosphere and using it for fuel reduces greenhouse gas emissions. The methane saved from these voluntary actions often pays for the costs of recovery and also can be cost-effective even without accounting for the broader social benefits of reducing greenhouse gases (GHG).

Beginning in the early 1990s, EPA launched five voluntary programs to promote cost-effective methane emission reductions:

- AgSTAR Program – works with livestock producers to encourage methane recovery from animal waste;
- Coalbed Methane Outreach Program (CMOP) – works with the coal and natural gas industries to collect and use methane that is released during mining;
- Landfill Methane Outreach Program (LMOP) – works with states, municipalities, utilities, and the landfill gas-to-energy industry to collect and use methane from landfills;
- Natural Gas STAR Program – works with the companies that produce, transmit, and distribute natural gas to reduce leaks and losses of methane; and
- Ruminant Livestock Efficiency Program (RLEP) – works with livestock producers to improve animal nutrition and management, thereby boosting animal productivity and cutting methane emissions.

Under these voluntary programs, industry partners voluntarily undertake cost-effective efforts to reduce methane emissions. EPA works with partners to quantify the results of their actions and account for reductions in historical methane emission estimates. One of the principal benefits of these voluntary programs is the sharing of information between government and industry and within industry on emissions, and emission reduction opportunities and associated costs. These programs have contributed significantly to EPA's understanding of the opportunities for emission reductions.

Many of these opportunities involve the recovery of methane emissions and use of the methane as fuel for electricity generation, on-site heat uses, or off-site sales of methane. These actions represent key opportunities for reducing methane emissions from landfills, coal mines, and livestock manure management. Other options may include oxidizing or burning the methane emissions. Catalytic oxidation is a new technology potentially applicable at coal mines; flaring is an option available at landfills and other sites.

The natural gas industry offers the most robust array of emission reduction options. The Natural Gas STAR Program has identified a number of best management practices for reducing leaks and avoiding venting of methane. In addition, partners in the program have employed a number of other strategies for reducing emissions. These strategies are described in the chapter on natural gas systems.

Conversely, few technology-specific reduction options have yet been identified for the ruminant livestock industry, where methane production is a natural by-product of enteric fermentation. The principal options are improving the efficiency of feedlot operations and animal feeds for ruminant livestock. Better feeds and animal management can increase yields of meat and dairy products relative to methane production.

A principal benefit of the various voluntary programs is abundant information developed on the efficacy of the emission reduction options and the costs of implementing these options. EPA uses this information to estimate the costs of reducing emissions. Partners in the various voluntary programs are already undertaking emission reduction efforts because they have been found to be cost-effective. While some of the emission reduction options are cost-effective in some settings, they are not in others, e.g., methane recovery and use may be more cost-effective at large coal mines and landfills than at small ones. In the next section the economics of decision making in the implementation of reduction options is discussed.

4.0 Economic Analysis of Reducing U.S. Methane Emissions

This report presents the results of extensive benefit-cost analyses conducted on the opportunities (technologies and management practices) to reduce methane emissions from four of the five major U.S. sources: landfills, natural gas systems, coal mining, and livestock manure. The analyses are conducted for the years 2000, 2010, and 2020. EPA selected these sources because well-characterized opportunities exist for cost-effective emission reductions. The results are in terms of abated methane (emission reductions) that can be achieved at various values of methane. The total value of methane is the sum of its value as a source of energy and as an emission reduction of a GHG.

Methane has a value as a source of energy since it is the principal component of natural gas. Therefore, avoided methane emissions in natural gas systems are valued in terms of dollars per million British thermal units ($/MMBtu). Similarly, methane also can be combusted to generate electricity and is valued in dollars per kilowatt-hour ($/kWh). The value of potential methane emission reductions is calculated relative to carbon equivalent units using methane's 100-year global warming potential (GWP) of 21 (IPCC, 1996a). The value of abated methane, as well as other GHGs, can thus be stated in terms of dollars per metric ton of carbon equivalent ($/TCE). Throughout the analysis, energy market prices are aligned to $0/TCE. This value represents a scenario where no additional price signals from GHG abatement values exist to motivate emission reductions; all reductions are due to responses to market prices for natural gas. As a value is placed on GHG reductions in terms of $/TCE, these values are added to energy market prices and allow for additional emission reductions to clear the market.

A benefit-cost analysis is applied to the opportunities for emission reductions and is defined as:

- **Benefits.** Benefits are calculated from the amount of methane saved by implementing the options multiplied by the value of the methane saved as its use as an energy resource; plus the value of methane as an emission reduction of a GHG, if available;
- **Costs (including capital expenditures and operation and maintenance expenses).** The costs of implementing specific reduction options are estimated for four of the five major anthropogenic sources. The applied discount rates are particular to each source-specific

analysis and set at eight percent for the aggregate analysis.[4] In the source-specific analyses, different discount rates are used to determine cost-effective reductions.

Because nearly all of the technologies and practices for reducing methane emissions produce or save energy, energy prices are a key driver of the cost analyses. The value of the energy produced or saved offsets to various degrees the capital and operating costs of reducing the emissions. Higher energy prices offset a larger portion of these costs, and in some cases make the technologies and practices profitable.[5]

In the source-specific analyses, energy market prices, in 1996 U.S. dollars, are used to establish whether an option is cost-effective. These prices are established based on the following approaches:

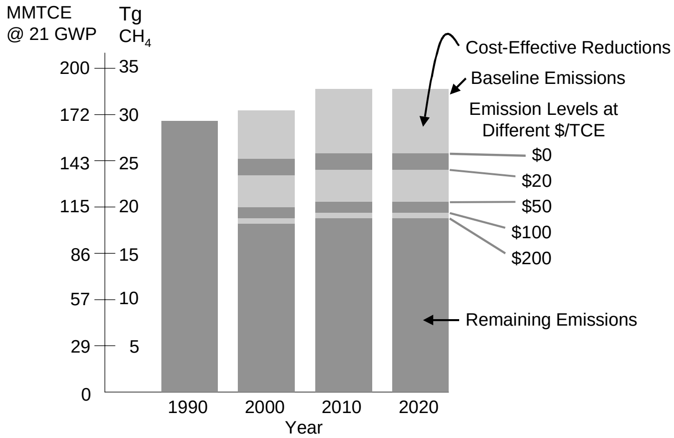
- For landfills, both electricity and natural gas prices are used in the analysis since landfills sell gas directly to consumers or use the recovered gas to generate electricity. For electricity prices, the analysis uses an estimated price of \$0.04/kWh to represent the value of electricity close to distribution systems and receiving a renewable energy premium. For natural gas, the price used is \$2.74/MMBtu. In this case, the analysis uses the average industrial gas price discounted by 20 percent to adjust for the lower Btu content of landfill gas (EIA, 1997).
- Coal mine methane is sold as natural gas to interstate pipelines, used to generate electricity, or used on-site. For natural gas, coal mine methane is valued at \$2.53/MMBtu, which is the average delivered price for natural gas in Alabama, Indiana, Kentucky, and Ohio. The electricity generated from coal mines is valued at \$0.03/kWh to reflect the greater distance from distribution systems.
- The set of energy prices for natural gas systems depends on where the emissions are reduced. Production emission reductions are valued at the average wellhead price of \$2.17/MMBtu; transmission savings are valued at \$2.27/MMBtu; and distribution system savings are valued at \$3.27/MMBtu (EIA, 1997).
- Livestock manure methane is used to generate electricity for farm use and offset electricity consumption from a utility grid. The analysis uses \$0.09/kWh for dairy farms and \$0.07/kWh for swine farms. These prices are weighted averages of retail commercial electricity rates based on dairy and swine populations, respectively. The national average price was discounted by \$0.02/kWh to reflect the effects of interconnect and demand charges and other associated costs.

In order to incorporate methane emission reduction values into the analysis, various \$/TCE values are translated into equivalent electricity and gas prices using the heat rate of the engine-generator (for electricity), the energy value of methane (1,000 Btu/cubic foot), and a GWP of 21. See individual chapters for greater detail.

5.0 Achievable Emission Reductions and Composite Marginal Abatement Curve

The aggregate results of the analyses are presented in this section. Exhibit 1-5 shows estimated total U.S. reductions at various values for abated methane in \$/TCE. These reductions are the summation of source-specific results where different discount rates are applied to each source: 8 percent for landfills, 10 percent for livestock manure management, 15 percent for coal mining, and 20 percent for natural gas systems. For 2010, EPA estimates that up to 34.8 MMTCE (6.1 Tg) of reductions are possible at energy market prices or \$0/TCE. Consequently, methane emissions could be reduced below 1990 emissions of 169.9 MMTCE (29.7 Tg) if many of the identified opportunities are thoroughly implemented. At higher emission reduction values, more methane reductions could be achieved. For example, EPA's analysis indicates that with a value of \$20/TCE for abated methane

Exhibit 1-5: U.S. Baseline Emissions and Potential Reductions (source-specific discount rates) (MMTCE)



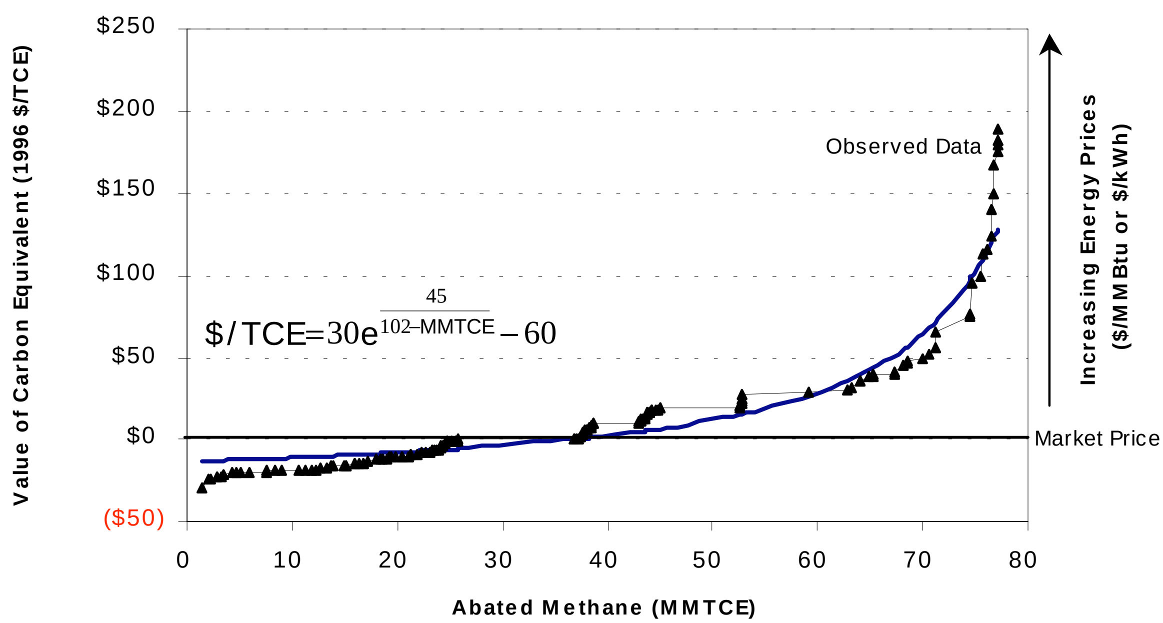
	2000	2010	2020
Baseline Emissions	173.9	186.0	183.7
Cumulative Reductions			
at $0/TCE	30.8	34.8	35.0
at $10/TCE	36.4	42.3	40.9
at $20/TCE	41.7	50.3	47.4
at $30/TCE	54.6	61.7	58.7
at $40/TCE	56.2	63.5	61.0
at $50/TCE	59.5	66.9	64.8
at $75/TCE	64.3	71.9	70.7
at $100/TCE	67.2	74.9	74.0
at $125/TCE	68.4	76.2	75.5
at $150/TCE	68.7	76.5	75.9
at $175/TCE	69.0	76.8	76.2
at $200/TCE	69.2	77.0	76.5
Remaining Emissions	104.7	108.9	107.2

added to the energy market price, U.S. reductions could reach 50.3 MMTCE (8.8 Tg) in 2010.

Exhibit 1-6 presents EPA's aggregate U.S. methane marginal abatement curve (MAC) for 2010 which is calculated using a discount rate of eight percent equally applied to all sources in order to properly construct the curve.[4] The MAC illustrates the amount of reductions possible at various values for methane and is derived by rank ordering individual opportunities by cost per emission reduction amount (IPCC, 1996b). Any point along a MAC represents the marginal cost of abating an additional amount of methane. A complete picture is revealed when the prevailing market prices for energy and GHG reductions are applied to the MAC to show the amount of available emissions that clear the market. Any "below-the-line" reduction amounts, with respect to $0/TCE, illustrate this dual price-signal market, i.e., energy market prices and emission reduction values.

The MAC illustrates the following key findings. First, substantial emission reductions, 36.8 MMTCE (6.4 Tg), can be cost-effectively achieved, that is, at energy market prices with no additional emissions reduction values or $0/TCE. Second, at $20/TCE and $50/TCE

Exhibit 1-6: Marginal Abatement Curve for U.S. Methane Emissions in 2010 (at an 8 percent discount rate)



estimated reductions are 52.6 MMTCE (9.2 Tg) and 70.0 MMTCE (12.2 Tg), respectively. Third, at $100/TCE, achievable reductions are estimated at 75.5 MMTCE (13.2 Tg). Finally, above $100/TCE, the MAC becomes inelastic, that is, non-responsive to increasing methane values which indicates the limits of the options considered. At higher energy and emission reduction values, additional options, which have yet to be developed, will likely become available. By not estimating potential, future higher-cost options, this analysis under-estimates the ability to reduce emissions at higher values for abated methane.

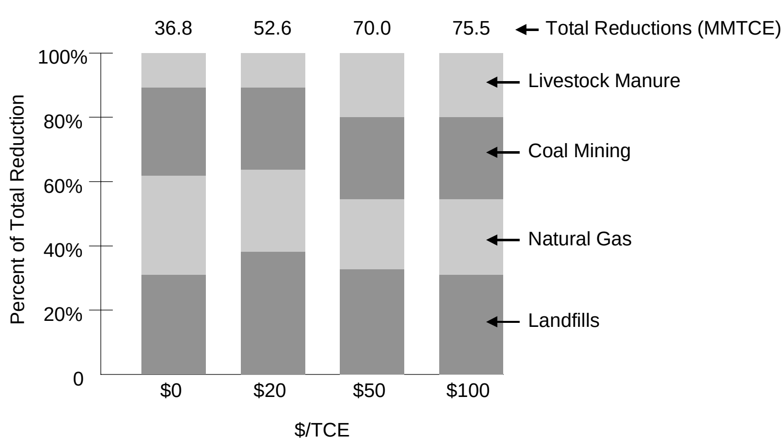
The MAC is based on approximately 160 observations. These results are from the benefit-cost analyses conducted on the identified opportunities to abate methane emissions.

An analytic approximation of the MAC is calculated in order to make these results useful to larger economic models concerned with GHG reduction costs. The estimated relationship is obtained by using an exponential trendline, expressing the relationship between methane values/abatement costs and the quantity of abated methane.[6] This function is described as: $/TCE = 30 exp [45/(102 – MMTCE)]-60.

Exhibit 1-7 illustrates the relative contribution of each of the sources to reducing methane emissions. Of the four sources, landfills contribute the most to the emission reductions, i.e., over one-quarter of the reductions. Coal mining and natural gas systems each account for about one-quarter of total emission reductions. Livestock manure contributes up to about one-fifth of the reductions, primarily at higher energy prices and emission reduction values. Several key aspects of the analysis are highlighted below:

- The methane recovery efficiency at landfills is estimated at 75 percent for all landfills and is assumed to remain constant. Below $0/TCE, using the recovered methane directly in boilers or similar equipment is more cost-effective than producing electricity in most cases.
- Because of the diverse sources of methane emissions from natural gas systems, a large number of technologies and practices are evaluated. Among the options evaluated, replacing high-bleed pneumatic devices and techniques for reducing emissions from compressor stations are the most significant in terms of cost-effective emission reductions.
- The coal mine methane analysis includes a catalytic oxidation technology for recovering heat energy from the low concentration of methane in coal mine ventilation air. This technology becomes profitable at approximately $30/TCE, leading to substantial emission reductions from underground mining. Below this value, methane recovery is the primary method of reducing emissions.
- The principal methods for reducing methane emissions from livestock manure are to collect and combust the methane that would other-

Exhibit 1-7: Portion of Emission Reductions from Each Source in 2010 (at an 8 percent discount rate) (MMTCE)



wise be emitted from liquid manure management systems. Anaerobic digester technologies, the principal technology evaluated, produce multiple benefits, including odor reduction at swine farms as well as producing energy for on-farm use.

6.0 Significance of This Analysis

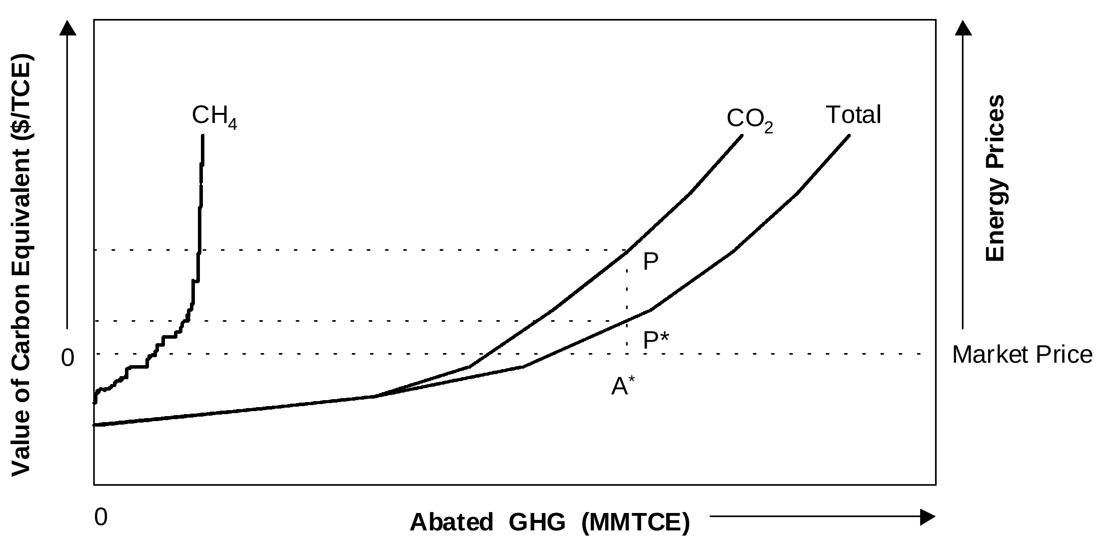
To date, most economic analyses of GHG reduction opportunities have focused on energy-related carbon emissions since CO_2 currently accounts for about 82 percent of the total U.S. emissions (weighted by 100-year global warming potentials) (EPA, 1999). The analyses provided in this report can be integrated with CO_2 economic analyses to provide a broader understanding of reducing the total cost of achieving GHG emission reductions. Recent comprehensive studies by the Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology (Reilly, 1999) and the Australian Bureau for Agricultural and Resource Economics (Brown, 1999) show that a multigas mitigation strategy can reduce the costs of achieving GHG emission reductions. Both of these studies utilized EPA's preliminary cost analysis on methane reductions (EPA, 1998).

The economic benefits of pursuing a mitigation strategy that includes methane is shown in Exhibit 1-8. Illustrative MACs are presented for methane (CH_4), CO_2, and for the summation of the two showing additional emission reductions with increases in $/TCE. Given a reduction target, A*, for both gases, the total cost of achieving that target is lower if available methane reductions are included than if only CO_2 reductions are made. At increasing values for emission reductions, more costly CO_2 reductions can be substituted by lower cost methane reductions, when available, thereby lowering the marginal cost, shown as the movement from P to P∗, and decreasing the total cost (the integral or area under the curve).

7.0 Background to This Report

EPA's first major report on methane appeared in 1993 as *Anthropogenic Methane Emissions in the United States, Estimates for 1990, Report to Congress* (1993a). This report was the first effort to increase general knowledge about methane emissions by presenting a detailed and comprehensive treatment of the sources of methane emissions as part of the effort to quantify these emissions. Following this report, EPA published Opportunities to Reduce Anthropogenic

Exhibit 1-8: Illustrative MACs for Methane and Carbon Dioxide



Methane Emissions in the United States (EPA, 1993b). For all major sources of methane emissions – landfills, natural gas systems, coal mines, livestock manure, and livestock enteric fermentation – this report described the technologies available that could reduce emissions. Using these technologies, the report estimated the amount of emission reductions that would be technically feasible and the amount of emission reductions that would be economically justified. The latter included taking into account the value of methane (as a fuel) as well as a value for emission reductions.

Since the publication of these reports, EPA has sponsored additional work in the estimation of baseline emissions and the costs of emission reductions. These efforts include, for example, a 15-volume report on Methane Emissions from Natural Gas Systems co-sponsored with the Gas Research Institute (EPA/GRI, 1996).

The information from the various voluntary programs in addition to other research was used extensively in the EPA's Costs of Reducing Methane Emissions in the United States, Preliminary Report (EPA, 1998). This report first developed the overall approach for estimating the cost of emission reductions and was reviewed by a number of industry and source experts. Their subsequent recommendations as well as other improvements have been incorporated into the current document.

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9.0 Explanatory Notes

[1] The enhanced greenhouse effect is the concept that the natural greenhouse effect has been enhanced by anthropogenic emissions of greenhouse gases. Increased concentrations of carbon dioxide, methane, and nitrous oxide, CFCs, HFCs, PFCs, SF_6, and other photochemically important gases caused by human activities such as fossil fuel consumption, trap more infra-red radiation, thereby exerting a warming influence on climate. Exhibit 1-1, which illustrates relative contributions to the enhanced greenhouse effect by gas, is based on the increase in atmospheric concentrations at each gas between pre-industrial times and 1992. This exhibit does not include methane's indirect effect of tropospheric ozone and stratospheric water vapor production, which are estimated to be equivalent to about 25 percent of the direct effects.

[2] Microbial communities in upper soils constitute a much smaller methane sink.

[3] The U.S. CCAP was initiated in 1993 and designed to reduce U.S. emissions of greenhouse gases. CCAP Programs promote actions that are both cost-effective for individual private sector participants as well as beneficial to the environment.

[4] In the construction of a national or aggregate marginal abatement curve, a single discount rate is applied to all sources in order to equally evaluate various options. Given a particular value for abated methane, all options up to and including that value can be cost-effectively implemented. An eight percent discount rate, the lowest in the range of the source-specific rates (8 to 20 percent), is used since it is closer to social discount rates employed in national level analyses. The results from the single, eight percent discount rate analysis are slightly higher than the results where source-specific discount rates are used because a lower discount rate reduces project costs enabling additional reductions.

[5] The effects of energy price changes are analyzed only from the revenue side and do not consider effects to capital and O&M expenses. Therefore, the projected methane reductions may be overestimated for increases and underestimated for decreases to energy prices.

[6] For the estimated relationship, $\$/TCE = 30 \exp [45/(102 – MMTCE)] - 60$, the regression analysis yielded an R^2 of 0.95. Conversely, the relationship also can be expressed in standard economic terms as the quantity of abated methane as a function of price ($/TCE): $MMTCE = 102 – 45/\ln [(\$/TCE+60)/30]$.

Appendix I: Supporting Material for Composite Marginal Abatement Curve

This appendix presents the data EPA used to develop the composite marginal abatement curve (MAC). The first section summarizes the incremental emissions reductions associated with each source, i.e., landfills, natural gas systems, coal mining, and livestock manure. The second section presents the approach to fit an equation to the MAC data.

I.1 Estimates for Composite Marginal Abatement Curve

This section presents estimates of the incremental emission reductions for each combination of carbon equivalent value and methane source. Exhibit I-1 presents these estimates. The exhibit also includes the cumulative emission reductions. These cumulative emission reductions form the composite MAC for 2010.

Exhibit I-1: Composite Marginal Abatement Curve Schedule of Options for 2010

Value of Carbon Equivalent $/TCE	Incremental Reductions (MMTCE)	Source	Cumulative Reductions (MMTCE)	Value of Carbon Equivalent $/TCE	Incremental Reductions (MMTCE)	Source	Cumulative Reductions (MMTCE)
($30.00)	0.29	Manure-Dairy	0.29	($16.32)	0.25	Coal	13.91
($30.00)	1.23	Manure-Swine	1.52	($16.00)	0.98	Natural Gas	14.89
($23.72)	0.45	Natural Gas	1.98	($15.74)	0.19	Natural Gas	15.08
($23.62)	0.23	Natural Gas	2.20	($15.67)	0.09	Natural Gas	15.17
($23.24)	0.64	Natural Gas	2.85	($15.11)	0.73	Natural Gas	15.89
($23.01)	0.12	Natural Gas	2.96	($14.45)	0.05	Natural Gas	15.95
($22.95)	0.24	Natural Gas	3.20	($14.41)	0.35	Natural Gas	16.30
($20.85)	0.32	Natural Gas	3.52	($14.14)	0.41	Coal	16.71
($20.00)	0.77	Manure-Dairy	4.29	($14.02)	0.14	Natural Gas	16.86
($19.86)	0.33	Natural Gas	4.62	($13.41)	0.29	Coal	17.15
($19.77)	0.42	Natural Gas	5.04	($12.17)	0.90	Natural Gas	18.04
($19.51)	0.87	Coal	5.91	($11.78)	0.31	Coal	18.35
($19.32)	1.63	Natural Gas	7.54	($11.50)	0.26	Coal	18.61
($19.18)	0.01	Natural Gas	7.55	($11.32)	0.41	Coal	19.02
($19.14)	0.79	Coal	8.34	($11.01)	0.20	Natural Gas	19.22
($19.13)	0.59	Natural Gas	8.93	($10.65)	0.04	Natural Gas	19.27
($18.96)	1.63	Coal	10.55	($10.59)	0.16	Coal	19.43
($18.87)	0.77	Coal	11.32	($10.50)	0.42	Coal	19.84
($18.69)	0.57	Coal	11.89	($10.39)	0.65	Natural Gas	20.49
($18.42)	0.48	Coal	12.37	($10.28)	0.02	Natural Gas	20.52
($16.86)	0.39	Natural Gas	12.76	($10.00)	0.62	Manure-Dairy	21.14
($16.70)	0.43	Natural Gas	13.20	($9.51)	0.04	Natural Gas	21.18
$16.41)	0.47	Coal	13.67	($9.23)	0.19	Coal	21.37

Exhibit I-1: Composite Marginal Abatement Curve Schedule of Options for 2010 (continued)

Value of Carbon Equivalent $/TCE	Incremental Reductions (MMTCE)	Source	Cumulative Reductions (MMTCE)	Value of Carbon Equivalent $/TCE	Incremental Reductions (MMTCE)	Source	Cumulative Reductions (MMTCE)
($9.16)	0.56	Natural Gas	21.93	$12.41	0.09	Coal	43.32
($7.87)	0.47	Coal	22.40	$12.78	0.11	Coal	43.43
($7.68)	0.38	Coal	22.78	$12.87	0.09	Coal	43.52
($7.50)	0.39	Natural Gas	23.17	$14.32	0.03	Coal	43.55
($6.92)	0.06	Natural Gas	23.24	$15.60	0.16	Coal	43.71
($6.77)	0.33	Coal	23.57	$16.23	0.07	Coal	43.78
($6.50)	0.09	Coal	23.66	$16.51	0.14	Coal	43.92
($6.23)	0.22	Coal	23.88	$16.78	0.11	Coal	44.03
($4.77)	0.34	Coal	24.21	$16.87	0.03	Coal	44.06
($3.80)	0.01	Natural Gas	24.22	$17.51	0.09	Coal	44.15
($3.23)	0.20	Coal	24.42	$18.42	0.06	Coal	44.21
($2.50)	0.14	Coal	24.56	$18.71	0.06	Natural Gas	44.27
($1.61)	0.01	Natural Gas	24.57	$18.84	0.35	Natural Gas	44.63
($1.41)	0.17	Coal	24.74	$18.84	0.22	Natural Gas	44.84
($1.32)	0.07	Coal	24.81	$19.06	0.14	Natural Gas	44.98
($0.86)	0.27	Coal	25.07	$19.69	0.06	Coal	45.04
($0.82)	0.60	Natural Gas	25.67	$20.00	0.20	Manure-Dairy	45.24
($0.59)	0.03	Coal	25.70	$20.00	1.54	Manure-Swine	46.78
($0.05)	0.10	Coal	25.80	$20.00	5.79	Landfills	52.57
$0.00	0.50	Manure-Dairy	26.30	$21.14	0.04	Coal	52.62
$0.00	10.55	Landfills	36.85	$21.51	0.02	Coal	52.63
$0.41	0.06	Coal	36.91	$22.87	0.07	Coal	52.70
$0.95	0.16	Coal	37.07	$23.96	0.05	Coal	52.75
$1.05	0.07	Coal	37.13	$24.51	0.03	Coal	52.77
$1.32	0.25	Coal	37.38	$24.65	0.00	Natural Gas	52.77
$2.05	0.15	Coal	37.53	$27.87	0.06	Coal	52.83
$3.51	0.15	Natural Gas	37.68	$29.70	6.28	Coal	59.10
$4.96	0.02	Coal	37.70	$30.00	0.18	Manure-Dairy	59.28
$5.23	0.24	Coal	37.94	$30.00	2.28	Manure-Swine	61.57
$5.25	0.02	Natural Gas	37.96	$30.00	1.22	Landfills	62.79
$6.45	0.14	Natural Gas	38.10	$31.59	0.51	Natural Gas	63.30
$6.58	0.04	Natural Gas	38.14	$35.52	0.77	Natural Gas	64.07
$6.60	0.10	Natural Gas	38.24	$35.52	0.00	Natural Gas	64.07
$7.19	0.03	Natural Gas	38.27	$38.14	0.87	Natural Gas	64.94
$7.62	0.21	Natural Gas	38.47	$38.60	0.42	Natural Gas	65.36
$9.32	0.18	Coal	38.65	$39.77	0.00	Natural Gas	65.36
$9.59	0.03	Coal	38.68	$40.00	0.16	Manure-Dairy	65.52
$10.00	0.31	Manure-Dairy	39.00	$40.00	1.45	Manure-Swine	66.97
$10.00	0.12	Manure-Swine	39.11	$40.00	0.29	Landfills	67.26
$10.00	3.89	Landfills	43.01	$40.88	0.00	Natural Gas	67.26
$11.23	0.03	Coal	43.04	$45.21	0.94	Natural Gas	68.20
$11.41	0.04	Coal	43.08	$47.09	0.32	Natural Gas	68.52
$11.69	0.07	Coal	43.14	$47.54	0.02	Natural Gas	68.54
$12.04	0.00	Natural Gas	43.14	$50.00	0.16	Manure-Dairy	68.70
$12.14	0.09	Coal	43.23	$50.00	1.18	Manure-Swine	69.88

Exhibit I-1: Composite Marginal Abatement Curve Schedule of Options for 2010 (continued)

Value of Carbon Equivalent $/TCE	Incremental Reductions (MMTCE)	Source	Cumulative Reductions (MMTCE)	Value of Carbon Equivalent $/TCE	Incremental Reductions (MMTCE)	Source	Cumulative Reductions (MMTCE)
$50.00	0.11	Landfills	69.98	$100.00	0.02	Landfills	75.54
$52.10	0.67	Natural Gas	70.65	$113.08	0.12	Natural Gas	75.66
$56.12	0.56	Natural Gas	71.22	$116.47	0.45	Natural Gas	76.10
$65.77	0.00	Natural Gas	71.22	$125.00	0.30	Manure-Dairy	76.41
$75.00	0.42	Manure-Dairy	71.63	$125.00	0.08	Manure-Swine	76.49
$75.00	2.77	Manure-Swine	74.40	$140.29	0.01	Natural Gas	76.50
$75.00	0.05	Landfills	74.45	$150.00	0.27	Manure-Dairy	76.77
$76.24	0.08	Natural Gas	74.53	$166.22	0.03	Natural Gas	76.80
$95.34	0.21	Natural Gas	74.74	$175.00	0.23	Manure-Dairy	77.03
$95.47	0.00	Natural Gas	74.74	$188.35	0.07	Natural Gas	77.10
$100.00	0.38	Manure-Dairy	75.12	$200.00	0.19	Manure-Dairy	77.29
$100.00	0.40	Manure-Swine	75.52				

I.2 Equation for Composite Marginal Abatement Curve

The relationship between the additional value of carbon equivalent ($/TCE) and the cumulative emission reductions, i.e., abated methane in MMTCE is shown in Exhibit II-2. The cumulative emission reductions increases relatively slowly as a function of the value of carbon equivalent. As the cumulative emission reductions reach about 75 MMTCE, the reduction plateau and cannot be further abated at higher $/TCE values. In order to represent the steepness of the curve at values close to 75 MMTCE, EPA determined a best-fit curve based on the data points. This equation is defined by:

$$y = \text{parameter}_1 * \exp\,[\text{parameter}_2\ /\ (\max - x)] \quad \text{offset}$$

where:
y = additional value of carbon equivalent ($/TCE)
x = cumulative emission reductions (MMTCE)
parameter_1, parameter_2, offset, and max = determined parameters

All values of x, i.e., cumulative emission reductions, must be less than the value of max. This curve has the property that as the x value increases to the value of max, the y value will tend to infinity, so the curve will approximate the steep rise at the maximum x value.

EPA used the method of least squares to find the best fitting curve. This method estimates the parameters by minimizing the mean square error (MSE), i.e., the average squared difference between the actual and fitted values of y: MSE = $(\text{actual } y \quad \text{fitted } y)^2 / n$, where n is the number of pairs, i.e., 159 pairs of abated methane and additional value of carbon equivalent. The minimum MSE is 68.6. The fitted parameters are:

- offset = 60
- parameter_1 = 30
- parameter_2 = 45
- max = 102

The resulting equation is given by:

$y = 30 * \exp[45/(102\text{-}x)] - 60$

The squared correlation coefficient (R squared) between the actual and predicted values of *y* is 0.95, showing a reasonably good fit on a scale of zero to one, one being a perfect fit. Although the model was fitted using the method of least squares, the optimum least squares solution for this problem is also the solution with the maximum possible R squared. Exhibit II-2 presents the 159 data points and the fitted curve.

Exhibit II-2: Marginal Abatement Curve for U.S. Methane Emissions in 2010